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# CEDR Contractor Report 2019-03

# Definition and Validation of a Smart Infrastructure Access Policy Utilising Performance-Based Standards

## CEDR Call 2015: Freight and Logistics in a Multimodal Context

May 2019

# Definition and Validation of a Smart Infrastructure Access Policy Utilising Performance-Based Standards

## CEDR Call 2015: Freight and Logistics in a Multimodal Context

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# Abbreviations

General:

| | |
|---|---|
| ABS | Anti-lock Braking System |
| CEDR | Conference of European Directors of Roads |
| EMS | European Modular System |
| EU | European Union |
| FALCON | Freight and Logistics in a Multimodal Context |
| HCV | High Capacity Vehicle |
| PBS | Performance Based Standards |
| RRCU | Rearmost Roll-Coupled Unit |
| SIAP | Smart Infrastructure Access Policy |

Performance standards:

| | |
|---|---|
| St. | Startability |
| Gr. A | Gradeability A |
| Gr. B | Gradeability B |
| AC | Acceleration Capability |
| LSSP | Low-Speed Swept Path |
| FS | Frontal Swing |
| DoM | Difference of Maxima |
| MoD | Maximum of Difference |
| TS | Tail Swing |
| STFD | Steer-Tyre Friction Demand |
| DTFD | Drive-Tyre Friction Demand |
| TC | Turning Circle |
| SRT | Static Rollover Threshold |
| RA | Rearward Amplification |
| HSTO | High-Speed Transient Off-tracking |
| HSSO | High-Speed Steady-state Off-tracking |
| DLTR | Dynamic Load Transfer Ratio |
| YDC | Yaw Damping Coefficient |
| TASP | Tracking Ability on a Straight Path |

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# Executive Summary


The FALCON project ("Freight and Logistics in a Multimodal Context") is a collaborative effort funded by the Conference of European Directors of Roads (CEDR) and has set out to address ambitious carbon emission reduction targets set by the European Commission. A primary goal of the project is to define a potential Performance-Based Standards (PBS) framework for cross-border road freight transport in Europe. Such a framework would accommodate high capacity vehicles, which have been shown to have a large beneficial impact on road freight transport efficiency and emissions. This report details the work of FALCON tasks 3.1, 3.5 and 3.6, in which a proposed PBS framework is formulated through a simulation-based analysis of on-road vehicle behaviour and impact on the infrastructure.

## Summary of methodology

*Representative heavy vehicle fleet*

A representative fleet of heavy vehicle combinations was formulated in collaboration with industry. These vehicles were loaded with selected European modular loading units, considering both a representative loading scenario (based on observed data) and a heavier critical loading scenario. The fleet included conventional 96/53/EC-compliant combinations, EMS-type combinations, and longer (>30 m) combinations which have been tested in isolated national pilot programmes. In total, 27 combinations were considered, ranging from 16.2 m and 29.7 tonnes, up to 36.5 m and 73.8 tonnes. The fleet is summarised in Table 1.

*Selection of Performance-Based Standards to consider*

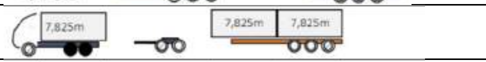
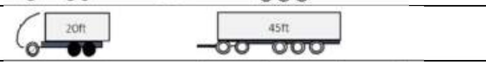
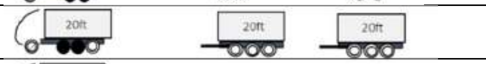
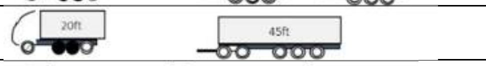
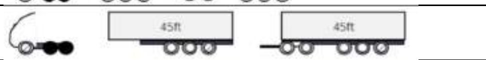
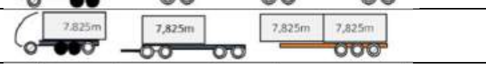
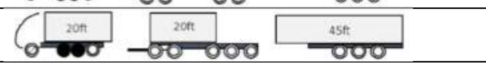
The literature was consulted to identify all existing performance-based standards for heavy vehicles which could be applicable to the European case. Standards were adopted from the Australian PBS framework [1], Directive 97/27/EC [2], Netherlands Directive JBZ 2013/ 9832 [3], Canadian PBS [4], and UNECE regulations [5], which included considerations for winter conditions. The result was a set of 27 performance standards/considerations, covering driveability, manoeuvrability, high-speed stability, winter conditions, bridge loading, and road wear impact. The full range of standards considered is given in Table 2.

*Simulations*

An extensive range of simulations was carried out to assess the performance of the representative fleet against all of the considered performance standards. The simulation results, together with knowledge of existing European infrastructure (FALCON Task 3.2), existing vehicle regulations throughout Europe and existing PBS schemes throughout the world (FALCON Task 3.3), and infrastructure design criteria and legislation throughout Europe (FALCON Task 3.4), would inform the following:

- Which standards are appropriate for Europe and which are not appropriate or redundant?
- Which standards need revisiting, either in their definition or performance criteria?
- Which vehicle combinations perform poorly, and require active intervention systems?
- Is there a need for additional performance standards to address European winter conditions?
- What methodologies are appropriate for assessing bridge and road wear impact?

*Table 1: Representative vehicle fleet (r/c = representative/critical loading)*

| Vehicle group and code † | | Vehicle description | Length (m) | Mass (r/c) (tonnes) | |
|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) |  | 16.2 | 33.5 | 41.3 |
| 1.2 | TR6x2-ST3 (2x7.8m) |  | 18.5 | 37.4 | 46.2 |
| 1.3 | TR4x2-ST3 (13.6m) |  | 16.4 | 29.7 | 37.7 |
| 1.4 | TR4x2-ST3 (14.9m) |  | 17.7 | 31.8 | 43.3 |
| 2.1 | TK6x2-CT2 (2x7.8m) |  | 19.3 | 35.4 | 44.3 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) |  | 18.5 | 35.4 | 44.3 |
| 2.3 | TK6x2-CT3(2x20ft) |  | 16.9 | 29.8 | 35.9 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) |  | 23.7 | 47.3 | 58.1 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) |  | 27.9 | 53.3 | 66.6 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) |  | 27.7 | 56.1 | 69.4 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) |  | 23.9 | 48.5 | 59.3 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) |  | 26.7 | 53.2 | 66.5 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) |  | 26.7 | 53.2 | 66.5 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) |  | 24.4 | 46.0 | 56.8 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) |  | 25.0 | 47.0 | 57.8 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) |  | 27.9 | 51.4 | 64.7 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) |  | 24.3 | 43.2 | 52.4 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) |  | 24.9 | 46.7 | 57.6 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) |  | 31.1 | 62.6 | 78.2 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) |  | 31.6 | 63.6 | 79.2 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) |  | 36.5 | 73.8 | 91.6 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) |  | 31.2 | 62.5 | 76.4 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) |  | 35.4 | 71.0 | 88.7 |
| 6.2 | TK6x4-DY2-LT2-ST3 (2x7.8m+45ft) |  | 31.7 | 60.0 | 73.9 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) |  | 36.5 | 66.5 | 84.2 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) |  | 36.5 | 70.8 | 88.6 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) |  | 31.6 | 59.7 | 73.6 |

† ***TR***axb= Tractor (a = # of wheels, b = # of driven wheels), ***TK***axb = Rigid truck (a = # of wheels, b = # of driven wheels), ***ST***a = Semi-trailer (a = # of axles), ***CT***a = Centre-axle trailer (a = # of axles), ***FT***a+b = Full trailer (a = # of front axles, b = # of rear axles), ***LT***a = Link trailer (a = # of axles), ***DY***a = Dolly (a = # of axles)

*Table 2: Performance standards evaluated*

| Standard | Manoeuvre | Source |
|---|---|---|
| Driveability | | |
| Startability | Start on incline | Australian PBS |
| Gradeability A (Maintain motion) | Maintain motion on an incline | Australian PBS |
| Gradeability B (Maintain speed) | Maintain speed on 1% incline | Australian PBS |
| Acceleration Capability | Accelerate from rest | Australian PBS |
| Manoeuvrability | | |
| Low-Speed Swept Path | 90° turn, radius 12.5 m | Australian PBS |
| Frontal Swing | 90° turn, radius 12.5 m | Australian PBS |
| Difference of Maxima | 90° turn, radius 12.5 m | Australian PBS |
| Maximum of Difference | 90° turn, radius 12.5 m | Australian PBS |
| Tail Swing | 90° turn, radius 12.5 m | Australian PBS |
| Steer-Tyre Friction Demand | 90° turn, radius 12.5 m | Australian PBS |
| EU Turning circle | Roundabout, OR = 12.5 m (270°) | Directive 97/27/EC |
| NL TC 1 (inner radius & tail swing) | Roundabout, OR = 12.5 m (270°) | JBZ 2013/ 9832 (NL) |
| NL TC 2 (inner radius & tail swing) | Roundabout, OR = 12.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 3 (inner radius & tail swing) | Roundabout, OR = 14.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 4 (inner radius & tail swing) | Roundabout, OR = 16.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 5 (inner radius & tail swing) | Roundabout, OR = 19.4 m (120°) | Extrapolated from JBZ |
| NL TC 6 (inner radius & tail swing) | Roundabout, OR = 22.0 m (120°) | Extrapolated from JBZ |
| High-speed stability | | |
| Static Rollover Threshold | Tilt-table / Constant radius turn | Australian PBS |
| Rearward Amplification (RRCU) | Single lane change (ISO 14791) | Australian PBS |
| Rearward Amplification (last trailer) | Single lane change (ISO 14791) | Australian PBS (modified) |
| High-Speed Transient Off-tracking | Single lane change (ISO 14791) | Australian PBS |
| Yaw Damping Coefficient | Pulse steer input @ 80 km/h | Australian PBS |
| Tracking Ability on a Straight Path | Rough road & cross slope at speed | Australian PBS |
| High-Speed Steady-State Off-tracking | Constant radius turn | Canada |
| Dynamic Load Transfer Ratio (RRCU) | Single lane change (ISO 14791) | Canada |
| Winter conditions | | |
| Low friction braking | Straight line ABS stop (low mu) | ECE Reg. 16 |
| Steer tyre friction demand | 90° turn, radius 12.5 m (low mu) | Australian PBS, low mu |
| Drive tyre friction demand | 90° turn, radius 12.5 m (low mu) | Canada, but Aus. manoeuvre |
| Low friction startability | Start on incline (low mu) | Australian PBS, low mu |
| High-speed dynamics standards | Not yet defined | Not yet defined |
| Infrastructure | | |
| Bridge loading | N/A | Custom approach |
| Road wear | N/A | Custom approach |

Vehicle dynamics simulations were carried out by the CSIR in South Africa using TruckSIM and MATLAB, and additional winter considerations were evaluated by VTI Sweden using MATLAB SimMechanics and existing performance data from Sweden. Existing performance criteria were used as the initial reference for comparing performance. The results of the simulations were used to assess the applicability of the standards considered in the light of numerous factors described above.

Bridge-loading simulations were carried out by IFSTTAR France using the ST1 software. The fleet was assessed against a catalogue of bridges including simply-supported single span bridges, two-span continuous bridges, each at spans of 10, 20, 35, 50 and 100 m, identified in FALCON Task 3.2 [6]. Both the extreme and fatigue effects of shear and bending moments were studied, and the impact was assessed relative to the conventional truck combination 2.1. The results were used to propose a bridge-loading impact assessment methodology which could be suitable for a European PBS framework.

The impact of the representative fleet on roads was assessed by BRRC in Belgium using the Alizé-LCPC software. Four pavement structures were evaluated, including a flexible pavement, a thick bituminous pavement, a semi-rigid pavement, and a concrete pavement. A standard axle of 10kN was used as a reference, and the vehicle combinations were ranked according to aggressiveness. Additional rankings were carried out according to aggressiveness normalised by payload volume, payload mass, and combination mass, using conventional combinations 1.3 and 2.1 as reference vehicles. The results were used to propose a road wear impact assessment methodology which could be suitable for a European PBS framework.

A final set of simulations were carried out by HAN University of Applied Sciences to assist in defining suitable road access levels for the PBS framework. Simulations were carried out using MATLAB and SimMechanics models, cross-validated with the CSIR's models. In these simulations, the representative fleet was assessed against a set of realistic critical infrastructure segments including highway exists, single lane roundabouts, and multi-lane roundabouts. Performance was assessed against failure modes of rollover, jack-knifing, lane departure and inability to maintain speed. The results were used to propose a methodology for matching vehicle performance to a suitable road classification framework on a regional level.

### Summary of recommendations

Based on the simulation results, coupled with the findings of the other FALCON tasks, a final proposal is made which includes the following:

- A review of all performance standards that were considered is given, together with recommendations for which standards are relevant for European PBS, which require tailoring, and how the performance criteria for each standard should be reviewed going forwards for suitability to Europe. This is summarised in Table 3.
- Methodologies for the assessment of bridge-loading and road wear impact of PBS vehicles are proposed. A summary of these is included in Table 3.
- A proposed methodology to match European PBS vehicles with the infrastructure is discussed, and a sample road network classification system is given based on selected infrastructure segments (which may need to be reviewed per jurisdiction). The sample proposal is given in Table 4.

The proposed PBS framework should be accompanied by suitable support programmes and systems which address driver training, speed monitoring, vehicle maintenance, loading control, and vehicle tracking. Reference should be made to the Australian Intelligent Access Programme (IAP) and National Heavy Vehicle Accreditation Scheme (NHVAS) [7], and the South African Road Transport Management System (RTMS) [8]. Any existing equivalent systems in Europe should be used where possible.

*Table 3: Final recommendations for a proposed PBS framework for Europe*

| Performance Standard | Include ? | Recommendations |
|---|---|---|
| Driveability | | |

| | | |
|---|---|---|
| Startability | Y | Consider reducing L1 to 12%. Allow jurisdictions to review criteria based on local road grades. |
| Gradeability A (Maintain motion) | Y | Consider reducing criteria in accordance with adjustments on startability. Allow jurisdictions to define limits on local conditions. |
| Gradeability B (Maintain speed) | Y | Appropriate as is (aligned to speed limits). |
| Acceleration Capability | Y | Review criteria. Allow jurisdictions to review the criteria based on local intersection and crossing geometries. |
| Manoeuvrability | | |
| Low-Speed Swept Path | Y | Criteria too lenient – review against existing European road geometries and roundabout standards. |
| Frontal Swing | Y | Criterion can possibly be reduced to 0.5 m for all levels, based on the fleet assessed. However there is no documented need to reduce the limit below the current 0.7 m. |
| Difference of Maxima | (review) | Potentially too complicated, and not aligned with direct safety risk. Could be removed or replaced with a single standard. Requires further investigation. |
| Maximum of Difference | (review) | |
| Tail Swing | Y | Criteria can possibly be reduced to 0.3 m for all levels (subject to further investigation). Car-carriers should be included in further investigations. |
| Steer-Tyre Friction Demand | Y | The ≤ 80% requirement is possibly too high and should be reviewed. |
| EU turning circle | Y (L1) | Applicable as an additional test for Level 1-type vehicles. |
| Netherlands turning circle | N | Found to offer no additional information vs. LSSP, while requiring multiple different manoeuvres to assess longer vehicle combinations. |
| High-speed stability | | |
| Static Rollover Threshold | Y | Applicable as is. |
| Rearward Amplification (last trailer) | Y | Criterion of 2 requires further review, as appropriate to the rear trailer method, and once the vehicle designs have been optimised further. |
| Rearward Amplification (RRCU) | N | Last trailer method preferable, as the standard has been decoupled from assessing direct rollover risk. |
| Dynamic Load Transfer Ratio | Y | A better indication of rear trailer rollover risk in transient manoeuvres. The criterion of 0.6 may require review in parallel with RA=2. |
| High-Speed Transient Off-tracking | Y | Vehicle and lane widths are similar to Australia and so the criteria may be transferable, but Level 1 vehicles may use minor roads of width 2.5 or 2. 75 m. This requires further investigation. |
| Yaw Damping Coefficient | Y | Applicable as is. |
| Tracking Ability on a Straight Path | N | Found to be highly correlated with HSTO, and prone to simulation error due to complexity. |
| High-Speed Steady-State Off-tracking | N | Found to be highly correlated with vehicle length, but also influenced by vehicle mass. Can be used to inform vehicle length limits per road access level, however for very heavy vehicles (i.e. higher than the loading conditions considered in this study), the influence of mass may become a limiting factor. |
| Winter conditions | | |
| Low friction braking | Y | The faultless function of ABS system is necessary for braking stability of HCVs in winter. |
| Steer-Tyre Friction Demand | N | Shown to be correlated with high friction performance for the fleet considered. High friction criteria could be set accordingly to ensure low friction performance.[1] |
| Drive-Tyre Friction Demand | N | Correlated with high friction performance, and found to be less meaningful than steer tyre friction demand, due to the dissimilar direction of the forces in a two-axle drive bogie. High friction criteria could be set accordingly to ensure low friction performance. |
| Low friction startability | N | Temporary drive axle load proportioning should be permitted to increase drive axle loads as required for starting. |

[1] For the most accurate results, friction demand should be simulated in winter conditions. However, if it is practical to perform all simulations in summer conditions without the need for winter-specific models, then correlation between summer and winter performance can be investigated (as done here) for the specific fleet under concern, and used to set a safe performance level to ensure both summer and winter performance.

| | | |
|---|---|---|
| Low friction high-speed standards | N | A speed reduction to 60 km/h was found to ensure comparable performance to high friction conditions. |
| Infrastructure | | |
| Bridge-loading | Y | The proposed methodology is to: (1) define suitably representative bridge structures to consider which may be region-specific, (2) assess the impact of the representative fleet on the bridges as demonstrated, and (3) fit a suitable bridge formula to the results, matching the order of the formula as required, which could be fitted according to the most aggressive effect. |
| Road wear impact | Y | The proposed methodology is to: (1) use combination 2.1 loaded to 40 tonnes as the reference, (2) select representative road structures applicable to the region (~3), (3) compute the aggressiveness of 2.1 on the road structures as the maximum permitted aggressiveness, (4), assess the aggressiveness of the proposed new vehicle, which should not exceed that of 2.1. Note that aggressiveness should be scaled by payload mass or volume, depending on which is more appropriate for regional traffic. |

*Table 4: Final road classifications proposal*

| Road access level | Description | Vehicles permitted |
|---|---|---|
| 0 | City access | TBC (not considered in this study) |
| 1 | Minor Roads | 1.1, 1.2, 1.3, 1.4 |
| 2 | Inter Urban Arterial Main Express Roads | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.4, 4.3, 4.4, 4.7 |
| 3 | Motorways | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 5.1, 5.2, 5.3, 5.4, 6.1, 6.2, 6.3, 6.4, 6.5 |

## Guidelines for implementation

The implementation of formal PBS schemes and pilot projects in Canada, Australia, Sweden and South Africa serve as a good blueprint for the way forward in adopting PBS in Europe. This will include pre-emptive research projects to assess regional relevance (such as in project FALCON), isolated pilot programmes, and data collection and monitoring. Furthermore, the existing European Modular System, in which vehicles may be up to 25.25 m for cross-border transport, is evidence of a move towards high capacity vehicles, and it is within such a cross-border framework which PBS may be best implemented. The recently ratified Directive (EU) 2015/719 also gives indications of forward-thinking relaxations of length and weight limits where vehicles demonstrate elements of sustainability, such as: axle weight relaxation for vehicles with alternative power sources, length relaxation for trucks with aerodynamic improvements, and height relaxation for vehicles with additional safety features.

These indicate that European PBS may be best implemented through a cross-border exemption system similar to EMS, or possibly could even be adopted as an upcoming revision and extension of the EMS scheme. Alternatively, or in addition, it may be incorporated as future amendments to Directive 96/53/EC, along the lines of Directive 2015/719.

# 1. Introduction

## 1.1. Background

The European Commission has set ambitious carbon emission reduction targets of 20% by 2020 and 80% by 2050, relative to 1990 levels [9]. The European transport sector contributes approximately 20% of current carbon emissions, and of this trucks and buses account for around a quarter [10]. Improving the efficiency of road freight transport is hence pivotal in recent carbon reduction efforts. The use of High Capacity Vehicles (HCVs) is a proven highly effective means of reducing the carbon emissions of road freight transport, which has been demonstrated in numerous countries including Australia [1] and South Africa [11]. In Europe, Directive 96/53EC [12] describes the European Modular System (EMS), which permits individual EU members to allow defined HCV combinations up to 25.25 m in length to operate internally. So far this has been adopted by Sweden, Finland, Netherlands, Germany and Spain [13]–[15]. However, there is a need for a uniform cross-border framework which permits HCVs on designated routes, and which permits HCVs that are more productive than those permitted by EMS in order to make more substantial headway in the reduction of carbon emissions.

The FALCON project ("Freight and Logistics in a Multimodal Context") is a collaborative effort funded by the Conference of European Directors of Roads (CEDR). Its objective is to assess the feasibility of a suitable framework for cross-border HCV transport in Europe. The consortium members consist predominantly of research entities and industry organisations in Europe. As part of this effort, a framework based on Performance-Based Standards (PBS), coupled with a suitable "Smart Infrastructure Access Programme" (SIAP) was to be conceptualized and evaluated, as defined in Tasks 3.1, 3.5 and 3.6 of the FALCON project.

## 1.2. Global PBS Initiatives

PBS initiatives have been implemented to varying degrees of formalisation in a number of countries throughout the world. These initiatives serve as a good backdrop to the current European initiative and provide useful insights into the challenges faced and the processes followed. Some of the most notable examples will be discussed in the current section.

### 1.2.1. Implementation of PBS in Canada

PBS were first introduced in Canada during a successful effort to harmonize heavy vehicle weight and dimension regulations during the mid-1980s [4], [16], [17]. In Canada each province independently controls its own truck size and weight policy, for all roads within its jurisdiction. The Canadian approach [18] sought to achieve regulatory harmonization of size and weight policy by conducting a comprehensive size and weight study based on rigorous scientific study and engineering methods to analyse pavement and vehicle performance.

Using the PBS and the results of the sensitivity analysis, the Implementation Committee developed a set of "vehicle envelopes" defining the general vehicle layout including ranges for certain component variables such as axle spacing and hitch placement [19]. This PBS/Prescriptive approach provides flexibility in design for various vehicle classes. The envelope concept reduces the burden of compliance evaluation by giving the vehicle designer some flexibility for vehicle optimization within a prescriptive regulatory system. To qualify vehicles that are outside of the envelopes, PBS can be used as a compliance tool to judge acceptability.

The specifications were attached to and formed part of the "Federal-Provincial-Territorial Memorandum of Understanding on Interprovincial Weights and Dimensions" ("the M.oU."). The M.o.U. was simply an understanding that each minister would make their best effort to implement the content within their own jurisdiction [4], [16]. Each province and territory have either adopted each M.o.U. vehicle configuration into their regulations or has adapted their regulations so that a vehicle meeting the specification of the M.o.U. can operate within the province or territory on a road network specified by the province or territory. A province and territory may allow other configurations not covered by the M.o.U., either as new vehicles, or as existing vehicles grandfathered from a previous set of regulations, by regulation, or by special permit. A province or territory may allow less restrictive values for certain limits set in the M.o.U., generally higher for a weight limit, shorter for a minimum dimension, longer for a maximum dimension, or may not regulate a particular limit at all.

### 1.2.2. Implementation of PBS in Australia

Australia implemented a nationwide PBS system for regulating weights and dimensions that is tied to a road access network based on freight vehicle class. As with Canada, the Australian PBS was developed in response to what were broadly agreed as inflexible prescriptive heavy vehicle regulations [1]. The original objectives of the Australian PBS effort can be summarized as follows:

1. Provide more sustainable transport systems through improved road vehicle regulations controlling heavy vehicle safety and infrastructure impacts; and
2. Provide more flexible road transport regulations that allow increased innovation and more rapid adoption of new technologies, while providing seamless operations nationally.

The focus of the PBS system was towards individual vehicle assessment spanning the space between generic high productivity vehicle such as B-doubles and highly innovative vehicles that are often required by the agriculture and mining industries.

The road to implementing PBS in Australia was long requiring comprehensive analysis, significant institutional change within a judicious process. The project consisted of six phases [20], [21] spanning some 12 years:

- Phase A: Performance Measures and Standards – identifying the appropriate performance measures and standards and surveying the performance of the current heavy vehicle fleet.
- Phase B: Regulatory and Compliance Processes – establishing a regulatory system in which Performance Based Standards can operate as a seamless national alternative to existing prescriptive regulations including national compliance and enforcement arrangements.
- Phase C: Guidelines – preparing guidelines detailing the procedures and processes for the consistent application of Performance Based Standards.
- Phase D: Legislation – developing the legislative arrangements for Performance Based Standards to operate as an alternative to prescriptive regulations.
- Phase E: Case Studies – assembling work previously conducted and demonstrating the practical application of Performance Based Standards to nationally agreed priorities.
- Phase F: Implementation – putting in place the necessary legislative and administrative systems to allow Performance Based Standards to operate nationally and providing the training and information to support these changes.

### 1.2.3. Implementation of PBS in Sweden

From July 2018, heavy vehicles up to 74 tonnes and 25.25 m have been allowed on a designated part of the road network in Sweden, which is classified as a new category of roads with higher bearing capacity. The new road class, BK4, was added to the three previously existing classes with bearing capacities BK1-BK3. The BK4 road network will be successively expanded by the Swedish Transport Administration (Trafikverket), as a process of infrastructure reinforcement continues.

The access of vehicles heavier than 64 tonnes to the BK4 road network will be regulated using a PBS system, which is defined in a regulation issued by the Swedish Transport Agency (Transportstyrelsen). The new regulation on technical requirements of vehicles heavier than 64t is in effect from May 2018 [22], and includes the following PBS requirements:

- Static Rollover Threshold (≥ 0.35·g, if the vehicle is not equipped with an active rollover prevention system)
- Rearward amplification of yaw rate (≤ 2.4)
- Yaw damping coefficient (≥ 0.15)
- Tracking ability (≤ 0.4 m off-tracking on a straight path with 5% banking)
- Startability (≥ 12%, if the load on driven axles is less than 20% of total weight)
- Engine effect (5 kW/t up to 44t and 2 kW/t for the excessive weight over 44t)
- Coupling strength (according to ISO 18868:2013)
- Parking brake of the towed vehicle (should hold the vehicle on a 12% road grade)
- Braking activation delay for the complete vehicle (≤ 0.6 s, if the vehicle is not equipped with an Electronic Braking System, EBS)

Performance of heavy vehicles will be assessed using a web tool which is publicly available. The web tool uses information available in the registered data of the constituent units to assess the performance of the complete vehicle. The current maximum combination length in Sweden is 25.25 m, however longer heavy vehicles might be allowed in future. Furthermore, dispensations of longer and heavier vehicles have been issued in the recent years. Thus, expansion of the web tool for inclusion of further performance measures, relevant for assessment of longer heavy vehicles, is under investigation.

#### 1.2.4. Implementation of PBS in South Africa

In South Africa’s 2004 National Overload Control Strategy [23], the Department of Transport recommended a combination of Performance-Based Standards (PBS) and self-regulation as a possible solution to the country’s many challenges in the road freight sector, including: reducing the cost of logistics, reducing greenhouse gas emissions, protecting an ageing infrastructure from the impact of ever-growing freight demand, and improving alarming road safety statistics. In 2003, in line with these recommendations, the Council for Scientific and Industrial Research (CSIR), in collaboration with the Department of Transport, initiated a PBS pilot project (known also as the “Smart Truck” programme). Operators who wish to participate in the pilot project are required to be certified with the Road Transport Management System (RTMS) accreditation scheme [24].

A PBS Steering Committee was formed in 2004, with represented stakeholders from government, industry, and academia. A PBS strategy was developed by the committee [25]. A letter of support for the pilot project was issued by the Minister of Transport in January 2006, with the specific requirement that the pilot project should demonstrate improved payload efficiency, vehicle safety and protection of road infrastructure through innovative vehicle design. The Australian performance standards were adopted, except for the infrastructure standards. For infrastructure, existing axle loads limits were retained, and vehicles are required to meet the abnormal load bridge formula. Further, each vehicle has to undergo a road wear impact assessment on selected South African road structure designs. Over time, some of the interpretations and pass/fail criteria have been adjusted based on observations in the South African PBS pilot project and existing regulations. For example:

1. The tail swing reference point was updated to accommodate the fact that trailers could be significantly wider than tractor units, compared to Australia.
2. The pass criteria for MoD and DoM were made less strict, due to observed shortcomings in the existing vehicle regulations, allowing for wider trailers and longer front overhangs compared with Australia.

3. The pass criteria for TASP were made less strict, again to accommodate the wider trailers in South Africa.

In 2007, the first two PBS demonstration vehicles were introduced in the forestry industry in KwaZulu-Natal. By 2017 there were 245 demonstration vehicles, in 10 industries, primarily in the provinces of KwaZulu-Natal, Mpumalanga, and Limpopo. Each vehicle is systematically and continually monitored, and monitoring data are being continually collated and studied by the CSIR and project partners and collaborators in industry and academia, in order to objectively evaluate and validate the veracity of the project impact. Vehicles operating in the pilot project are operating under abnormal load permits, currently the only legal mechanism to operate these vehicles on public roads during the pilot phase.

The project has generated over 100 000 000 truck kilometres of data to date, which is being constantly monitored and processed. Importantly, for every PBS truck or truck fleet, data has also been collected for the equivalent “baseline” vehicles: conventional vehicle combinations operated by the same operator performing the same freight task. Relative to the baseline vehicles, the PBS vehicles have resulted in a 12% reduction in fuel consumption and greenhouse gas emissions per tonne-km of freight moved. An average of R2.22 million of fuel is saved every month. A total of 6 238 truck journeys and 737 220 km of truck travel are saved per month, thereby reducing the number of trucks on South African roads. And critically, a 39% reduction in crash rate has been observed compared with the baseline vehicles.

Additionally, perhaps unique to the South African case, there was a need to develop local expertise in vehicle dynamics and PBS to sustain the project into the future. Since inception, the project has trained a number of students, resulting in three MSc degrees and two PhD degrees on PBS topics, and has trained five locally accredited PBS assessors (to perform the PBS vehicle dynamics simulations). A number of software tools were also developed locally to address the needs the PBS project.

Going forward, it is envisaged that the pilot project will continue to grow, with more vehicles from more industries and more provinces, increasing the collection rate and quality of monitoring data. During this time an implementation strategy will also be prepared, should the Department of Transport decide to formalise PBS into national regulations.

## 1.3. Objectives

The primary objective of Work Package C of the FALCON project is to define a draft PBS framework for Europe, according to local geographical and legislative conditions. The Work Package consists of a number of tasks towards this end. The current report covers the specific tasks of defining the PBS framework, as follows:

- Task 3.1: Define a representative fleet of heavy vehicle combinations, which will be used as the basis of the other studies. This will comprise existing vehicle conventional combinations, EMS combinations, and proposed future combinations.
- Task 3.5: Define a proposed PBS framework, under which cross-border high capacity vehicles might operate in Europe, using the representative fleet for analysis purposes.
- Task 3.6: Validate the proposed framework by assessing the performance of the representative fleet in realistic European road conditions.

In Tasks 3.2, 3.3 and 3.4, important preliminary investigations were carried out to provide useful inputs to Tasks 3.5 and 3.6. The findings of these tasks are detailed in other reports [6], [26], [27], and can be summarised as follows:

- Task 3.2: Establish an extensive infrastructure catalogue, for which design criteria will be chosen, and for which the PBS framework can be adapted. The catalogue includes details of pavements, bridges, tunnels, road geometry elements, safety barriers and warehouses.

- Task 3.3: Review existing vehicle policies throughout Europe. The report provides a review of the international regulations for commercial vehicle combinations, including the PBS schemes in Australia, New Zealand and Canada, as well as the PBS investigations in South Africa and Sweden. Furthermore, the vehicle policies in the European countries involved in the FALCON project are summarized and compared, and the similarities and differences are identified.
- Task 3.4: Summarize infrastructure design criteria and legislation in Europe, with an emphasis on roads, bridges and tunnels.

This report details the methodology, analysis, recommendations for a proposed PBS framework for Europe, and the vehicles which might operate in such a framework. The report proceeds as follows:

1. The methodologies used in this study are presented, including the overall methodology used in the development of the representative fleet and PBS framework, as well as the detailed methodologies involves in conducting specific simulations of vehicle dynamics, road wear impact and bridge loading.
2. The definition of the representative vehicle fleet is presented, detailing the choice of the vehicle combinations, their detailed specification, and the choice of loading conditions.
3. The selection of a set of relevant performance standards, from which the final selection will be made, is explained.
4. Details of the simulation exercises and results are given for vehicle dynamics, bridge loading, and road wear impact assessments respectively.
5. A detailed analysis leading to a recommended methodology for defining road access levels is presented. An example road classification for a given set of conditions is provided.
6. A summary of the proposed PBS framework and methodologies is presented.
7. Final conclusions and recommendations are made.

## 1.4. Methodology

In order to define a suitable PBS framework for Europe, inspiration was drawn primarily from the process which Australia followed in the development of the established Australian PBS scheme [28]. This included reviewing existing performance standards from other countries, assessing the performance of the existing fleet in the country, and reviewing the applicability of standards and criteria for local conditions and the local fleet. Taking into consideration the resources available in the FALCON project, the following methodology was chosen (addressing Tasks 3.1 and 3.5):

1. Define a representative fleet of current heavy vehicle combinations and proposed high capacity vehicles in Europe.
    a. Vehicle units and loading units should be modular in line with EMS.
2. Gather all potentially relevant performance standards from various countries. These should address:
    a. low- and high-speed vehicle dynamics,
    b. vehicle dynamics in winter conditions, and
    c. the impact of the vehicles on roads and bridges
3. Simulate the representative fleet against all potential performance standards. Assess:
    a. a representative loading case (based on available EU statistics), and
    b. a critical loading case (with high mass and centre of gravity).
4. Observe the performance of the representative fleet, and assess the following:
    a. Which standards are appropriate for a European PBS framework?

   b. Which standards are not, or need to be redefined?
   c. Which standards are highly correlated and redundant?
   d. Which combinations perform poorly, and require active intervention systems?
   e. Do any of the pass/fail criteria need refining for European conditions?
   f. Is there a need for additional performance standards to address European winter conditions?
5. Using the simulation results (and making use of the findings of Tasks 3.2, 3.3, and 3.4), give recommendations on:
   a. a proposed European PBS framework, addressing both vehicle safety and infrastructure interaction, comprising a set of performance standards and recommended pass/fail criteria for each,
   b. a proposed road access classification system for European PBS, and
   c. a supporting framework including intelligent access, self-regulation, etc.

A large component of this work is the simulation exercise (step 3), in which the entire representative fleet would be assessed against every performance standard. The results of these simulations are fundamental to the choice of performance standards going forward, the selection of suitable pass/fail criteria, and the highlighting of specific vehicle combinations as suitable or unsuitable. The simulation exercise comprised four primary work packages, each carried out by different consortium members:

- Vehicle dynamics (carried out by CSIR)
- Vehicle dynamics in winter conditions (carried out by VTi)
- Bridge loading (carried out by IFSTTAR)
- Road wear impact (carried out by BRRC)
- Road class classification (HAN)

# 2. Representative Fleet

The representative fleet was defined from a number of sources, and importantly had to present multimodal potential in line with Directive 96/53EC. The representative fleet included existing EU combinations complying with Directive 96/53EC, current EMS combinations operating in some EU member states, and longer combinations being tested in isolated pilot programmes in certain countries (potential "EMS 2" vehicles). All vehicle combinations were simulated carrying standardized multimodal loading units, all of which were considered uniformly loaded with a cargo of uniform density. The loading units considered were: 20' / 40' / 45' / 13.6 m / 14.92 m containers, and the C782 swap body.

## 2.1. Loading conditions

To determine suitable representative EU loading conditions, the relevant literature was reviewed [29]–[34]. It was concluded that the mass utilization for a typical tractor semi-trailer in the EU is 50-60%, whereas volume utilization is typically 80-90%. Loading deck surface utilization for a tractor-semitrailer is typically 85-95%. For long-haul transport (> 150 km), volume utilisation increases with trip length [33]. Therefore, payload was assumed to be volume-based. To find a representative payload density, average tractor-semitrailer "load factors" in a number of EU countries were reviewed, as shown in Figure 1 (EU average in the centre). The load factor is defined as the ratio of the average load to the total vehicle load capacity, in either tonnes or volume. It is calculated from aggregated transport data, as the number of tonne-km divided by the number of vehicle-km.

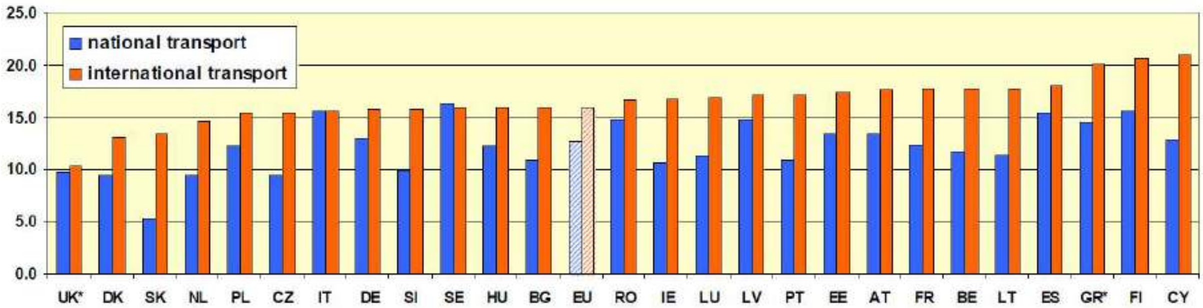



*Figure 1: Average load factor per country, 2010* [30]

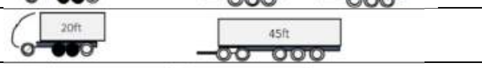
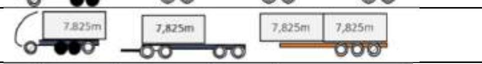
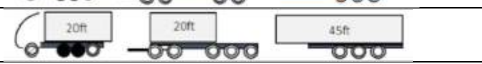
Given that a typical 13.6 m EU semitrailer carries approximately 28 tonnes of loaded cargo, and has an internal volume of 87 $m^3$, the average density was calculated to be 156.3 $kg/m^3$. A 20% safety factor was added to this to yield a "representative" payload density of 187$kg/m^3$. A second "critical" loading case was defined by increasing the density uniformly for all vehicle units until allowable axle loads were approached while maintaining acceptable combination mass. This critical loading density was found to be 280 $kg/m^3$.

The volume utilization determines the height of the centres of gravity, which is critical in influencing lateral and roll dynamics of the vehicles. The average volume utilization in Europe is 82% [32]. Assuming homogenous cargo, the centre of gravity of the loaded cargo is at 41% of the internal height of each loading unit. This correlates well with a common assumption regarding mixed freight: that the load is distributed with 70% of the mass in the lower half of the load space and 30% in the top half, giving a centre of gravity height of 40% of the internal loading space [35]. This centre of gravity height was assumed to be the same for both representative and critical loading cases.

## 2.2. Vehicle combinations

The representative fleet of heavy vehicle combinations is summarised in Table 5. The fleet was categorised into six groups. Groups 1 and 2 represent vehicle combinations that comply with 96/53/EC and represent vehicles that are legal to operate for EU cross border transport (combinations 1.2 and 1.4 are exceptions). Groups 3 and 4 represent EMS-type vehicles that are currently operating in number of EU member states on a national level. Finally, Groups 5 and 6 are combinations with lengths typically above 30 m that are being tested in isolated national pilot programmes. The UK "longer semi-trailer" has been included in the fleet (2x7.825 m).

*Table 5: Representative vehicle fleet (r/c = representative/critical loading)*

| Vehicle group and code † | | Vehicle description | Length (m) | Mass (r/c) (tonnes) | |
|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) |   | 16.2 | 33.5 | 41.3 |
| 1.2 | TR6x2-ST3 (2x7.8m) |   | 18.5 | 37.4 | 46.2 |
| 1.3 | TR4x2-ST3 (13.6m) |   | 16.4 | 29.7 | 37.7 |
| 1.4 | TR4x2-ST3 (14.9m) |   | 17.7 | 31.8 | 43.3 |
| 2.1 | TK6x2-CT2 (2x7.8m) |   | 19.3 | 35.4 | 44.3 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) |   | 18.5 | 35.4 | 44.3 |
| 2.3 | TK6x2-CT3(2x20ft) |   | 16.9 | 29.8 | 35.9 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) |   | 23.7 | 47.3 | 58.1 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) |   | 27.9 | 53.3 | 66.6 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) |   | 27.7 | 56.1 | 69.4 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) |   | 23.9 | 48.5 | 59.3 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) |   | 26.7 | 53.2 | 66.5 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) |   | 26.7 | 53.2 | 66.5 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) |   | 24.4 | 46.0 | 56.8 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) |   | 25.0 | 47.0 | 57.8 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) |   | 27.9 | 51.4 | 64.7 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) |   | 24.3 | 43.2 | 52.4 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) |   | 24.9 | 46.7 | 57.6 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) |   | 31.1 | 62.6 | 78.2 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) |   | 31.6 | 63.6 | 79.2 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) |   | 36.5 | 73.8 | 91.6 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) |   | 31.2 | 62.5 | 76.4 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) |   | 35.4 | 71.0 | 88.7 |
| 6.2 | TK6x4-DY2-LT2-ST3 (2x7.8m+45ft) |   | 31.7 | 60.0 | 73.9 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) |   | 36.5 | 66.5 | 84.2 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) |   | 36.5 | 70.8 | 88.6 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) |   | 31.6 | 59.7 | 73.6 |

† ***TR***axb= Tractor (a = # of wheels, b = # of driven wheels), ***TK***axb = Rigid truck (a = # of wheels, b = # of driven wheels), ***ST***a = Semi-trailer (a = # of axles), ***CT***a = Centre-axle trailer (a = # of axles), ***FT***a+b = Full trailer (a = # of front axles, b = # of rear axles), ***LT***a = Link trailer (a = # of axles), ***DY***a = Dolly (a = # of axles)

## 2.3. Vehicle parameters

The configurations and dimensions of the combinations were defined in consultation with operators and tractor and trailer manufacturers. Minor modifications were made to ensure modularity between combinations. Vehicle parameters such as suspension characteristics, centres of gravity, roll centre height *etc.* were agreed by members of the consortium to be representative of current European vehicles and were sourced from OEMs and published data. It was assumed that no active control systems were present, such as roll stability control, or electronic stability control, as passive performance was to be measured (with the exception of simulating an ABS braking manoeuvre).

Tyre properties (in summer conditions) such as lateral force versus slip curves were sourced from experimental measurements captured previously and were corroborated by Michelin for representativeness. Separate winter tyre data were used for low friction simulations, provided by VTI, sourced from data gathered on ice at the VTI tyre testing facility. All prime mover tyres were 315/70 R22.5, with dual tyres only on the drive axles. Trailer and dolly tyres were 385/65 R22.5 singles. Suspension data were categorised into light-duty steer axle, heavy-duty steer axle, drive axle, tag axle, dolly axle and trailer axle. Data for each group were standardised, with all spring, damper, stabiliser and airbag data being provided by a number of OEMs. 4x2 and 6x2 prime movers were simulated with light-duty steer axles, with the remainder of the prime movers simulated with the heavy-duty steer axles. The heavy-duty steer axles were specified with a slightly higher auxiliary roll stiffness and vertical spring stiffness than the light-duty axles.

Prime mover drivetrains were specified per prime mover type. The vehicle combinations were assigned a drivetrain (engine power and torque curves and gearbox and diff ratio) according to prime mover type and gross combination mass. Truck and trailer moments of inertia (MOI) were scaled from historic values obtained from published data, or directly from OEMs. MOI values were calculated for the sprung mass of each vehicle unit. Chassis compliance and hitch damping was neglected. Hitch lash of ±1° was incorporated into the fifth wheel models.

Axle Loading was an output from the simulation software and was a function of the payload volume of each combination, and thus the loading distribution was not fixed, but a function of the layout of each combination. The resulting axle group loads were used as the inputs into the road and bridge loading study, and thus the results thereof may be sensitive to variations in actual loading distributions.

Detailed vehicle parameter data are provided in Appendix A.

# 3. Selection of Performance Standards

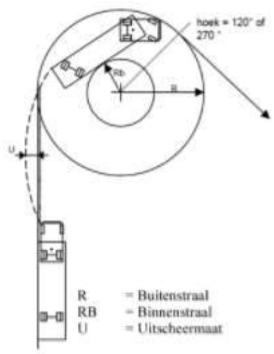
Potential performance standards were sourced from: the Australian PBS framework [1], Directive 97/27/EC [2], Netherlands Directive JBZ 2013/ 9832 [3], Canadian PBS [4], and UNECE regulations [5]. It was important to explore performance standards beyond the extensive Australian framework as the operating and regulatory conditions are clearly different between Australia and Europe. Factors that shaped the Australian scheme initially and over time, such as existing legislation and the performance of the existing Australian fleet, will not in general be the same in Europe.

For driveability standards, the four Australian standards of Startability, Gradeability A, Gradeability B, and Acceleration Capability were included for consideration.

For manoeuvrability standards, a combination of Australian and EU standards was included for consideration. The Australian PBS includes standards such as low-speed swept path, frontal swing, and tail swing, measured with a 90° turn. In addition, two variations of a “roundabout” manoeuvre were added, sourced from existing EU standards. This includes the standard UK/EU roundabout test from Directive 97/27/EC, which is important in order to incorporate for the UK as a potential participant in a European PBS-type scheme, as this is a non-negotiable element of heavy vehicle regulation in the country. However, this roundabout test was designed for standard tractor semi-trailer combinations; combinations longer than this are unlikely to pass, and even longer combinations are unlikely to be able to complete the manoeuvre at all. It will therefore only be a requirement for a limited road access class of vehicles.

An alternative roundabout manoeuvre from the Dutch Directive JBZ 2013/9832 [3] that accommodates both the standard roundabout manoeuvre and long vehicle combinations was also considered (see Figure 2). The test is divided into four levels, where level 1 is the standard roundabout test for combinations less than 17 m in length, and the vehicle must perform the full 12.5 m 270° turn. Longer vehicle combinations are accommodated in Levels 2–4, which only require a 120° turn to be performed at increasing outer radii. The minimum inner radius is also adjusted accordingly. To accommodate for longer vehicles than accounted for in the JBZ standard, two more turning circles, TC5 and TC6, were defined by extrapolating the outer radii, inner radii and tail swing.

The sizes are determined when entering, passing through and exiting the circles according to the figure above.
When driving in, the widest vehicle (part) must be driven along the tangent and then followed by the front corner point of the towing motor vehicle, the circular path and the exit tangent.
In the case of retractable vehicles, the tests shall be carried out with a combination length as close as possible to the upper limit value of the test in question, depending on the length and the setting possibility of the towed vehicle.




| Test | Combination length (m) | Outside radius (m) | Covered job (m) | Within radius (m) | Cutaway size (m) | Passed angle (°) |
|---|---|---|---|---|---|---|
| 1 | CL ≤ 17.00 | 12.50 | ≤ 7.20 | ≥ 5.30 | ≤ 0.80 | 270 |
| 2 | 17.00 <CL ≤ 20.00 | 12.50 | ≤ 7.20 | ≥ 5.30 | ≤ 1.20 | 120 |
| 3 | 20.00 <CL ≤ 23.00 | 14.50 | ≤ 8.00 | ≥ 6.50 | ≤ 1.40 | 120 |
| 4 | 23.00 <CL ≤ 27.00 | 16.50 | ≤ 9.00 | ≥ 7.50 | ≤ 1.70 | 120 |

*Figure 2: Netherlands HCV roundabout manoeuvre (Directive JBZ 2013/ 9832)*

Another approach to the assessment of roundabout performance of longer vehicles is to simply reduce the inner radius requirement of the standard 12.5 m directive 96/53 roundabout manoeuvre. This has been adopted in Sweden for EMS vehicles. The value of this approach will be assessed in this report through the assessment of the standard roundabout, in which the achievable inner radius for each vehicle will be observed. However, it is predicted that this approach will not be applicable for vehicles in the representative fleet which are longer than the typical EMS combinations, which are likely to jack-knife during the manoeuvre.

For high speed dynamic standards, all the Australian standards were included for consideration, including static rollover threshold, high-speed transient off-tracking, and tracking ability on a straight path. In addition to this, two Canadian standards, high-speed steady state off-tracking and dynamic load transfer ratio, were included. Finally, an additional variation of the rearward amplification standard was assessed. In the normal Australian standard, lateral acceleration of the rearmost roll-coupled unit (RRCU) is the variable of interest. The second variation is closer to the earlier RTAC (Roads and Transport Association of Canada) definition: the amplification was measured at the rearmost trailer (not roll-coupled unit). In both cases, only the ratio of lateral accelerations was considered as a pass/fail metric, i.e. not linked to the rollover threshold of the rear trailer/s as in Australian PBS. Load transfer ration on the other hand, is directly assessing rollover risk, and so the RCCU concept was retained for this standard.

Regarding winter conditions, it was decided that instead of a full assessment of all low and high-speed standards under low friction conditions, only braking and low-speed manoeuvrability considerations would be assessed. This assumes that the worst realistic scenario is that a driver would have to decelerate quickly in sudden unexpected icy conditions and must then navigate safely at low speed. This is a simpler approach and avoids parameter-sensitive simulations of high-speed low friction dynamics. Additionally, some of the high-speed standards were assessed in low friction conditions, to determine safe operating speeds in winter. This is supported by the fact that existing PBS schemes in Australia and South Africa impose additional requirements to ensure that drivers are of a standard of at least above legal minimums, and that speeding is strictly monitored and managed. The drive tyre friction demand is a modification of the Canadian friction demand in a tight turn standard, adjusted to be assessed using the same 90° turn as the Australian standards.

For infrastructure standards pertaining to roads and bridges, it was decided to conduct in depth analyses into what type of standards would be appropriate for Europe. Two chapters of this report are dedicated specifically to this work.

Table 6 summarises the performance standards considered, categorised into: driveability, manoeuvrability, high-speed stability, winter conditions, and infrastructure. The manoeuvre used to assess the standard, and the source of the standard are shown. Summer and winter coefficients of friction were taken to be 0.8 and 0.3 respectively. Further details of the performance standards are given in Appendix B.

*Table 6: Performance standards evaluated*

| **Standard** | **Manoeuvre** | **Source** |
|---|---|---|
| Driveability | | |
| Startability | Start on incline | Australian PBS |
| Gradeability A (Maintain motion) | Maintain motion on incline | Australian PBS |
| Gradeability B (Maintain speed) | Maintain speed on 1% incline | Australian PBS |
| Acceleration Capability | Accelerate from rest | Australian PBS |
| Manoeuvrability | | |
| Low Speed Swept Path | 90° turn, radius 12.5 m | Australian PBS |
| Frontal Swing | 90° turn, radius 12.5 m | Australian PBS |

| | | |
|---|---|---|
| Difference of Maxima | 90° turn, radius 12.5 m | Australian PBS |
| Maximum of Difference | 90° turn, radius 12.5 m | Australian PBS |
| Tail Swing | 90° turn, radius 12.5 m | Australian PBS |
| Steer-Tyre Friction Demand | 90° turn, radius 12.5 m | Australian PBS |
| EU Turning circle | Roundabout, OR = 12.5 m (270°) | Directive 97/27/EC |
| NL TC 1 (inner radius & tail swing) | Roundabout, OR = 12.5 m (270°) | JBZ 2013/ 9832 (NL) |
| NL TC 2 (inner radius & tail swing) | Roundabout, OR = 12.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 3 (inner radius & tail swing) | Roundabout, OR = 14.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 4 (inner radius & tail swing) | Roundabout, OR = 16.5 m (120°) | JBZ 2013/ 9832 (NL) |
| NL TC 5 (inner radius & tail swing) | Roundabout, OR = 19.4 m (120°) | Extrapolated from JBZ |
| NL TC 6 (inner radius & tail swing) | Roundabout, OR = 22.0 m (120°) | Extrapolated from JBZ |
| High-speed stability | | |
| Static Rollover Threshold | Tilt-table / Constant radius turn | Australian PBS |
| Rearward Amplification (RRCU) | Single lane change (ISO 14791) | Australian PBS |
| Rearward Amplification (last trailer) | Single lane change (ISO 14791) | Australian PBS (modified) |
| High-Speed Transient Off-tracking | Single lane change (ISO 14791) | Australian PBS |
| Yaw Damping Coefficient | Pulse steer input @ 80 km/h | Australian PBS |
| Tracking Ability on a Straight Path | Rough road & cross slope at speed | Australian PBS |
| High-Speed Steady-State Off-tracking | Constant radius turn | Canada |
| Dynamic Load Transfer Ratio (RRCU) | Single lane change (ISO 14791) | Canada |
| Winter conditions | | |
| Low friction braking | Straight line ABS stop (low mu) | ECE Reg. 16 |
| Steer tyre friction demand | 90° turn, radius 12.5 m (low mu) | Australian PBS, low mu |
| Drive tyre friction demand | 90° turn, radius 12.5 m (low mu) | Canada, but Aus. manoeuvre |
| Low friction startability | Start on incline (low mu) | Australian PBS, low mu |
| High-speed dynamics standards | Not yet defined | Not yet defined |
| Infrastructure | | |
| Bridge loading | N/A | Custom approach |
| Road wear | N/A | Custom approach |

Table 7 shows the existing pass/fail criteria for each of the performance standards, where these already exist in the Australian PBS framework or the other relevant sources. These are used as the “reference” criteria against which to assess the performance of the representative fleet, but are not necessarily the criteria which are suitable for Europe. The criteria are categorised according to the existing Australian road access levels, where Level 1 pertains to unrestricted road access, and Level 4 is the most restricted road access. EU and NL turning circles have been shown as independent of Australian road access level, but will in reality require some road access level grouping (which is dealt with later in Section 7). The criteria for high-speed steady state off-tracking come from early Australian work on this [28], but the standard was subsequently not included in the Australian PBS framework. Given the slightly modified definition of rearward amplification, where the pass/fail criteria was to be set only as a ratio, a new criterion was sought. The Australian limit is $5.7 \cdot SRT_{rrcu}$, where $SRT_{rrcu}$ is the static rollover threshold of the rearmost roll-coupled unit. Clearly the limit is tied to the rollover threshold of the trailer/RRCU. A “raw measure” of RA was extracted from this limit by noting the SRT limit to be $0.35 \cdot g$, hence the new limit for this study was set to 2 (= 5.7*0.35).

*Table 7: Existing/reference performance criteria*

| Standard | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| Driveability | | | | |
| Startability | ≥ 15% | ≥ 12% | ≥ 10% | ≥ 5% |
| Gradeability A (Maintain motion) | ≥ 20% | ≥ 15% | ≥ 12% | ≥ 8% |
| Gradeability B (Maintain speed) | ≥ 80 km/h | ≥ 70 km/h | ≥ 70 km/h | ≥ 60 km/h |
| Acceleration Capability | ≤ 20.0 s | ≤ 23.0 s | ≤ 26.0 s | ≤ 29.0 s |
| Manoeuvrability | | | | |
| Low Speed Swept Path | ≤ 7.4 m | ≤ 8.7 m | ≤ 10.6 m | ≤ 13.7 m |
| Frontal Swing | ≤ 0.7 m | | | |
| Difference of Maxima | ≤ 0.20 m | | | |
| Maximum of Difference | ≤ 0.40 m | | | |
| Tail Swing | ≤ 0.30 m | ≤ 0.35 m | ≤ 0.35 m | ≤ 0.50 m |
| Steer-Tyre Friction Demand | ≤ 80% | | | |
| EU Turning Circle (inner radius) | ≥ 5.3 m | | | |
| NL turning circle 1 (inner radius) | ≥ 5.30 m | | | |
| NL turning circle 2 (inner radius) | ≥ 5.30 m | | | |
| NL turning circle 3 (inner radius) | ≥ 6.50 m | | | |
| NL turning circle 4 (inner radius) | ≥ 7.50 m | | | |
| NL turning circle 5 (inner radius) | ≥ 9.07 m | | | |
| NL turning circle 6 (inner radius) | ≥ 10.50 m | | | |
| NL turning circle 1 (tail swing) | ≤ 0.80 m | | | |
| NL turning circle 2 (tail swing) | ≤ 1.20 m | | | |
| NL turning circle 3 (tail swing) | ≤ 1.40 m | | | |
| NL turning circle 4 (tail swing) | ≤ 1.70 m | | | |
| NL turning circle 5 (tail swing) | ≤ 2.06 m | | | |
| NL turning circle 6 (tail swing) | ≤ 2.42 m | | | |
| High-speed stability | | | | |
| Static Rollover Threshold | ≥ 0.35 g (≥ 0.40 g for hazardous goods) | | | |
| Rearward Amplification (RRCU) | ≤ 2 | | | |
| Rearward Amplification (last trailer) | ≤ 2 | | | |
| High-Speed Transient Off-tracking | ≤ 0.6 m | ≤ 0.8 m | ≤ 1.0 m | ≤ 1.2 m |
| Yaw Damping Coefficient | ≥ 0.15 | | | |
| Tracking Ability on a Straight Path | ≤ 2.9 m | ≤ 3.0 m | ≤ 3.1 m | ≤ 3.3 m |
| High-Speed Steady-State Off-tracking | ≤ 0.3 m | ≤ 0.5 m | ≤ 0.7 m | ≤ 0.7 m |
| Dynamic Load Transfer Ratio (RRCU) | ≤ 0.6 | | | |
| Winter conditions | | | | |
| Low friction braking | Not yet defined | | | |
| Steer-Tyre Friction Demand | Not yet defined | | | |
| Drive-Tyre Friction Demand | Not yet defined | | | |
| Low friction startability | Not yet defined | | | |
| High speed dynamic standards | Not yet defined | | | |
| Infrastructure | | | | |
| Bridge loading | Not yet defined | | | |
| Road wear | Not yet defined | | | |

# 4. Simulations: Vehicle Dynamics

## 4.1. Methodology and assumptions

Vehicle dynamics simulations in summer conditions were carried out by the CSIR South Africa using a combination of commercial vehicle dynamics software and first principle calculations, using TruckSIM and MATLAB. The entire representative fleet was modelled and assessed against all identified performance standards in Table 6. The Netherlands turning circle consisted of a number of different manoeuvres depending on the vehicle length. The first manoeuvre is equivalent to the EU/UK roundabout manoeuvre, and this was only simulated once.

Standards addressing winter conditions were assessed by VTI Sweden. Simulations were carried out using MATLAB SimMechanics models. Both summer and winter tyre data were modelled using the TNO MF-SWIFT tyre model [36]. All other vehicle parameter data were identical to those used in the vehicle dynamics simulations.
As discussed in Section 3, only low-speed standards (startability and friction demand) and braking were considered. However, high speed transient manoeuvring was also simulated to identify safe operating speeds in winter conditions. Particular focus areas of these simulations were:

- Evaluate startability performance in winter conditions
- Investigate low speed friction demand performance in winter conditions
- Identify safe operating spends in winter conditions
- Assess the need for ABS in winter conditions

## 4.2. Simulation results and discussion

Detailed simulation results have been included in the appendices, due to the large amount of simulation data. In the following sections, the results will be reviewed and discussed as they are relevant to the objectives of this work, i.e. to give insights into the comparative performance of existing vehicles and the proposed HCVs, identify useful performance boundaries between groups of vehicles, identify problematic vehicle combinations, and highlight where existing pass/fail criteria need to be revisited for European conditions.

Detailed tabulated results for the vehicle dynamics simulations are given in Appendix C, for both representative and critical loading cases. Performance results are given numerically, but to aid interpretation the data have been shaded to indicate the road access level achieved according to the ‘reference” pass/fail criteria (Table 7). Additionally, the results of the correlation study and a discussion thereof are given in Appendix D. Specific results will be referred to where relevant in the following text, but the section may be read as a section by itself for information.

### 4.2.1. Driveability

Detailed driveability results are given in Table 78 and Table 82 in Appendix C.

Performance in the Startability and Gradeability A standards is summarised in Figure 3 and Figure 4, respectively. Results for the representative and critical loading cases are shown, and the existing performance criteria limits are indicated (“L1” = Level 1, etc.). Note that for this standard, higher performance is better. Both of these standards pertain to driving on steep inclines, and performance is varied and perhaps limiting. Vehicle 1.1, a standard 45-foot tractor semi-trailer, achieves only Level 4 performance in Startability and Gradeability A. This is limited by the available friction of the 6x2 configuration which is shared by these two combinations. Vehicles 4.6 and 4.7, and 6.4 and 6.5 are the only 8x4 combinations, and exhibit notably reduced Gradeability A performance relative to their neighbours in their respective groups. This is a result of reduced drive axle loads (in the region 3700–5000 kg per axle) compared to the other combinations. Commercial load-proportioning systems will help to alleviate these issues for 6x2 and 8x4 prime movers in practice. The LST combination 1.2 exhibits similarly poor performance, though it benefits slightly from an increased drive axle load.

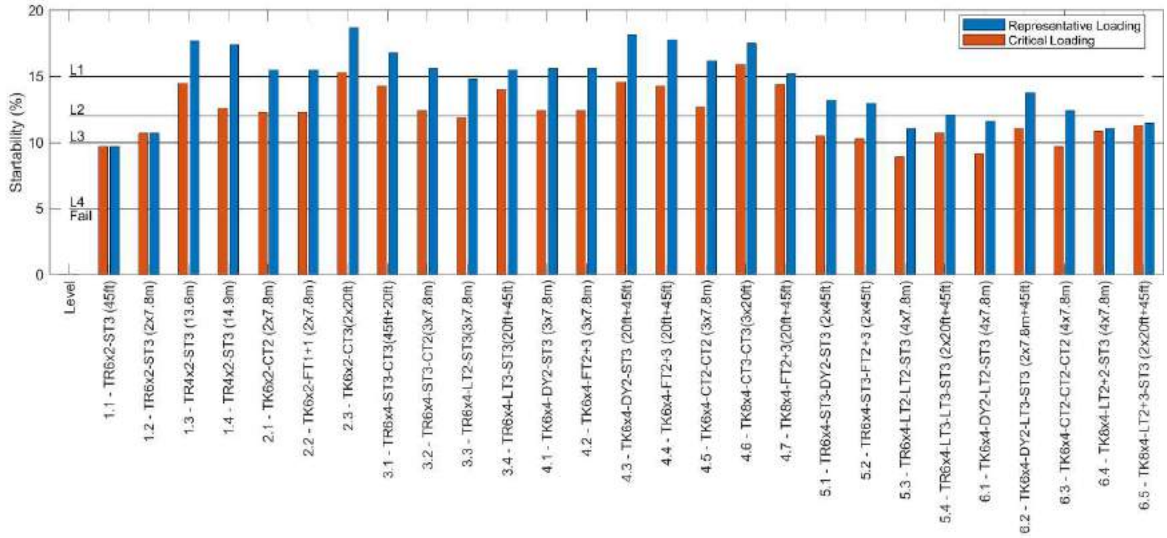



*Figure 3: Vehicle dynamics simulation results: Startability*

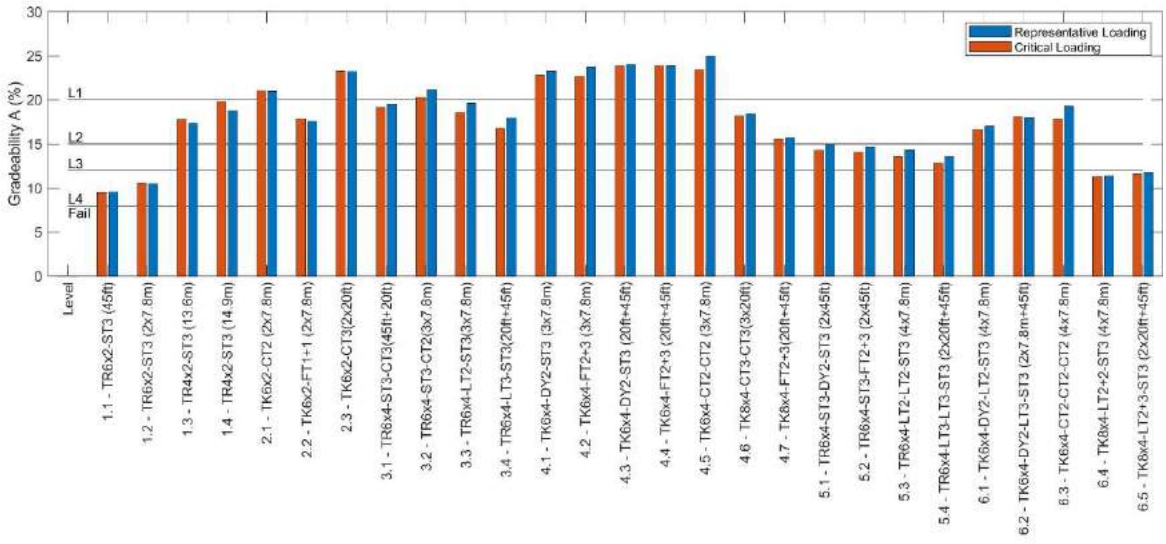



*Figure 4: Vehicle dynamics simulation results: Gradeability A*

There is a logical delineation of performance at groups 5 and 6, in Startability and Gradeability A, with mostly Level 2 and 3 performance (this is clearer in Table 78, Appendix C). These are expected to be Level 3-type vehicles given their length and mass. Existing regulations in Europe require startability of 12% [2], measured in a similar manner to the Australian standard, which is the Australian Level 2 limit. This suggests that it may be desirable to align the proposed performance standard with this, possibly setting the limit of 12% for both Levels 1 and 2, while keeping Level 3 at 10% (based on the observed results). Level 4 is unlikely to be appropriate for Europe. In comparison, the Gradeability A requirement of 20% at Level 1 may be too restrictive, and needs reviewing for European application. <u>This could be dropped by a comparable percentage to Startability (i.e. by 15 − 12% = 3%)</u>.

Gradeability B and acceleration capability results are summarised in Figure 5 and Figure 6. In comparison, performance in these standards does not seem to be problematic, with most vehicles meeting the Australian Level 1 requirement. Vehicles 5.3 and 6.1 meet the requirements for Level 2, which is expected, as these vehicles are not expected to be Level 1-type combinations. The Level 1 limit of ≤ 80 km/h is tied to the Australian heavy vehicle speed limit, which is comparable for Europe.

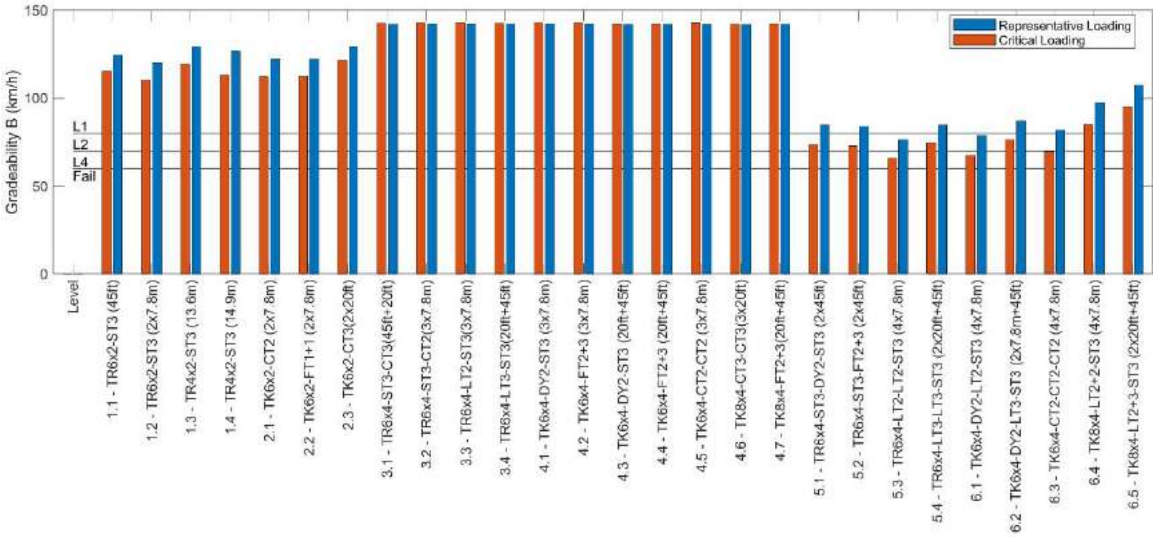



*Figure 5: Vehicle dynamics simulation results: Gradeability B*

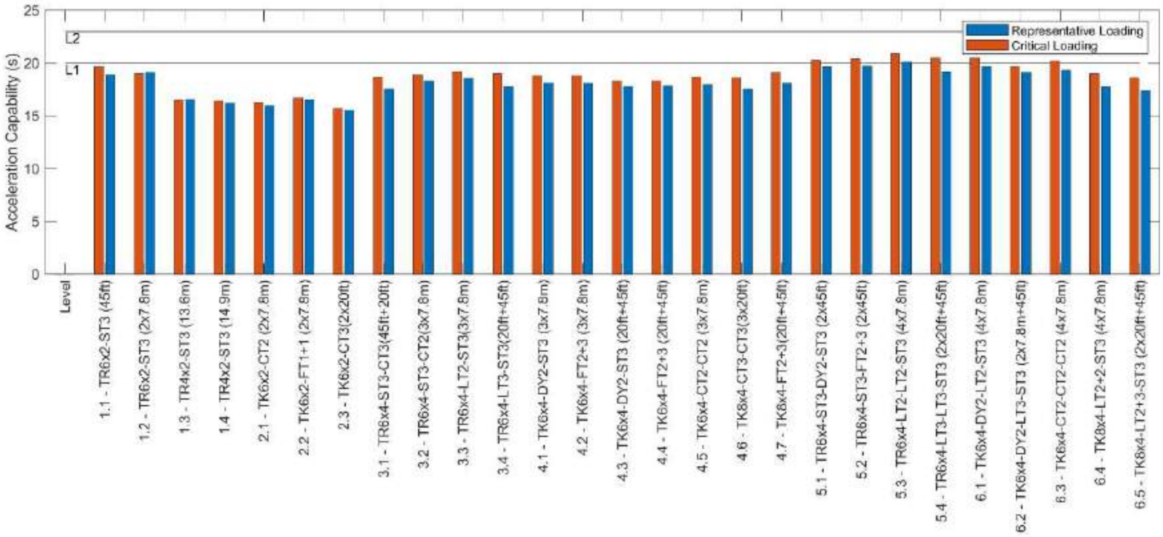



*Figure 6: Vehicle dynamics simulation results: Acceleration Capability*

Under critical loading, performance in the startability standard is most prominently impacted, with most vehicles falling into a higher road access category. Groups 1-4 achieve mostly Level 2 performance across the standards, while groups 5-6 achieve Level 3 and 4 performance.

In Europe, existing standards address drive axle load and engine power (in kW) as a function of combination mass. These standards can be considered to be partly performance-based, and partly prescriptive, and could potentially be considered to be sufficient to address issues of startability and gradeability. However, such standards neglect to take account of gear and axle ratios, which can vary significantly between truck models, and so this approach does not fully match the performance-based standards philosophy. It is considered safer to assess on-road performance as is the case with the Australian standards, and so an on-road performance standard is recommended.

### 4.2.2. Low-speed manoeuvrability

Detailed low-speed manoeuvrability results are given in Table 79 and Table 83 (Australian standards) and in Table 80 and Table 84 (turning circle standards) in Appendix C.

Low-Speed Swept Path (LSSP) performance is shown in Figure 7. Performance is acceptable, with groups 1-2 meeting Level 1 performance, groups 3-4 meeting at least Level 2 performance, and groups 5-6 meeting at least Level 3 performance, with most at Level 2. Only the three combinations in excess of 35 m length achieving level 3 performance.

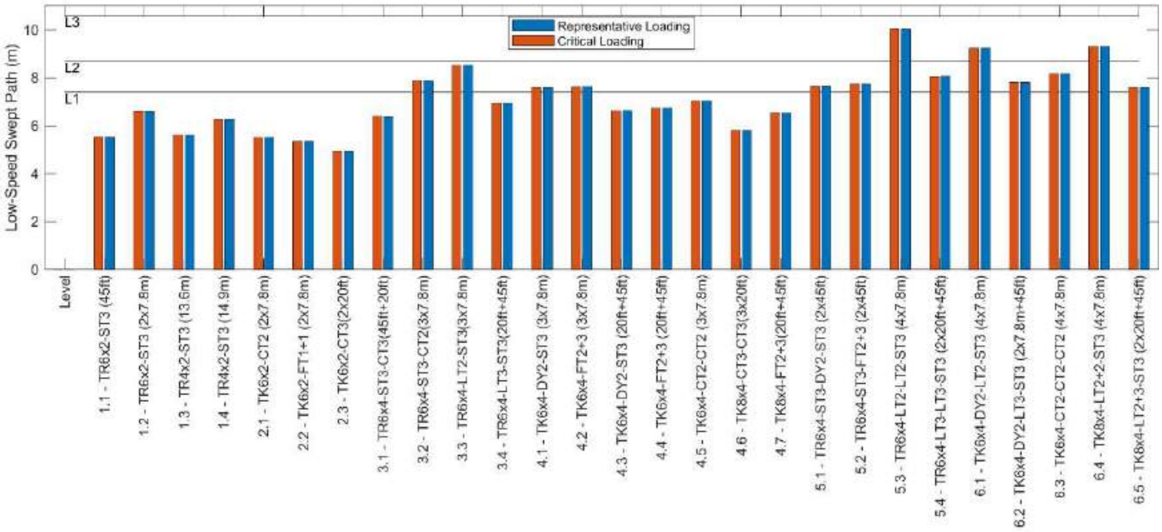



*Figure 7: Vehicle dynamics simulation results: Low-Speed Swept Path*

A Frontal Swing (FS) “pass” is achieved by all vehicles, with a maximum of 0.5 m (see Figure 8). This is mostly dictated by front overhangs and prime mover wheelbase. This may indicate that the criterion can be reduced to 0.5 m, however there is no documented need to reduce the limit below the current 0.7 m. Other, longer wheelbase truck and tractor units and buses would potentially not meet a 0.5 m limit, and future aerodynamic cab advancements may also deem a 0.5 m limit unobtainable. Bonneted truck-tractors may also exhibit higher frontal swing, but may not be relevant to this discussion on freight transport in Europe, where cab-over truck-tractors dominate the market.

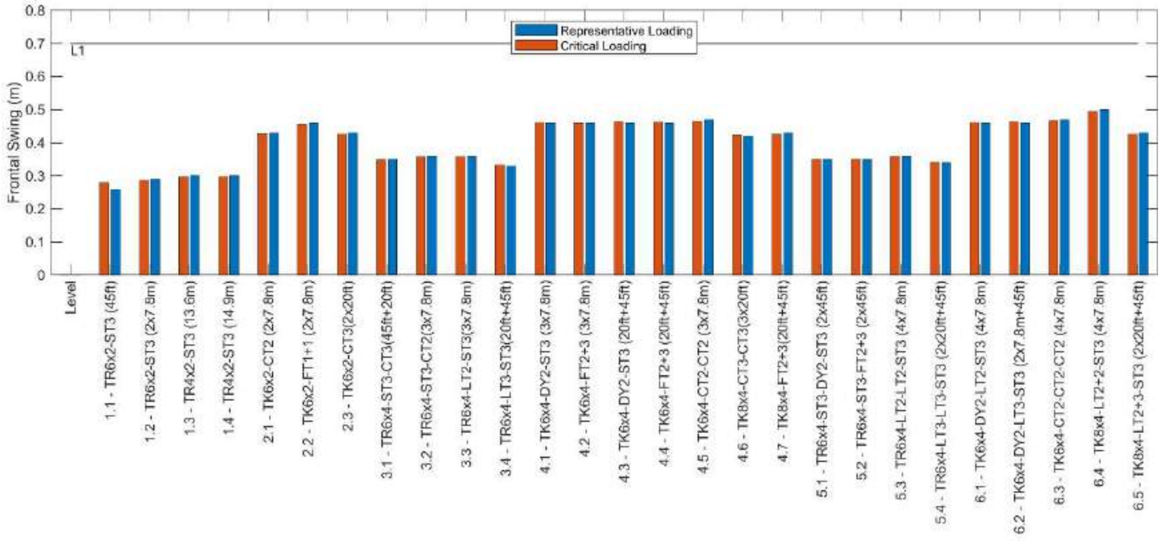



*Figure 8: Vehicle dynamics simulation results: Frontal Swing*

Australian Tail Swing (TS) performance is shown in Figure 9. All vehicles meet the Level 1 requirement, with no vehicles exhibiting more than 0.27 m. The Level 1 Australian limit is 0.3 m, while Levels 2 and 3 permit up to 0.35 m. This might suggest that the Level 1 limit can be imposed for all road access levels. However, no car transporter vehicles were included in the fleet, which are typically the vehicles which exhibit the highest tail swing. In comparison, the tail swing allowance in the EU/NL roundabout is 0.8 m, but there is little evidence to justify this figure. Further investigation is suggested into the safety risks of tail swing, and recorded incidents in Europe, otherwise, given the current results, <u>a limit of 0.3 m seems suitable across the board</u>.

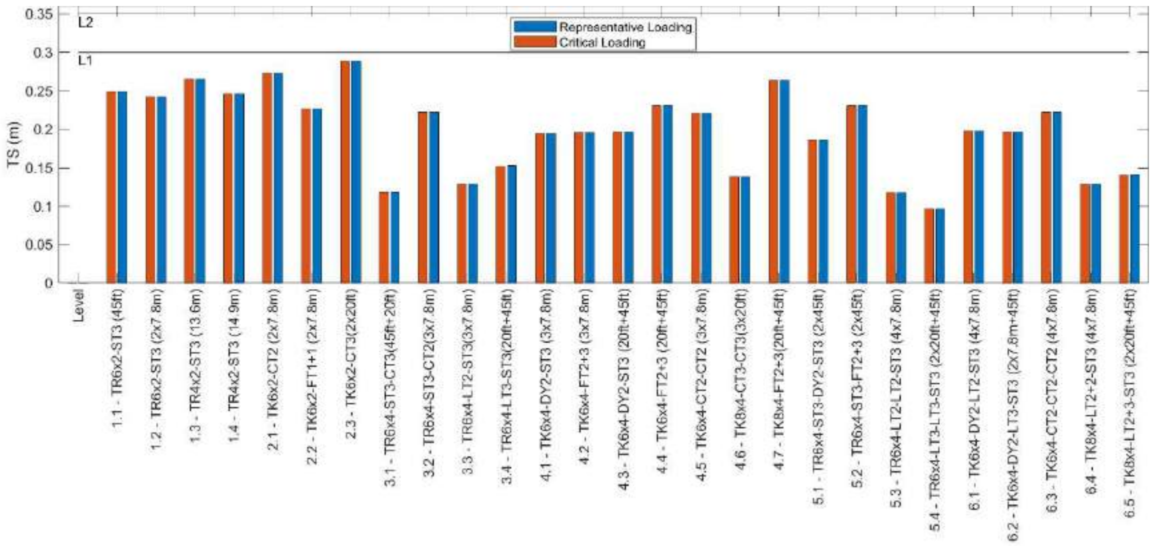



*Figure 9: Vehicle dynamics simulation results: Tail Swing*

Steer Tyre Friction Demand (STFD) performance is summarised in Figure 10. Performance is also acceptable, at a “pass” for all vehicles. However, this does shouldn’t suggest that the standard be removed or relaxed, as potential tri-drive combinations, not included in the current fleet, could exhibit critical performance in this standard. However, it is also noted that the limit of 80% seems unnecessarily high and does not leave much safety margin to the point of sliding (100% friction demand). <u>The validity of the 80% limit should be investigated further, for possible review in European PBS</u>.

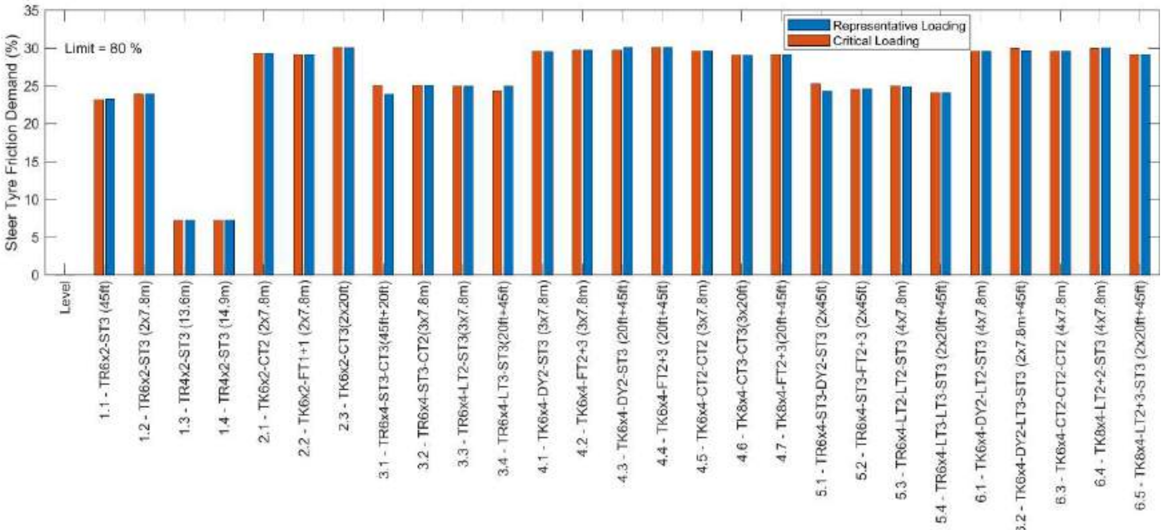



*Figure 10: Vehicle dynamics simulation results: Steer Tyre Friction Demand*

Results for DoM and MoD are shown in Figure 11 and Figure 12. A number of vehicles failed the Australian limits for one or more of these standards. This is particularly true of group 1 vehicles (tractor semi-trailers) and other combinations featuring a semitrailer as the second unit, as expected. This performance can be traced primarily to the relatively long semi-trailer front overhangs, coupled with cab-over prime movers with relatively short front overhangs. The value of these standards as safety critical in a European context, should be reviewed further, especially given that the four worst performing vehicles are legal European vehicles. The limits should be considered in the context of existing semi-trailer front overhang legislation, as has been the case in South Africa [37]. In the South African PBS pilot project, many of the existing truck combinations were found to have poor performance in these standards. It was found that the additional width of trailers 2.6 m compared with 2.5 m in Australia as well as large front overhangs accounted for the poor performance. The limits for South Africa were therefore relaxed to account for the dimensions that the local regulations allow. The value of the MoD and DoM tests is open to discussion. <u>Recommendations include removing them (supported by evidence of no incidents related to semitrailer swing out) or simplifying them (i.e. to a basic semitrailer frontal swing standard).</u>

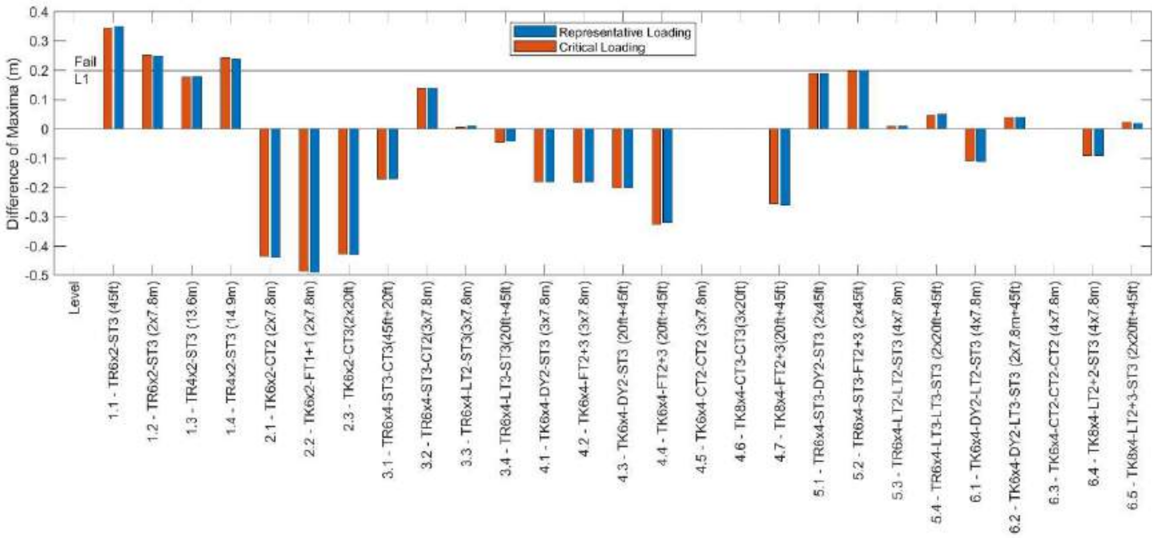



*Figure 11: Vehicle dynamics simulation results: Difference of Maxima*

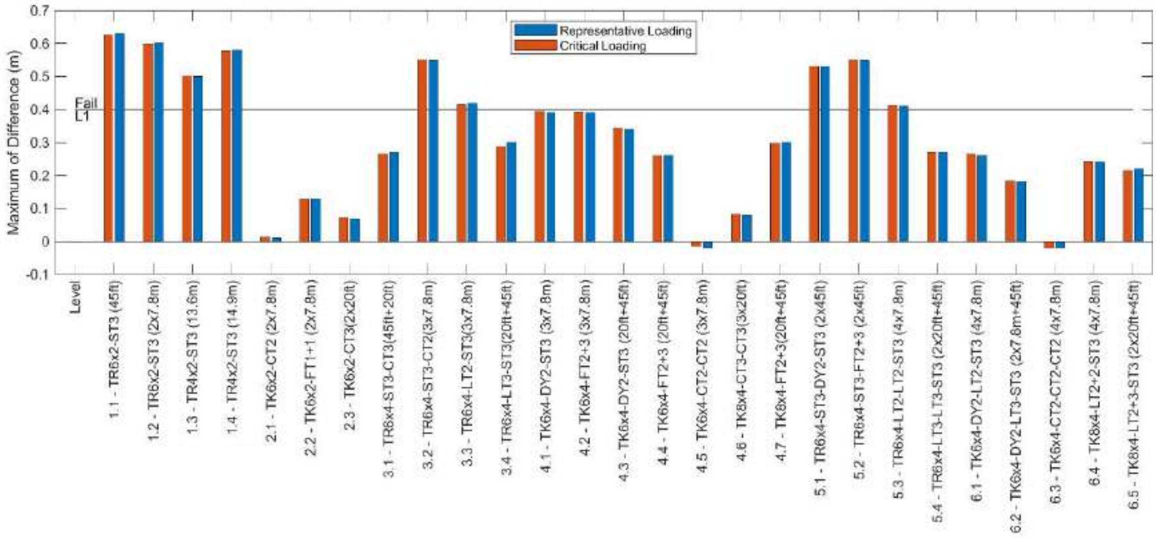



*Figure 12: Vehicle dynamics simulation results: Maximum of Difference*

Turning circle 1, or the EU/UK roundabout manoeuvre, exhibits inner radius performance as expected, as shown in Figure 13. “DNF” means “Did Not Finish”, indicating vehicles which could not complete the manoeuvre. Combinations 1.1 and 1.3, the legal EU tractor semi-trailers, meet the standard as expected. Combinations 1.2 and 1.4 fail (as expected) due to their long semi-trailers. Recall that no active steering was modelled (only a rear self-steering axle on the LST), and that such a system could be used to pass this test. Group 2 vehicles all passed the test as well, given their centre-axle trailers (2.1 and 2.3) and the short 1+1 full-trailer (2.2). Thereafter groups 3-6 (with the exception of 4.6) fail the roundabout test. It is not expected that these vehicles will be appropriate for unrestricted road access, where the roundabout test may be required. Turning Circle 2 results are shown in Figure 14.

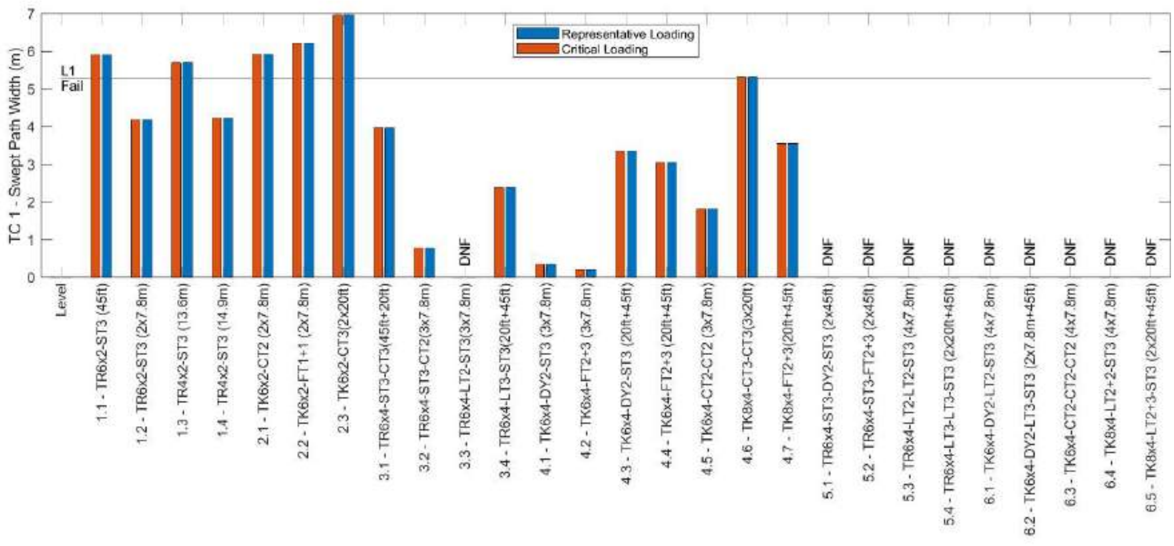



*Figure 13: Vehicle dynamics simulation results: Turning Circle 1, swept path*

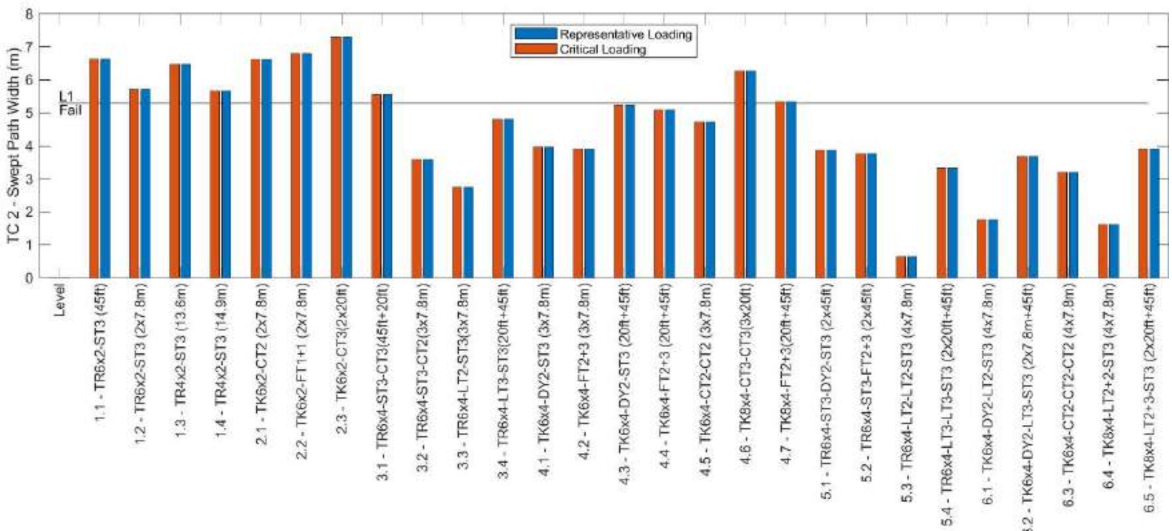



*Figure 14: Vehicle dynamics simulation results: Turning Circle 2, swept path*

Turning circle tail swing performance is shown in Figure 15 and Figure 16 for Turning Circles 1 and 2 respectively. Tail swing in the turning circles is not problematic according to the existing limits. (Note that this tail swing measure is distinct from the tail swing measured in the 90° manoeuvre, although the underlying safety concept is the same.) The highest exhibited tail swing is 0.367 m, for vehicle 1.2 in TC 2. The limit in the roundabout test is 0.8 m, which is much less strict than the Australian limit of 0.3 m, and arguably unsafe for Level 1 type roads. This could have implications for cyclist safety for example, which is an important aspect of European road transport. However, with the exception of 1.2, all vehicles have a tail swing of less than 0.3 m in all manoeuvres. However, it should be noted that trailer steering systems such as “command steer”, may increase tail swing. Overall, groups 1 and 2 meet the requirements for TC 2, groups 3 and 4 mostly meet the requirements for TC 3 (except 3.2 and 3.3), and groups 5 and 6 mostly meet the requirements for TC 4 (with three exceptions at TC 5).

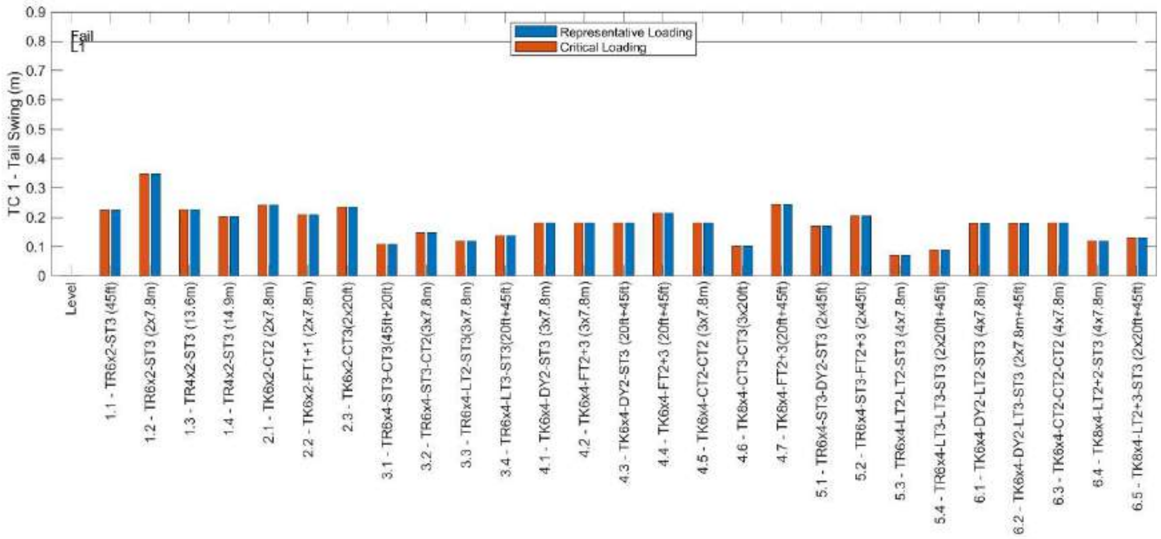



*Figure 15: Vehicle dynamics simulation results: Turning Circle 1, tail swing*

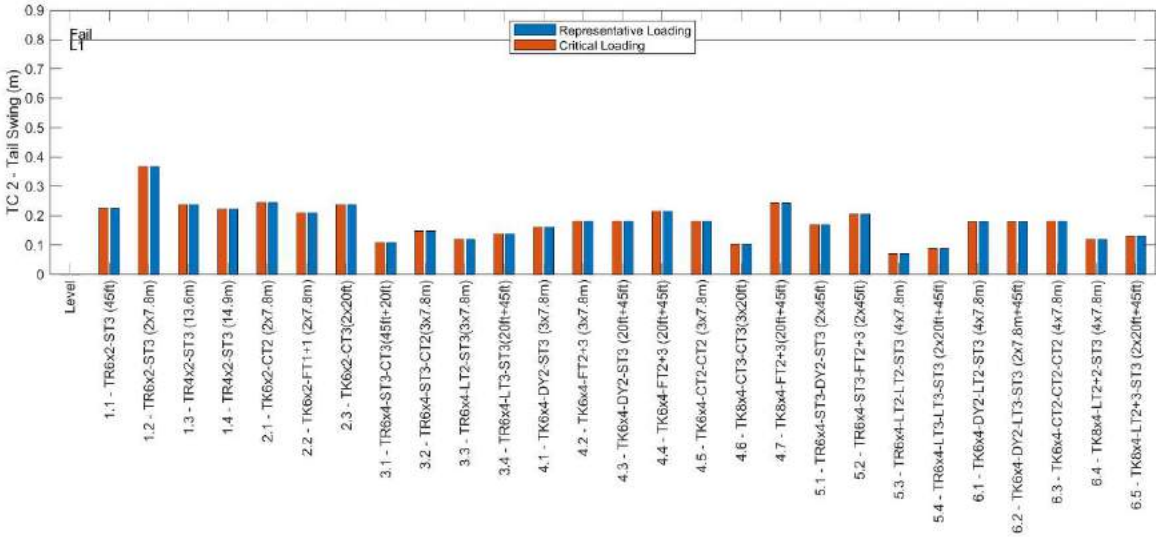



*Figure 16: Vehicle dynamics simulation results: Turning Circle 2, tail swing*

Performance between representative and critical loading is almost identical in all low-speed manoeuvrability standards.

In the correlation study, Low-Speed Swept Path was shown to be highly correlated with both the EU roundabout (Figure 81), and the various NL turning circle tests. The EU roundabout should be retained, as it is likely to be a non-negotiable requirement for general access vehicles. Then in terms of a second performance standard to accommodate longer vehicles, either the NL or Australian option should be used. However, the Australian 90° turn manoeuvre is simpler than the NL manoeuvre (requiring 4+ variations in definition and pass criteria), and also includes well-established methods of measuring tail swing and frontal swing (with more reasonable limits set on tail swing than the NL standard). In addition, the higher-level NL turning circles would require substantially more road space to assess in field tests. <u>It is therefore proposed that a combination of the EU roundabout and Australian low-speed standards be retained</u>.

In terms of pass/fail criteria, it is also clear from Figure 81 that the turning circles appear to the more limiting case compared to the equivalent Australian road access levels. This suggests that the Australian limits may be too lenient for European conditions. For example, the standard EU turning circle seems to correlate with LSSP≈6 m (Level 1), NL TC2 with LSSP≈6.3 m (Level 1), NL TC3 with LSSP≈7.9 m (Level 2), and NL TC4 with LSSP≈9 m (Level 2). These correlations may be used to refine the LSSP criteria according to European-specific road access levels. The cut-off limits for the Netherlands turning circles may or may not be representative enough of Europe; <u>this should be investigated further</u>.

### 4.2.3. High-speed stability

Detailed high-speed stability results are given in Table 81 and Table 85 in Appendix C.

Static Rollover Threshold (SRT) performance is summarised in Figure 17, and was acceptable across the board except for vehicles 1.2 and 1.4 in the critical loading scenario. Recall that SRT must be *higher than or equal to* 0.35·g to pass (as indicated on the left of the bar chart). The vehicles with the lowest SRT are group 1. This may be partly due to the lack of a second drive axle, or tag axle which has reduced roll stiffness compared to a second drive axle. The limit of 0.35·g is widely accepted as a safe limit around the world. The Australian standard requires an SRT of 0.4·g for hazardous goods; similarly, existing European regulations UNECE 111 requires 0.4·g for tanker vehicles.

Critical loading performance presents a very similar performance profile to the representative loading case, with reduced SRT across the board. Under critical loading, two tractor semi-trailer combinations marginally fail the standard: combinations 1.2 and 1.4. It should be recalled that the critical loading case considered is highly critical, with maximum mass coupled with a very high centre of gravity. In practise, this is unlikely to be experienced.

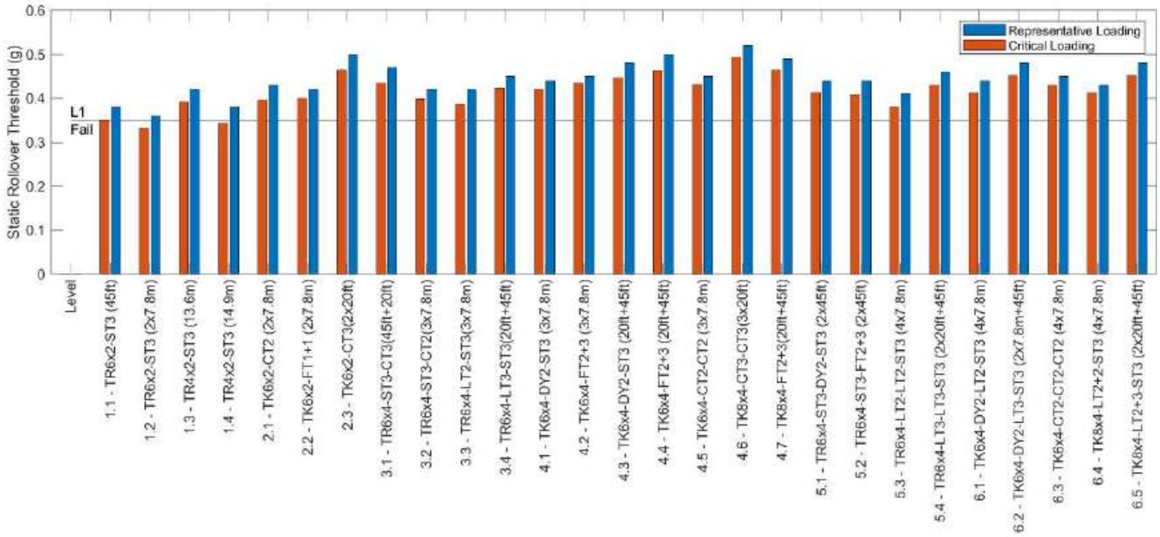



*Figure 17: Vehicle dynamics simulation results: Static Rollover Threshold*

Rearward Amplification (RA) performance is summarised in Figure 18. At an RA limit of 2, over half of the fleet fails, assessed in both RRCU and rear trailer methods (the bar chart shows the rear trailer results). The performance is not well delineated between groups. Assessing RA at the rearmost trailer tends to yield worse performance outcomes than using the RRCU concept as expected. The worst performers are the centre-axle trailer combinations, 4.5, 4.6, and 6.3. Given that RA is highly sensitive to dimensional parameters such as wheelbases and hitch offsets, it was deduced that this was likely a shortcoming of the given vehicle designs. In particular, the A-double combination 5.1 performed less well than expected from experience in Australia and South Africa, but was shown to perform well with minor and representative modifications to wheelbases, hitch locations and drawbar length. This is investigated further in Section 4.3. The RA limit of 2 should also be reviewed for applicability to the rearmost trailer method, once vehicle designs have been optimised, especially given that the existing criteria are largely based on tractor semi-trailer fleets from the Unites States and Canada. Values higher than 2 have been considered in other countries: Sweden are considering a criterion of RA ≤ 2.4, though for rearward amplification of yaw rate [22]. This could be considered going forwards.

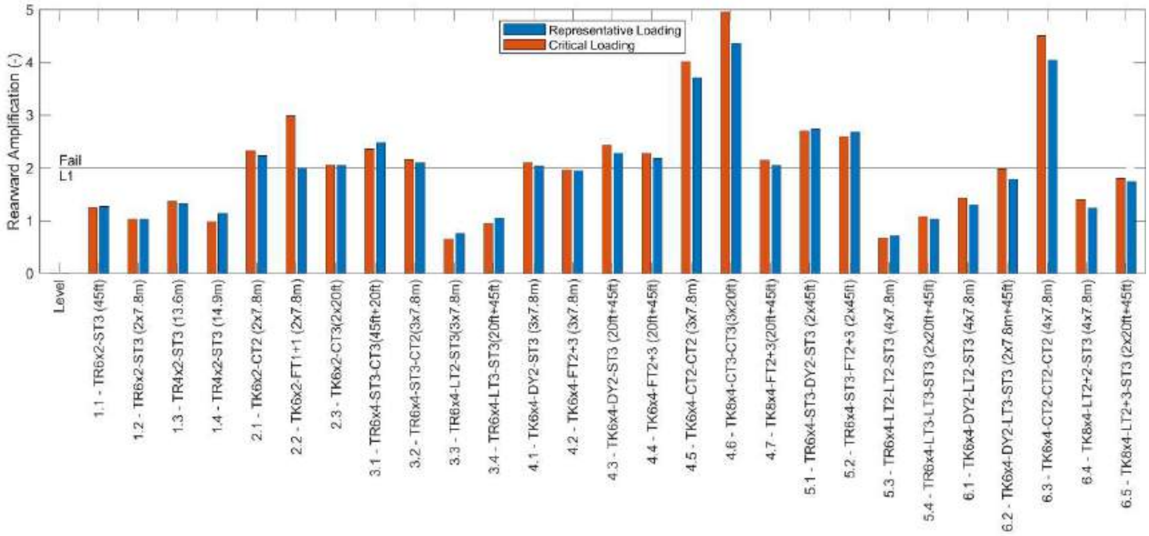



*Figure 18: Vehicle dynamics simulation results: Rearward Amplification*

The Load Transfer Ratio (LTR) results, summarised in Figure 19, mostly echo those of the other lane-change standards, and similar conclusions with respect to vehicle design optimisation and centre-axle trailers may be made. The centre-axle trailer combinations 4.5, 4.6, and 6.3 all exhibited a Load Transfer Ratio of 1, meaning that they experienced wheel-lift during the lane-change manoeuvre. These vehicles were consistently poor performers in other safety-critical standards, including Rearward Amplification. Combination 2.2 (the only combination with the FT1+1 trailer) also performed poorly relative to its peers in Group 2. Thus, to be able to include these combinations in a future European HCV framework, their performance should be improved by tuning design parameters such as coupling location or wheelbase, or through active control systems.

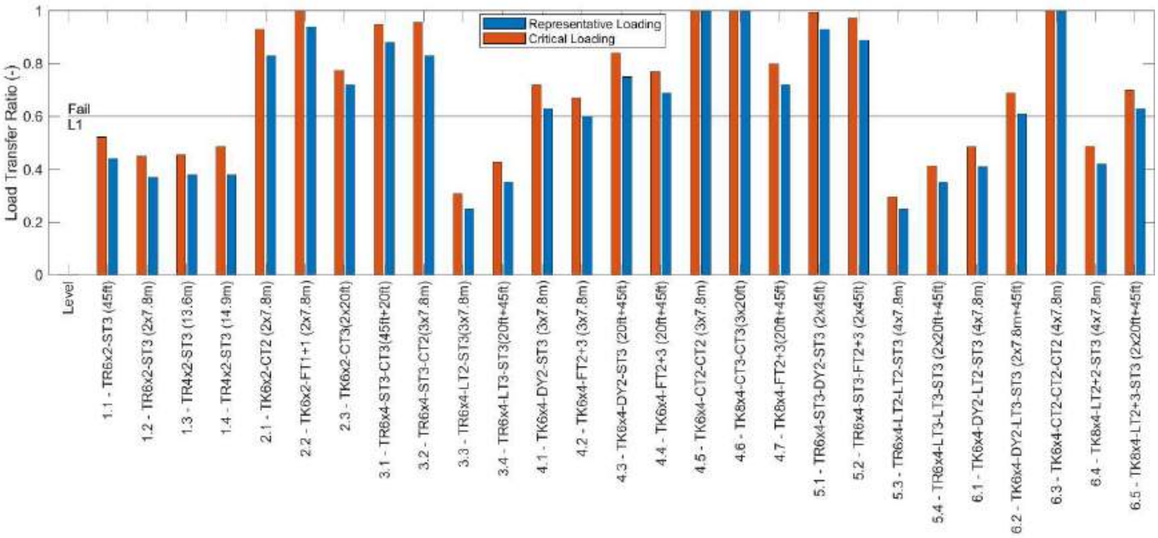



*Figure 19: Vehicle dynamics simulation results: Load Transfer Ratio*

Strong correlation was exhibited between Load Transfer Ratio and Rearward Amplification (Appendix D, Figure 96). This might suggest that LTR can be excluded (as in the Australians PBS scheme), on the grounds that the standard is difficult to measure in the field, and so RA was preferable while capturing most of the same effects. However, the need to experimentally test LTR is no longer a primary concern as it was in the early days of PBS, and it has value in giving a very direct measure of the rollover risk of the rearmost trailer. Both LTR and RA are assessed in the same manoeuvre and so there is negligible added simulation effort in assessing both. It is therefore recommended that LTR be retained to address the rollover risk

<u>of the whip-crack effect, making use of the RRCU concept. RA should then be retained as a direct measure of the degree yaw-plane amplification of acceleration, measured only at the rearmost trailer (not RRCU)</u>.

From Figure 96 (Appendix D), it seems that an RA limit of 2 correlates to an LTR closer to 0.7 than to 0.6, for the current vehicle designs. Should the RA limit be reviewed, the LTR limit of 0.6 should be reviewed accordingly. Conversely, the LTR limit of 0.6 is arguably better established and recognised in the field, and so the limit for RA could be adjusted accordingly instead, and from Figure 96 (for the non-optimised vehicles) this seems to correlate with RA≈1.8.

High-Speed Transient Off-tracking (HSTO), shown in Figure 20, tended to increase with vehicle length, but again is very sensitive to vehicle design and loading conditions. The worst performers are again the centre-axle trailer combinations. Similar conclusions regarding vehicle design made above are applicable here. The pass/fail criteria are potentially suitable, and vehicle design is likely the critical factor. In the cases of both RA and HSTO, it should be noted that these trailers have single tyres, while in Australia it is more common to have dual tyres which tend to exhibit improved performance in these standards. This may lead to slightly reduced performance of European combinations. <u>Further investigation is recommended</u>.

In refining the pass/fail criteria for HSTO, it is recommended that these be made in line with lane widths in Europe. The most limiting lane widths from all countries should be used to define universal HSTO limits. In Australia, the Level 1/2/3 limits are 0.6/0.8/1.0 m, and standard road widths are 3.5 m, reduced to 3.3 m if there is little truck traffic. Motorway lane widths in Europe are approximately similar to Australia, ranging from 3 m to 3. 75m. In Europe, minor (general access) roads, which could be used by Level 1 trucks, may be as narrow as 2.5 m or 2. 75 m. However, speeds on these roads are expected to be limited to far lower than 88 km/h (at which HSTO is assessed), and closer to 50 km/h. Realistic HSTO performance in an evasive manoeuvre would be accordingly reduced. <u>It may therefore be the case that the current Australian limits are applicable to Europe as well (and vehicle widths are also the same at 2.55 m). However further investigation is recommended.</u>

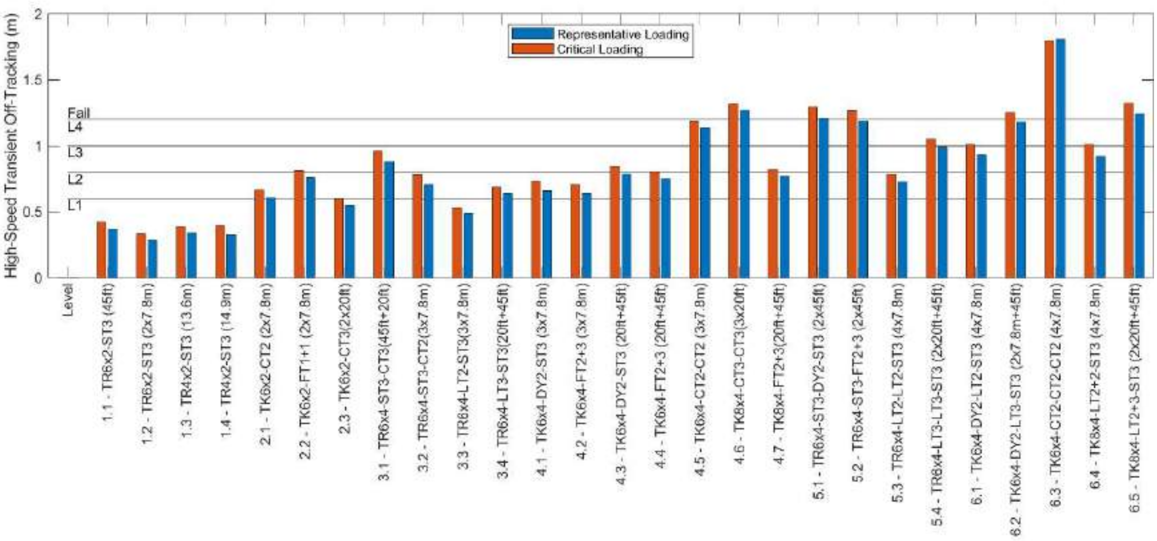



*Figure 20: Vehicle dynamics simulation results: High-Speed Transient Off-tracking*

Yaw damping performance was mostly acceptable across the board, with only the centre-axle trailer combinations failing, as summarised in Figure 21. Under critical loading, the FT1+1 combination fails. The results suggest that the standard is acceptable and serves to highlight the poor dynamic performers in the form of centre axle and FT1+1 combinations. <u>There is no</u>

reasonable justification to review the existing limit of 0.15, which is well established (see ISO 14791).

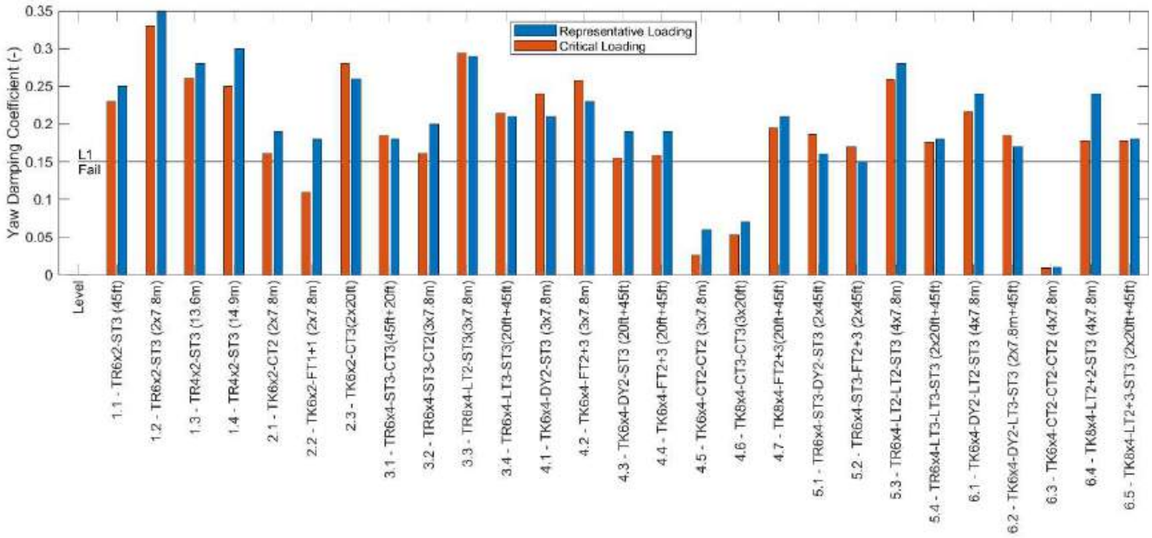



*Figure 21: Vehicle dynamics simulation results: Yaw Damping Coefficient*

Tracking Ability on a Straight Path (TASP) performance was acceptable in general, with groups 1-4 achieving Level 1 (except for 4.5 and 4.6, centre-axle trailer combinations), and groups 4-6 achieving Level 2 (with the exception of vehicle 6.3, also a centre-axle trailer combination). Results are summarised in Figure 22. In the correlation analysis, TASP was shown to be highly correlated with High-Speed Transient Off-tracking (Appendix D, Figure 84), and the existing pass/fail criteria for HSTO were consistently shown to be the limiting case for all vehicles. Additionally, the TASP standard was noted by South African PBS assessors to be problematic in terms of complexity and the consistency of simulations between assessors, and it requires the simulation of a unique manoeuvre to obtain a single performance result. Note as well that TASP is also expected to be highly correlated to HSSO, since vehicle response to the TASP cross-slope is similar to that of sustained lateral acceleration in a curve, with different magnitude. However, since it has been suggested to exclude HSSO from the PBS standards, the TASP correlation with HSTO was investigated instead. It is recommended that the TASP be discarded.

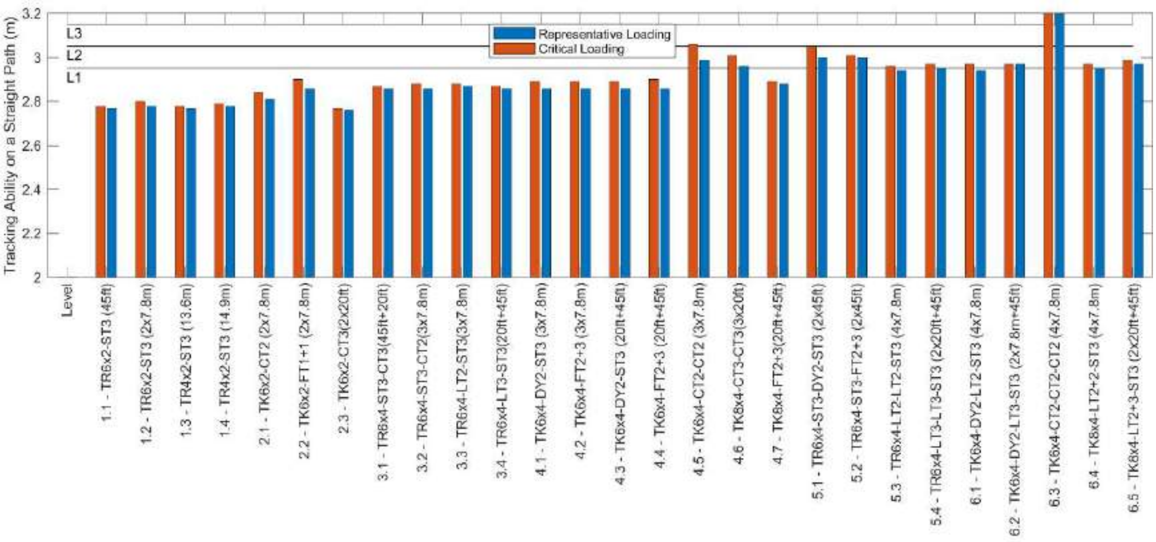



*Figure 22: Vehicle dynamics simulation results: Tracking Ability on a Straight Path*

As shown in Figure 23, most vehicles fail the Australian limits for High-Speed Steady-state Off-tracking (HSSO). The standard was excluded from consideration in the Australian scheme in early stages of their PBS programme, and so the limits set at that point were not reviewed further for suitability and refinement. In the correlation analysis, High-Speed Steady-state Off-tracking was shown to be highly correlated with combination length (Appendix D, Figure 95), suggesting that it does not add additional value. However, in cases of very heavy vehicles (i.e. higher than the loading conditions considered in this study), the influence of mass may become a limiting factor, and this standard may become more relevant. Also, it should be noted that vehicles in the fleet were modelled with similar suspension, and CoG heights would be similar due to the payload modelling process used. Larger differences in these parameters between vehicles may yield different levels of correlation. It is recommended that HSSO be excluded from the initial PBS standards, and suitable length limits per road access level could be imposed instead, or road access levels could be defined according to vehicle width and lane widths.

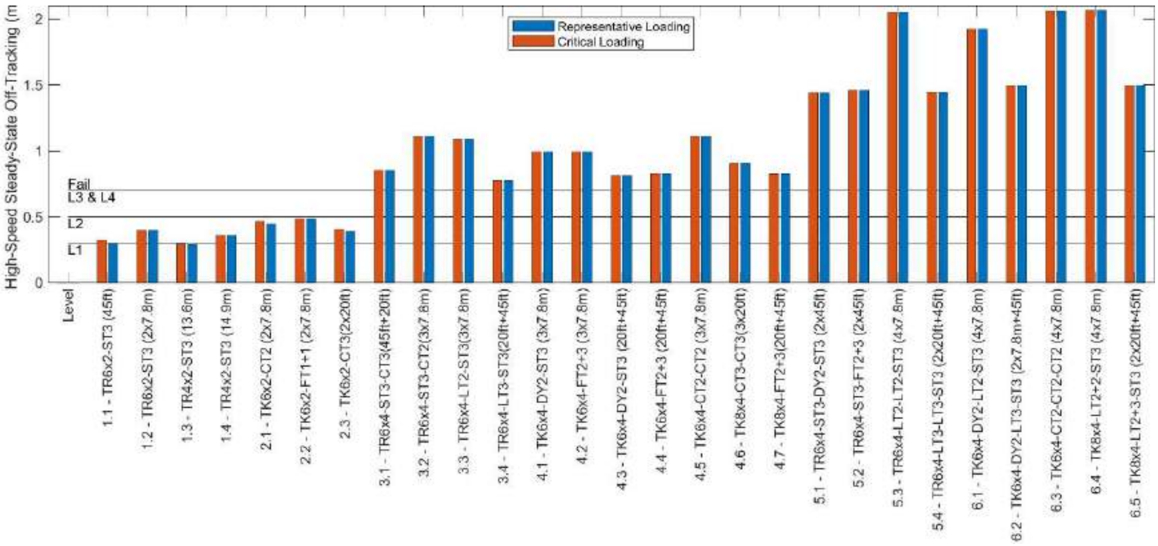



*Figure 23: Vehicle dynamics simulation results: High-Speed Steady-state Off-tracking*

### 4.2.4. Winter conditions

Detailed winter simulation results are given in Appendix E. An overview and discussion of the results will be presented in the following subsections.

#### *4.2.4.1. Braking deceleration*

The existing European regulations for braking performance of heavy vehicles, ECE R13, is already performance based. ECE R13 also includes winter related performance criteria such as braking performance on split friction road surface, or transient braking from a high friction road surface to a low friction road surface and vice versa.

The expected braking deceleration levels in ECE R13 are only defined for summer conditions, which is 4 $m/s^2$ from initial speed of 90 km/h (80 km/h for tractors) and 5 $m/s^2$ from 60 km/h. Only the latter initial speed is relevant for winter conditions, assuming that driver's exhibit a speed response appropriate for the conditions. Looking at some braking tests in winter conducted by Volvo, deceleration levels of 5 $m/s^2$ from an initial speed of 60 km/h was achievable with a truck-B-double combination with common braking systems, even in winter. However, the deceleration level can reduce to 3 $m/s^2$ for icy conditions, i.e. after repetition of the test resulting in an icy test track surface [38].

Another concern for HCVs braking safety in winter is the vehicle stability during braking in a turn; this has been investigated in the Swedish PBS project [39], where braking stability of two

HCVS was investigated by Volvo on test track in winter conditions. The test results indicated that the vehicles stay stable during braking in a turn on snow, when the ABS function works properly. But, malfunctioning of the ABS on any axle groups, as well as extreme slippery conditions (wet ice), result in large off-tracking [38], [40]. An issue which should be further investigated is the effect of the braking delay on stability of long HCVs during braking in a turn. It should be noted that in Volvo test results no significant benefit was observed with using Electronic Braking System (EBS).

#### *4.2.4.2. Startability*

For startability analysis, data gathered in the Swedish PBS project, presented in [41], was used. In the Swedish PBS project, the startability of 10 vehicles on low friction road (μ=0.25) was compared with startability on high friction road (μ=0.9), with two different engines, 330hp and 750 hp. To generalize the results to the FALCON fleet, the data from the 330 hp engine was used, since it is closer to the engines considered for the FALCON fleet which are in the range of 400-480 hp. On average the calculated startability on low friction is about 18.7% of the startability on high friction with the 330 hp engine. Applying the same reduction to the FALCON fleet, the startability on low friction can be estimated as shown in Figure 24.

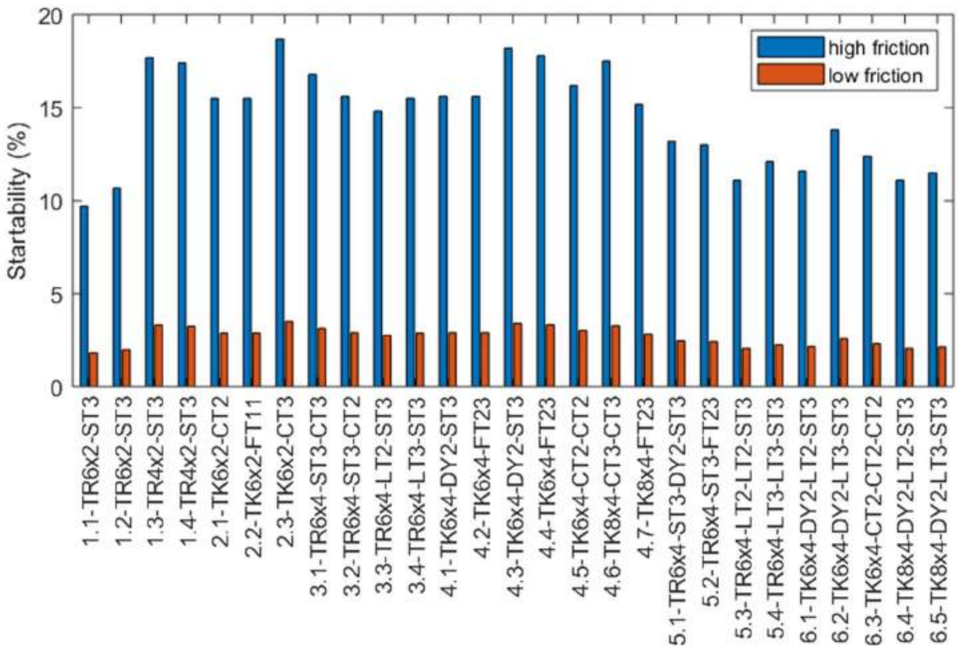



*Figure 24. Startability of the FALCON fleet in summer versus winter*

None of the vehicles in FALCON fleet, not even the conventional vehicles, will be able to start on a grade larger than 3% when the tyre-road friction level is low. This is far from 12% which a heavy vehicle combination should be able to start on during summer conditions. One solution to overcome the startability issue of the heavy vehicles in winter is to allow the driver axle load limit to be exceeded during a brief time at start up, by a type-approved, automated axle lift or other means of load transfer to drive axles.

#### *4.2.4.3. Friction demand*

The friction demand was calculated in the same roundabout manoeuvre used for swept path. To assess how much peak friction is required for the vehicle to complete the manoeuvre, first the absolute friction demand was calculated, i.e., the friction demand was calculated as the ratio of in-plane forces and normal forces, and was *NOT* normalized by friction coefficient, see Figure 25 and Figure 26. These figures show that the absolute friction demand of both the steered axle and drives axles are lowered in the snow condition (μ=0.3) compared to the dry asphalt (μ=0.8). This phenomenon can be explained by the fact that the friction demand is not only dependent on the friction, but also on other tyre properties such as cornering stiffness. This has been discussed further in the final report of the Swedish PBS project [39].

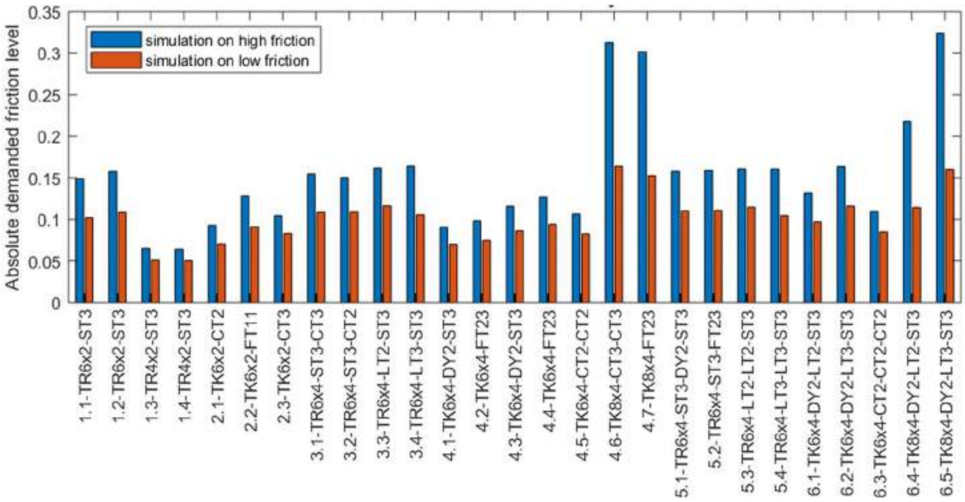



*Figure 25. Absolute friction demand of steer tyres, summer versus winter*

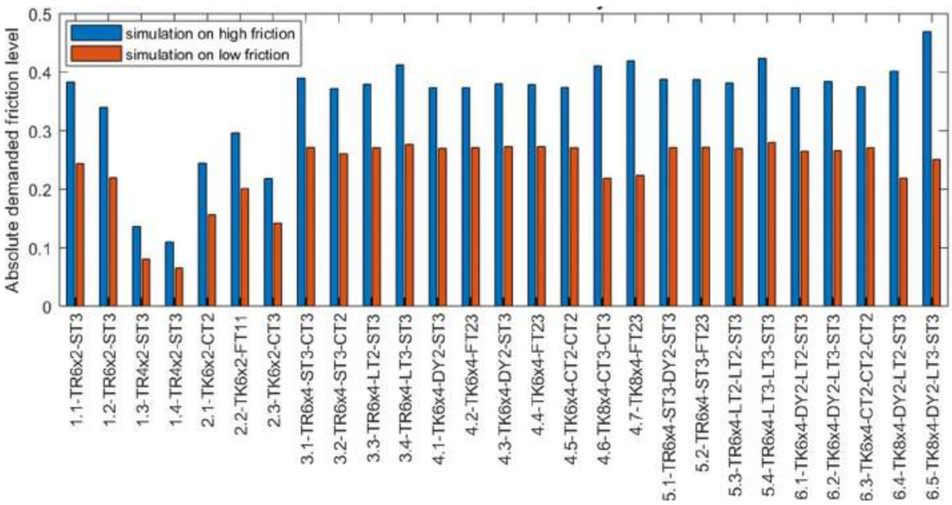



*Figure 26. Absolute friction demand of drive tyres, summer versus winter*

The simulation results suggest that calculating the friction demand on high friction as a means for assessing the performance on low friction might not be an appropriate approach, due to the dependency of the measure on both cornering stiffness and friction level. Considering that the available friction is lower in winter, a higher percentage of the available friction is demanded for manoeuvring in winter, compared with summer, depicted in Figure 27 and Figure 28, as expected.

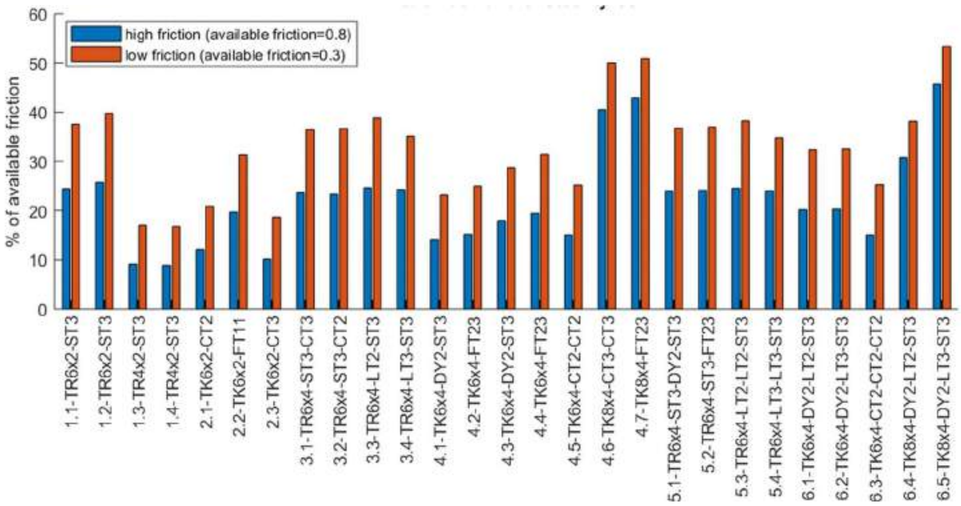



*Figure 27. Steer tyres friction demand (normalized by the coefficient of friction), summer vs. winter*

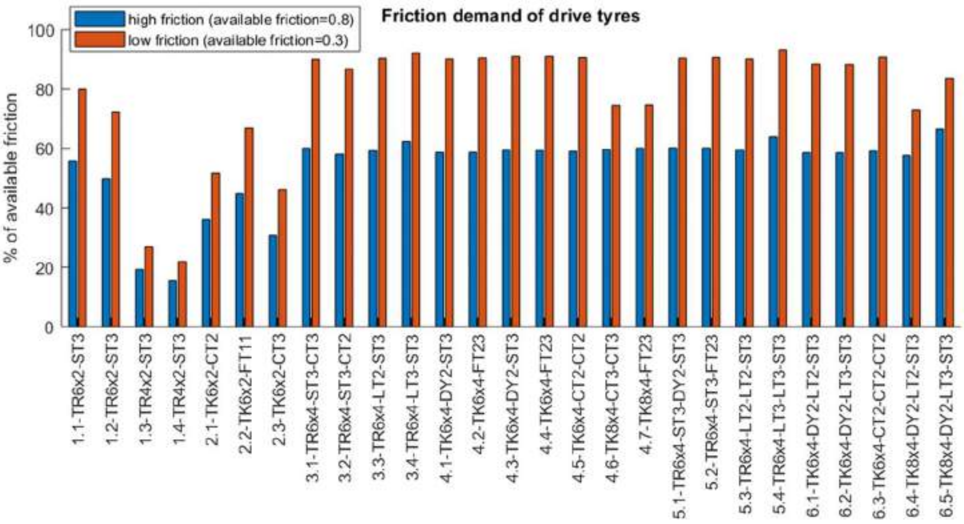



*Figure 28. Drive tyres friction demand (normalized by the coefficient of friction), summer vs. winter*

By normalizing the friction demand by the available friction (friction coefficient of the road surface), a correlation can be found between results of high friction and low friction simulation to be used for deciding the suitable measure and corresponding level.

Figure 29 illustrates the correlation between friction demand in winter and summer for steer tyres and drive tyres. Such a correlation investigation can be used to decide a friction demand level for high friction simulations, which ensure a safe friction demand on low friction condition as well. This is desirable, since assessing the friction demand on high friction is easier and reduces the required simulation work.

Finally, it should be noted that friction demand at steer axle tyres and drive axle tires on power units (tractors) are metrics that were developed during the RTAC Canadian Weights and Dimensions Study 1986. Most tractors in North America have two-axle drive bogies. Over time, low speed tractor drive axle friction demand was found to be less useful because the force vectors at the tyre road interface are in dissimilar direction due to slow speed vehicle yaw kinematics. On the other hand, the force vectors present at the steer tire are practically aligned providing a measure of the available tire lateral force capability. This measure is useful for ensuring low seed manoeuvrability particularly when triaxle drive groups are used.

Therefore, it may be appropriate to only assess the friction demand of steer tyres, though assessing drive tyre friction demand does not present any additional simulation effort.

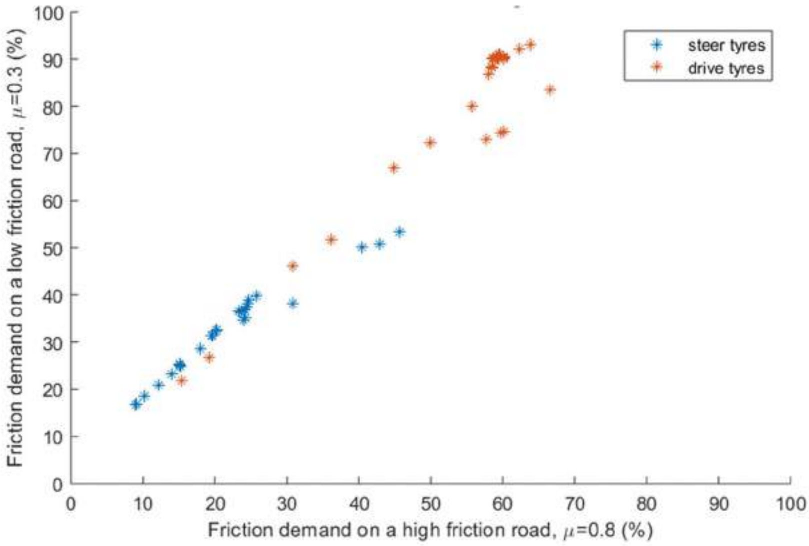



*Figure 29. Correlation between friction demand on high and low friction roads*

#### *4.2.4.4. High-speed lane-change*

The correlation between vehicle performance under winter and summer conditions in a single lane-change manoeuvre was investigated. Rearward amplification and high speed transient off-tracking were assessed according to the Australian PBS lane-change manoeuvre at 88 km/h, which originates from ISO 14791 [42].

In Figure 30, it is shown that HSTO was significantly larger under low friction conditions ($\mu$=0.3) compared with high friction conditions at approximately the same speed. It can also be seen that low friction HSTO performance at 60 km/h is comparable with high friction performance at 88 km/h. From this, it can be concluded that speed should be reduced or regulated to 60 km/h in winter conditions.

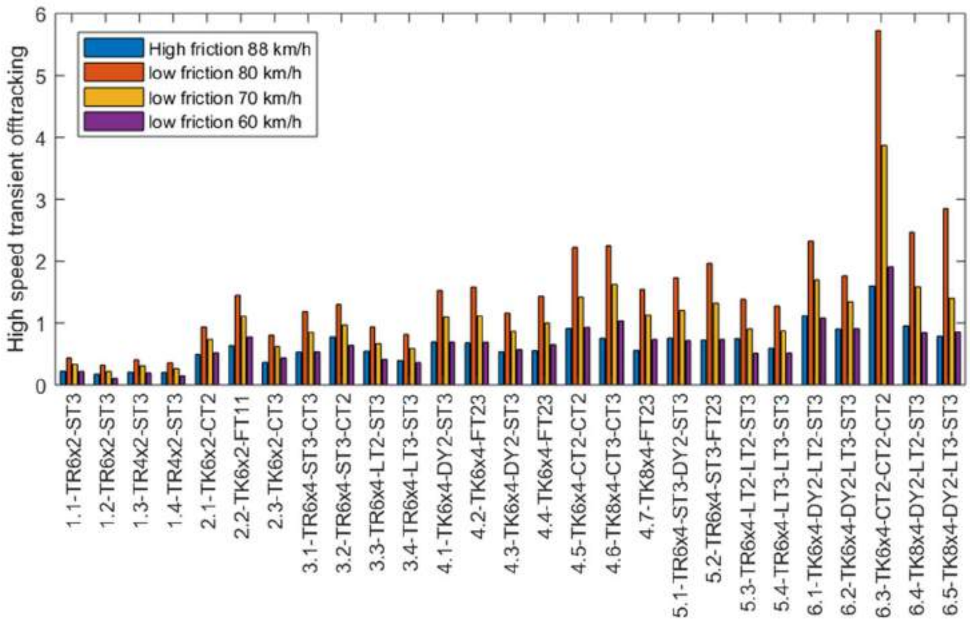



*Figure 30: High speed transient off-tracking, summer versus winter*

Due to low levels of lateral acceleration under winter conditions, rearward amplification of yaw rate was assessed instead of rearward amplification of lateral acceleration. RA of yaw rate can be used as an indicator trailer swing-out and a loss of yaw stability. Figure 31 shows that the RA values are generally comparable between winter and summer conditions at high speeds, though there are exceptions for vehicles with large summer RA values. For these vehicles, speed must be reduced to 60 km/h to achieve similar performance to summer conditions.

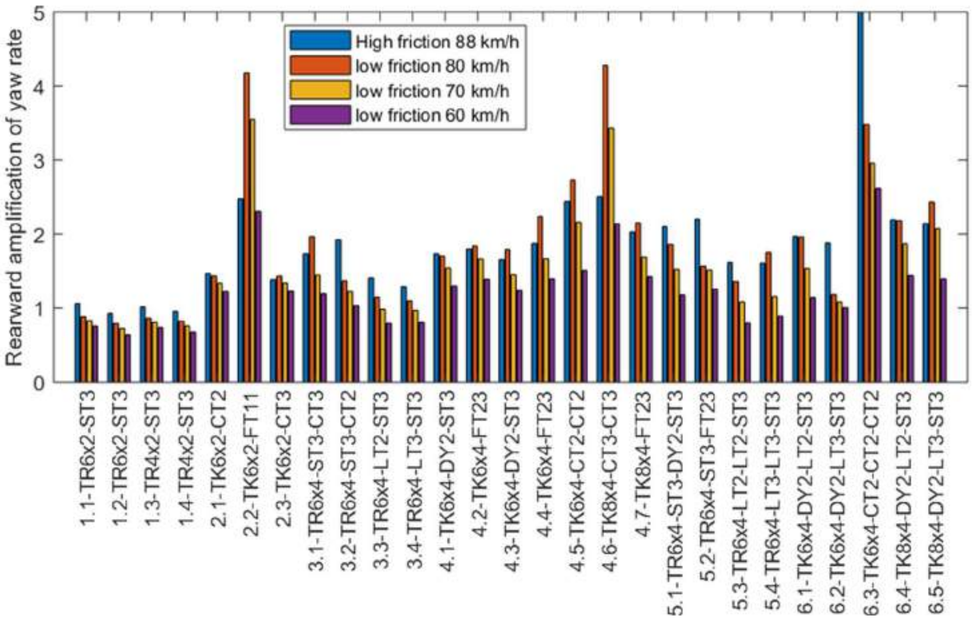



*Figure 31: Rearward amplification of yaw rate, summer versus winter*

#### *4.2.4.5. Comparison of rearward amplification of lateral acceleration and yaw rate*

Historically in Sweden, rearward amplification of yaw rate has been used to assess the lateral stability of heavy vehicles, instead of the more conventional RA of lateral acceleration. A benefit of this approach is that the measurement is independent of sensor location on each vehicle ‘body’ [13]. The performance of the fleet in the two performance standards were compared to give insights into the benefits of using yaw rate instead of lateral acceleration for assessing dynamic performance in winter conditions.

The results are shown in Figure 32. It can be seen that rearward amplification of lateral acceleration and yaw rate are better correlated for high friction surfaces. For the summer condition the plotted values in the left plot are close to equality, and the same trend can be seen in the bar chart on the right. However, on low friction lateral forces are limited, whereas large yaw motions are possible; *i.e.* the yaw rate RA can be higher than the lateral acceleration RA on low friction. The vehicle can lose yaw stability and swing outs to the side, especially at higher speeds, which explains the differences between the RA of yaw rate and lateral acceleration for the poorly performing vehicles (combinations 2.2, 4.6 and 6.3). The difference is reduced at lower speeds, since the vehicles are more stable.

Considering the lower speed operation in winter for HCT vehicles, introducing yaw rate rearward amplification as a separate measure does not seem necessary. Swing-out of the rearward units in a vehicle combination is addressed by HSTO.

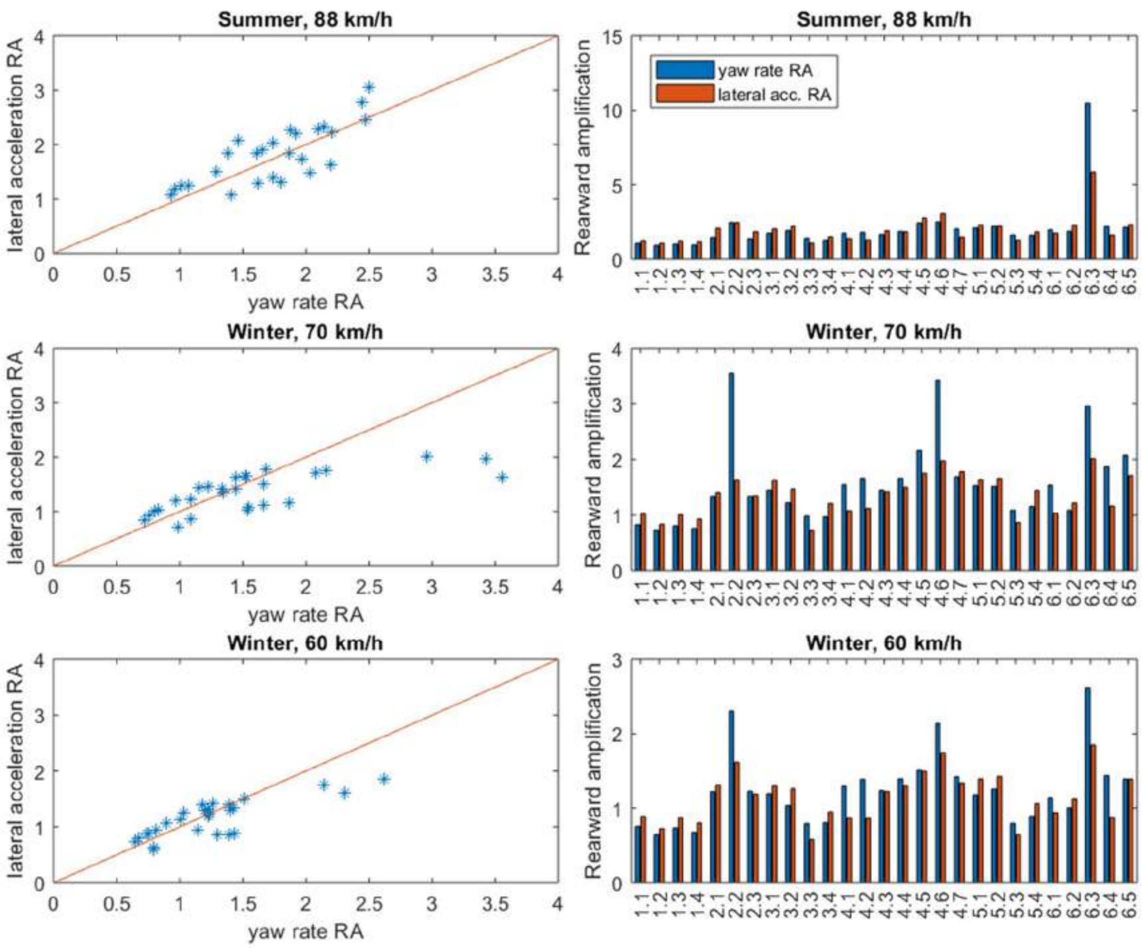



*Figure 32: Correlation between rearward amplification of yaw rate and lateral acceleration, summer and winter*

## 4.3. Vehicle design optimisation: case study

Performance exhibited by the representative fleet during the lane change manoeuvre was relatively poor across the board, when measured against the Australian PBS pass/fail criteria. Well over half of the representative fleet failed either rearward amplification, high-speed transient off-tracking, dynamic load transfer ratio, or some combination of these standards under representative loading conditions. We can conclude from this that either the pass/fail criteria are in need of significant refinement for European conditions, or that the vehicle combination designs provided by the OEMs and operators have not been adequately optimised for dynamic performance in this respect, or a combination of both. Given past experience with PBS vehicle design and assessment, and noting the sensitivities of vehicle performance to parameters such as wheelbases and hitch offset dimensions [28], it was concluded that the primary factor was probably non-optimal vehicle design.

To illustrate this point, and to show how the representative designs could be improved, a design case study was conducted using combination 5.1 with representative loading. This combination (an “A-double”) was chosen as it is known to be a strong PBS performer in Australia and South Africa, meeting at least Level 2 performance criteria in all standards. It was noted that the most impactful design parameters to investigate were wheelbases, drawbar length, and hitch locations. A parametric study was carried out, varying these parameters of the combination in an attempt to improve high-speed dynamic performance, while not negatively impacting other standards.

The resultant "optimised" design is shown in Figure 33, where the original dimensions are shown alongside the variations of these parameters which were settled on after the optimisation. The modifications are relatively minor and are in line with common A-double designs operating in South Africa and Australia. Semi-trailer wheelbases have been extended by just over a meter, the pintle hitch on the first trailer has been moved forwards by 200 mm, and the kingpin of the second trailer has been moved 50 mm ahead of the centre of the dolly axle group. This yielded an overall reduction in combination length of 0.05 m. No other changes were made.

The performance results of both the original and optimised vehicle are shown in Table 8. Performance results are shown relative to the existing predominantly Australian performance criteria for the four Australian road access levels. Rearward amplification has improved from a "fail" to a "pass" and high-speed transient off-tracking from a "fail" to a "Level 2 pass". Dynamic load transfer ration has improved significantly from 0.93 to 0.68, though this is still above the reference pass criterion of 0.6. Performance in other standards has also improved, including gradeability A, acceleration capability, tracking ability on a straight path, tail swing, steer tyre friction demand, and yaw damping coefficient. Low speed swept path has increased primarily due to the increased wheelbases, but still meets the Level 2 criterion. Performance in the difference of maxima, maximum of difference, and high-speed transient off-tracking standards deteriorated slightly, requiring additional optimisation, or a review of other design parameters.

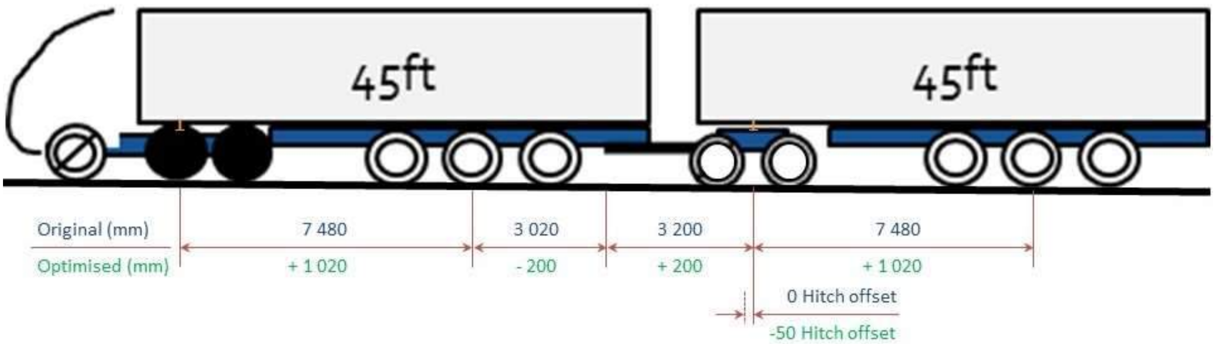



*Figure 33: Design case study, combination 5.1, showing original dimensions and modifications*

*Table 8: Design case study results, original versus optimised combination*

| | 5.1 Optimised | | Result | 5.1 Original | | Result | Required performance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Load condition:** | **Laden** | **Unladen** | | **Laden** | **Unladen** | | **Level 1** | **Level 2** | **Level 3** | **Level 4** |
| Startability | 13.2 | | **Level 2** | 13.2 | | **Level 2** | ≥ 15% | ≥ 12% | ≥ 10% | ≥ 5% |
| Gradeability A (Maintain motion) | 17.2 | | **Level 2** | 14.9 | | **Level 3** | ≥ 20% | ≥ 15% | ≥ 12% | ≥ 8% |
| Gradeability B (Maintain speed) | 84.8 | | Level 1 | 84.8 | | Level 1 | ≥ 80 km/h | ≥ 70 km/h | ≥ 70 km/h | ≥ 60 km/h |
| Acceleration Capability | 19.37 | | Level 1 | 19.66 | | Level 1 | ≤ 20.0 s | ≤ 23.0 s | ≤ 26.0 s | ≤ 29.0 s |
| Tracking Ability on a Straight Path | 2.91 | | **Level 2** | 3.00 | | **Level 2** | ≤ 2.9 m | ≤ 3.0 m | ≤ 3.1 m | ≤ 3.3 m |
| Low Speed Swept Path | 8.67 | 8.66 | **Level 2** | 7.67 | 7.68 | **Level 2** | ≤ 7.4 m | ≤ 8.7 m | ≤ 10.6 m | ≤ 13.7 m |
| Frontal Swing | 0.36 | 0.37 | Pass | 0.36 | 0.36 | Pass | ≤ 0.7 m | | | |
| Difference of Maxima | 0.25 | 0.25 | **Fail** | 0.20 | 0.20 | Pass | ≤ 0.20 m | | | |
| Maximum of Difference | 0.62 | 0.61 | **Fail** | 0.55 | 0.54 | **Fail** | ≤ 0.40 m | | | |
| Tail Swing | 0.10 | 0.10 | Level 1 | 0.25 | 0.25 | Level 1 | ≤ 0.30 m | ≤ 0.35 m | ≤ 0.35 m | ≤ 0.50 m |
| Steer-Tyre Friction Demand | 25.9 | 25.50 | Pass | 24.4 | 25.40 | Pass | ≤ 80% | | | |
| Static Rollover Threshold | 0.43 | | Pass | 0.44 | | Pass | ≥ 0.35·g | | | |
| Rearward Amplification | 1.95 | | Pass | 2.76 | | **Fail** | ≤ 5.7·SRT_rrcu* | | | |
| High-Speed Transient Offtracking | 0.80 | | **Level 2** | 1.22 | | **Fail** | ≤ 0.6 m | ≤ 0.8 m | ≤ 1.0 m | ≤ 1.2 m |
| Dynamic Load Transfer Ratio | 0.68 | | **Fail** | 0.93 | | **Fail** | ≤ 0.6 | | | |
| High-Speed Steady-State Offtracking | 1.52 | | **Fail** | 1.44 | | **Fail** | ≤ 0.3 m | ≤ 0.5 m | ≤ 0.7 m | ≤ 0.7 m |
| Yaw Damping Coefficient @ 100 km/h | 0.25 | | Pass | 0.15 | | Pass | ≥ 0.15 | | | |

This isolated case study has shown that some of the representative vehicle designs may not be fully optimised for PBS, especially the longer concept designs studied. The representative fleet has served as an effective tool for this study and has given indications of expected performance. It has helped to provide other useful observations such as correlations between certain standards. Should some or all of these vehicle combinations be considered further for operation in European cross-border transport, there would be a need to conduct an optimisation study such as this for each vehicle. Some vehicles in the fleet however, such as the combinations with two or three centre axle trailers, may not have sufficient scope for optimisation in this manner, and would require active intervention systems to meet the performance requirements.

### 4.4. Conclusions and recommendations

1. Driveability
    a. The pass/fail criteria of the Australian Startability and Gradeability A standards should be reviewed against local road grade conditions, and acceleration capacity should be reviewed against local intersection and road crossing geometries. Each jurisdiction should set these accordingly as relevant.
    b. The Level 1 Startability criterion could be reduced to 12% to match the Level 2 criterion and existing European rules. Level 3 should not be reduced below 10%, to accommodate vehicles in groups 5 and 6.
    c. The existing Gradeability B criteria are probably suitable as the speed limits are comparable between Australia and Europe (80 km/h at Level 1).
    d. The use of commercial drive axle load proportioning systems should be considered to improve Startability and Gradeability A performance in isolated scenarios as necessary.
    e. Existing European standards relating to traction limits and engine power are not fully performance-based, and do not take into account certain vehicle parameters. Although the EU standards could be used, and this would be the simplest approach, a fully performance-based approach is more reliable and future-proof, as it can accommodate the impact of future technologies such as tractive trailers and dollies, and hybrid powertrains with variable power proportioning.
2. Low-speed manoeuvrability
    a. The Australian low-speed standards should be used to assess performance for all road access levels. In addition, the EU roundabout should be used for assessing “Level 1” type vehicles. The EMS roundabout test could be considered for Level 2 vehicles.
    b. The Australian pass/fail criteria for Low-Speed Swept Path are seemingly too lenient for the European context and should be reviewed in the context of European road geometries such as lane widths and intersection layouts. These can be reviewed on a country-level to be appropriate for local conditions.
    c. For the current representative vehicle fleet, Tail Swing should be set to 0.3 m across the board. However, car-carrier combinations may require a more lenient limit.
    d. Based on the trucks and tractors considered, frontal swing could be reduced to 0.5 m. However, there is no documented need to reduce the limit below the current 0.7 m. Other, longer wheelbase truck and tractor units and buses would potentially not meet a 0.5 m limit, and future aerodynamic cab advancements may also deem a 0.5 m limit unobtainable. Front overhang legislation already exists in Europe and may be an adequate means of ensuring safe frontal swing. This should be subjected to further investigation.
    e. The Difference of Maxima and Maximum of Difference should be reviewed for relevance. Either one simplified standard could be adopted, or the standards

can be removed. A study of existing EU regulation of semitrailer front overhang legislation should be carried out in the light of these findings.
   f. The 80% upper limit on steer tyre friction demand may be too lenient, and the source of this value should be investigated further for applicability to Europe.

3. High-speed stability
   a. The Australian Static Rollover Threshold and Yaw Damping Coefficient standards and their existing criteria should be retained. Tracking Ability on a Straight Path and High-Speed Steady-state Off-tracking should be excluded. The High-Speed Steady-state Off-tracking performance should be used to define suitable combination length limits per road access level.
   b. Performance in the lane-change manoeuvre (for Rearward Amplification, High-Speed Transient Off-tracking, Load Transfer Ratio) highlighted that the vehicle designs were not optimised for transient high-speed stability, and these should be reviewed accordingly.
   c. Rearward Amplification should be assessed at the rearmost trailer (not at the rearmost roll-coupled unit). The pass criterion of ≥ 2 should be reviewed for applicability to this method, and to typical European combinations. A limit of 2.4 has been used for rearward amplification of yaw rate in Sweden [22], which could be used as a starting point.
   d. For High-Speed Transient Off-tracking (HSTO), vehicle and lane widths are similar to Australia and so the criteria may be transferable. However, Level 1 vehicles may use minor roads of width 2.5 or 2. 75 m in Europe, albeit at reduced speeds. This requires further investigation.
   e. The Load Transfer Ratio standard should be retained as this gives a direct indication pf high-speed transient rollover risk. The current criterion of 0.6 should be reviewed in parallel with the review of the Rearward Amplification criterion and vehicle design optimisation.

4. Winter conditions
   a. To ensure that heavy vehicles can start on a slope in low friction conditions, it should be permitted to exceed the drive axle load limit briefly at start up, via a lift axle or other means of load transfer to drive axles.
   b. The faultless function of ABS system is necessary for braking stability of HCVs in winter. Electronic Braking Systems (EBS) should be strongly considered as a potential prerequisite for high capacity transport in Europe. Crash-avoidance emergency braking systems are now compulsory for new trucks in Europe, which is beneficial to the potential introduction of high capacity transport and should be considered in other jurisdictions considering the introduction of high capacity transport.
   c. Speed should be reduced to 60 km/h in winter conditions, to ensure that performance is comparable to the safe high friction performance in a high-speed lane change.
   d. For the fleet considered, it can be adequate to assess steer and drive tyre friction demand under high friction conditions, in order to get a reliable indication of performance under low friction conditions. The criteria in high friction conditions could be set to ensure appropriate low friction performance.
   e. For the most accurate results however, friction demand should be simulated in winter conditions. However, if it is practical to perform all simulations in summer conditions without the need for winter-specific models, then correlation between summer and winter performance can be investigated (as done here) for the specific fleet under concern, and used to set a safe performance level to ensure both summer and winter performance

5. General:
   a. The centre-axle trailer combinations 4.5, 4.6, and 6.3 and the 1+1 full-trailer combination 2.2 demonstrated poor high-speed stability performance. However, these combinations are noted have practical value to the European

transport market. These vehicles should undergo a passive design optimisation exercise, followed by a performance assessment with additional active control systems, to try and achieve safe performance. Should safe performance be exhibited with such systems, they could be permitted to operate under a PBS regime on condition of the fitment of such systems.

b. The detailed design of the representative fleet combinations should be reviewed, in order to optimise the designs for safety performance while addressing practical and productivity needs.

# 5. Simulations: Bridge Loading

## 5.1. Methodology and assumptions

The impact of the representative fleet on bridges was assessed by IFSTTAR France using the ST1 software (http://www.setra.fr/html/logicielsOA/LogicielsOA/ST1/st1.html). Axle loads calculated for the vehicle models were provided by CSIR. The impact of the fleet was assessed on a catalogue of bridges, including simply-supported single span bridges, two-span continuous bridges, and spans of 10, 20, 35, 50 and 100 m. This selection was identified in the report of FALCON Task 3.2 [6]. The metrics considered were the bending moment at the mid-span, shear force at the supports, used for both extreme loading and fatigue calculations. Dynamic effects were not considered nor were dynamic load factors. Combination 2.1 was considered to be the reference case.

Bridges can exist in a variety of different forms, comprising many structural types and materials. They are typically classified as follows: (1) by type of material (masonry, pre-stressed concrete, reinforced concrete, etc.), (2) by number of spans, and (3) by the transport mode which utilises the bridge (rail, road, canal, etc.). Span lengths vary from approximately 5 meters (integral concrete frames) to several hundreds of meters (mostly steel bridges).

In a typical bridge design process, the designer chooses the number and location of supports and thus specifies the span length. The span length then dictates (approximately) the choice of material and construction method. The characteristics of the materials and the final dimensions of the elements (beams, plates, etc.) are then determined by considering the stresses induced in the structure by various load models prescribed in Eurocode 1, ensuring that the calculated stresses do not exceed the design stresses of the materials used.

There exist an infinite number of bridge configurations. Therefore, the best way to obtain a panel of these structures is to study the transfer functions between loads/actions and consequences in the structure (stress, strain, etc.). These transfer functions are called influence lines, which are a physical function corresponding to the response (shear, bending moment, etc.) of the structure as the downward unit load moves across the structure. As a consequence, studying a well-chosen panel of influence lines makes it possible to assess all bridges.

A bridge should be designed or assessed under both static and dynamic loading. A dynamic assessment corresponds to a complete VBI (Vehicle-Bridge Interaction) model and makes it possible to compare the eigenfrequencies of the bridge with those of the actions applied to the structure. Although important, this is not typically carried out in the initial stages of bridge design. Therefore, in the current context, only the static assessment of bridges will be considered. Fatigue effects were also considered, using static load conditions. Refer to Appendix F for more details.

### 5.1.1. Choice of influence lines

European bridges are designed according to load models defined in the Eurocode 1991-2. These load models incorporate safety margins and are supposed to represent the likely maximum traffic loading. The Eurocodes apply to all of Europe, and so bridges are designed and assessed according to the same standards throughout Europe. The only differences arising between countries are due to freedom in the selection of "$\alpha$-factors", which adjust the intensity of the load models to suit national traffic conditions.

Detailed bridge design criteria are given in deliverable D3.4 [27]. This catalogue of bridge structures contains an exhaustive list of theoretical structures to which these loads models are applied. These theoretical structures are represented by influence lines for the various primary responses to be considered as shown in Table 9 and Table 10. Here two types of bridges (single span and two-span bridges), with several types of primary responses, and 5 span lengths are studied. For these bridge structures, the results for the various vehicle configurations in the representative fleet were calculated. Table 10 details the number of “Effects”, linking them with the type of structure, the span length and the primary response that will be assessed in the bridge.

*Table 9: Catalogue of infrastructure to be assessed*

| Structure type | Bridge structure | Effect | Span length | Damage model |
|---|---|---|---|---|
| 1 | Simply supported, single span | Bending moment at midspan 1, shear at support 0 | 10m, 20m, 35m, 50m, 100m | Extreme Effects & Fatigue |
| 2 | Two-span, continuous bridge | Bending at midspan 1 and support 1, shear at support 0 | 10m, 20m, 35m, 50m, 100m | Extreme Effects & Fatigue |

*Table 10: Description and name of the various studied Effects.*

| Effect no. | Structure type | No. of spans | Span lengths | Primary response |
|---|---|---|---|---|
| 1 | 1 | 1 | 10 m | Bending moment mid-span |
| 2 | 1 | 1 | 20 m | Bending moment mid-span |
| 3 | 1 | 1 | 35 m | Bending moment mid-span |
| 4 | 1 | 1 | 50 m | Bending moment mid-span |
| 5 | 1 | 1 | 100 m | Bending moment mid-span |
| 6 | 1 | 1 | 10 m | Shear on support |
| 7 | 1 | 1 | 20 m | Shear on support |
| 8 | 1 | 1 | 35 m | Shear on support |
| 9 | 1 | 1 | 50 m | Shear on support |
| 10 | 1 | 1 | 100 m | Shear on support |
| 11 | 2 | 2 | 5 m – 5 m | Bending moment mid-span |
| 12 | 2 | 2 | 10 m – 10 m | Bending moment mid-span |
| 13 | 2 | 2 | 17.5 m – 17.5 m | Bending moment mid-span |
| 14 | 2 | 2 | 25 m – 25 m | Bending moment mid-span |
| 15 | 2 | 2 | 50 m – 50 m | Bending moment mid-span |
| 16 | 2 | 2 | 5 m – 5 m | Bending moment on central support |
| 17 | 2 | 2 | 10 m – 10 m | Bending moment on central support |
| 18 | 2 | 2 | 17.5 m – 17.5 m | Bending moment on central support |
| 19 | 2 | 2 | 25 m – 25 m | Bending moment on central support |
| 20 | 2 | 2 | 50 m – 50 m | Bending moment on central support |
| 21 | 2 | 2 | 5 m – 5 m | Shear at central support |
| 22 | 2 | 2 | 10 m – 10 m | Shear at central support |
| 23 | 2 | 2 | 17.5 m – 17.5 m | Shear at central support |
| 24 | 2 | 2 | 25 m – 25 m | Shear at central support |
| 25 | 2 | 2 | 50 m – 50 m | Shear at central support |

The calculations required are numerous (25*N calculations, where N is the number of vehicles in the fleet). From here on, the Effects that were calculated and compared will be called $E_1$ for Effect 1, $E_2$ for Effect 2, etc. The outer envelope of these Effect will be searched and provided as the upper limit for design criteria of a PBS.

### 5.1.2. Design loads and design physical values

In the current context, we are concerned with the design of new infrastructure, and not with the assessment of existing infrastructure. This means that all the information available on the infrastructure is theoretical: there is no a-posteriori information obtained from the monitoring or diagnosis of existing infrastructure. This extends to material properties (strength), the dimensions and design of the infrastructure and for the characteristics of the traffic (volume, loads, etc.). This means that the structural behaviour of the bridge is considered in the ideal case and neglects the effects of cracks, bearing instability, alkaline-aggregate reaction etc. Similarly, the input load considered here, imposed by the axles of the representative fleet, are based on theoretical loads, and do not consider trucks which are illegally overloaded for example, apart from the normal use of safety factors in bridge design calculations.

### 5.1.3. Design structural behaviour

It is also assumed that infrastructure elements are in nominal (i.e. design) shape, allowing their mechanical behaviour to be described analytically. This assumes that bridge bearing capacities and structural behaviour comply with the physical analytical theories (such as the Saint-Venant principle, material structural strengths, etc.) that have been used to design them. It is also assumed that the infrastructure is correctly designed against the other external loads other than traffic loading, and so the traffic loads are considered to be the design loads.

### 5.1.4. Linear elastic behaviour of the structure

It was assumed that the behaviour of the structure is linear elastic, meaning that after experiencing the stresses and strains during the passage of vehicles, the structure returns to a state of zero stress and strain state when no vehicles are present. More specifically, this means that extreme loads such as abnormal loads are not considered. These could lead to residual deformation in the bridge structures. It also means that the dynamic behaviour of the bridge is not considered, for example under combined vehicle and wind loading.

### 5.1.5. Absence of dynamic amplification

To calculate the Effect of the vehicles on the structures, the various influence lines of the chosen primary responses were convolved with the vehicle loads (succession of vertical loads at each axle, separated by fixed distances). No dynamic amplification was considered; this would require additional dynamic amplification factors or a dynamic vehicle-bridge interaction model. Given that the goal of the current exercise is fundamentally a comparison between theoretical vehicles, our methodology is considered sufficient. Complete bridge-vehicle interaction models are time-consuming, not adapted for regulation design and require many additional parameters and coefficients which need to be carefully chosen.

### 5.1.6. Load distributed uniformly on the loading surface

The representative fleet has been specified assuming that the payloads are uniformly distributed on the loading decks. In reality, severe bridge damage can be caused by vehicles with badly distributed loading, where much of the load is concentrated in one location on the truck or trailer. To illustrate:

- For a 5-axle tractor semi-trailer combination (1 steer + 1 drive + 1 tridem), if the load is concentrated at the front of the semi-trailer, the drive axle can be easily overloaded,

often to 15 tonnes or higher. This can cause excessive degradation of road pavements and short span bridges.
- Similarly, semi-trailers may also be loaded heavily at the back of the trailer, potentially overloading the tridem axle set. In this case, the load can exceed 35 tonnes over an axle span of approximately 3 meters, which again can impose excessively damaging effects to pavements and bridges.

For this reason, it is important that load distribution within the vehicle is effectively managed so that axle loads are maintained within the legal limits [43].

## 5.2. First comparison of Effects by the various vehicles: need for PBS

### 5.2.1. Comparison of the numerical value of Effect between the various vehicles

When calculating and comparing the Effect for the whole FALCON fleet, it should be noted that the vehicle with the maximum Effect within a group of vehicles is not always the same, as shown in Table 11.

Figure 34 and Figure 35 show the Effect of each vehicle divided by the maximum Effect for the whole fleet. A general trend can be seen for the vehicles, but it may be inaccurate to only focus on select “representative” vehicles from each group. For example, by comparing the first four columns of points of the figure, it can be seen that from group 1 (vehicles 1.1, 1.2, 1.3, 1.4), vehicle 1.2 is generally the most aggressive. Similarly, by comparing all the columns, it can be seen that the first two groups of vehicles (from 1.1 to 2.3) are generally less aggressive than the others. Moreover, within these two groups, vehicle 3 (column 3, vehicle 1.3) and vehicle 7 (column 7, vehicle 2.3) are the least aggressive. Moreover, if we compare the vehicles of only the first two groups, it can be seen that, vehicle 2.1 (vehicle 5, column 5) is not the most aggressive for all the Effects, contrary to what is expected. However, these two configurations have different payloads and loads (37 tonnes versus 35 tonnes), which highlights the need to normalize these Effects with the total vehicle mass (GCM). This conclusion is also supported by the ratio of the Effect of the various vehicles with the Effect of one reference vehicle (vehicle 2.1).

*Table 11: Vehicle with maximum Effect, for a sample of the calculated Effects*

| Effect | Truck with maximum Effect |
|---|---|
| 1 | 4.6 |
| 2 | 1.4 |
| 3 | 1.3 |
| 4 | 1.3 |
| 5 | 1.3 |
| 6 | 3.3 |
| 7 | 6.4 |

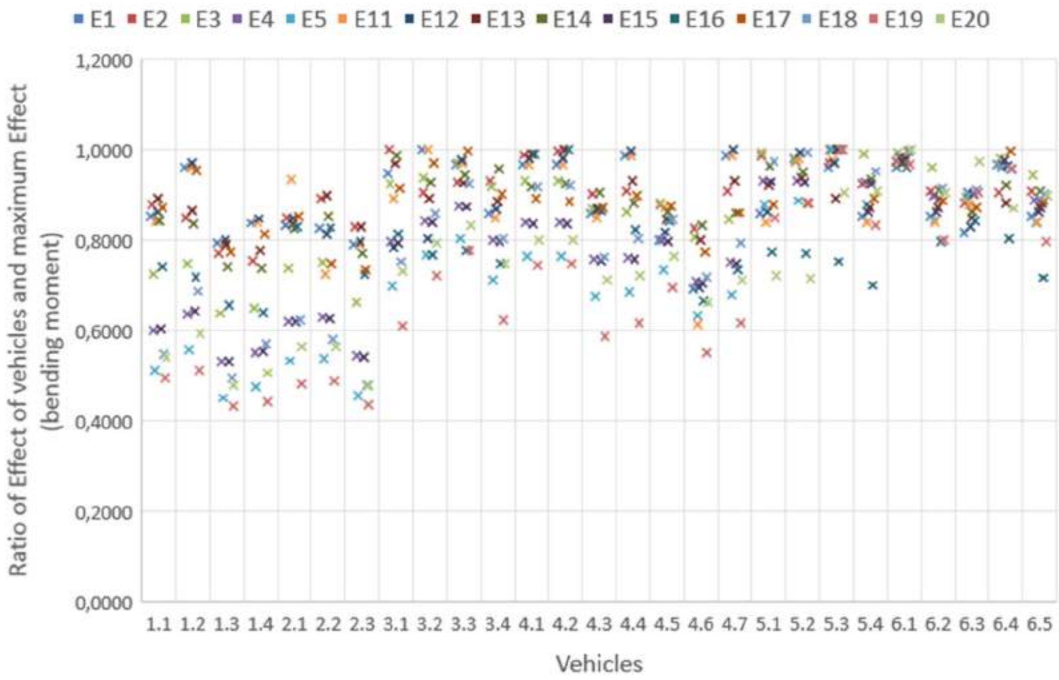



*Figure 34: Ratio of Effect (bending moments) to maximum Effect within the fleet*


*Figure 35: Ratio of Effect (shear) to maximum Effect within the fleet*

### 5.2.2. Ratio of the effect of the various vehicles with the effect of the reference vehicle

Figure 36 shows a comparison of the bending moment and shear Effects relative to the Effect of the reference vehicle 2.1. The ratio is quite small for the first two group of vehicles, but increases for other vehicles groups, approaching a ration of two in groups 5 and 6. Vehicles 5.3, 5.5 and 6.3 have the highest values in both cases.

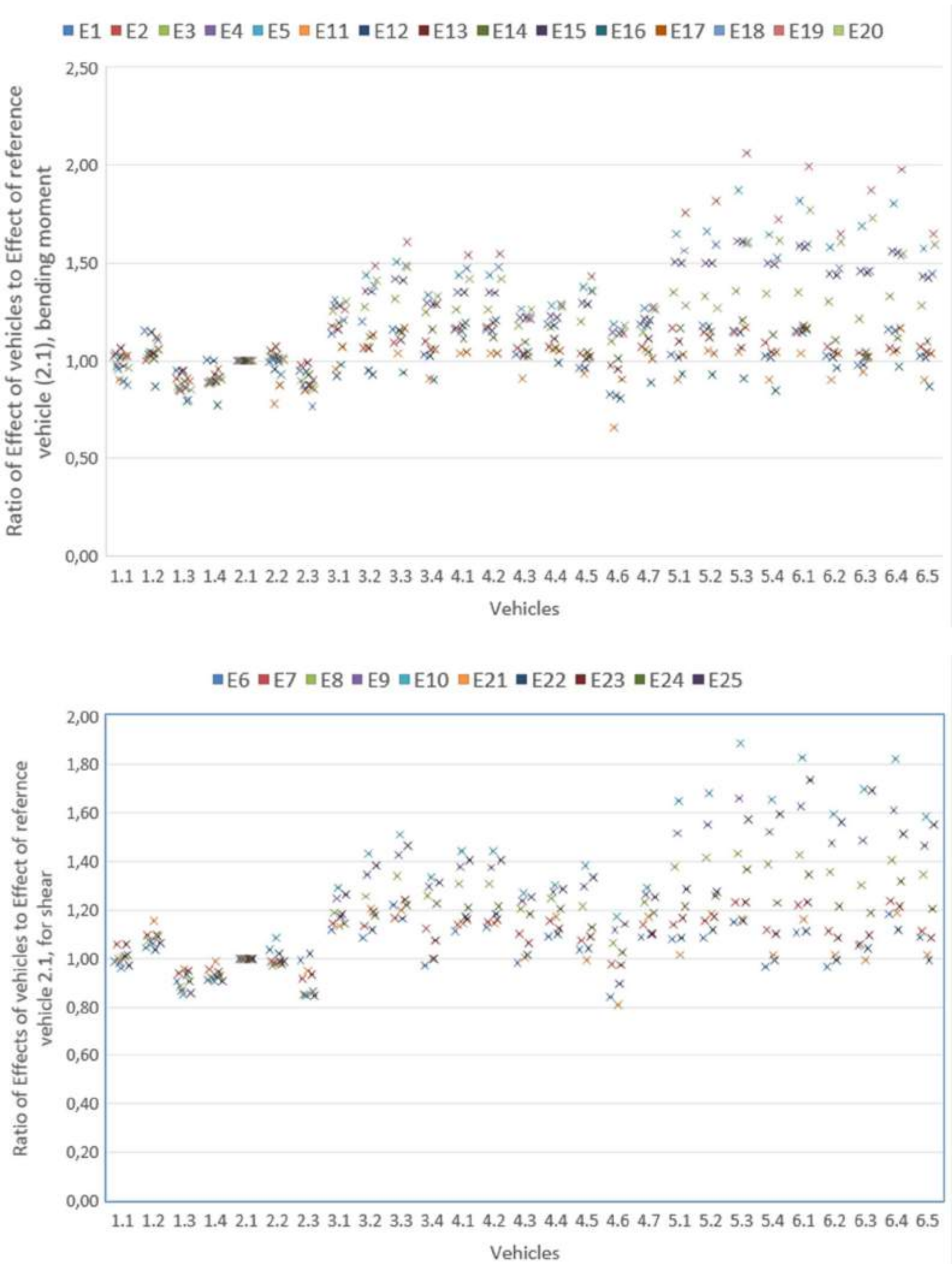



*Figure 36: Ratio of Effect with the Effect of reference vehicle (2.1), bending moments, top, and shear forces, bottom.*

The primary differences between groups 1/2 and groups 5/6 which can explain the observed differences in Effects are:

1. The loads of the vehicles, in terms of total load and axle load,
2. The length of the vehicle, which is parametrized by the distances between axles (linked with the distance between first and last axle) and the volume,
3. The number of axles.

It should be noted that generally the number of axles is linked to the ratio of load and the volume. So, parametrizing the Effects with respect to load and length might be sufficient. For the structural engineering side, it should be noted that for each vehicle, the ratios of the various Effects to the same Effect of vehicle 2.1 are scattered, in a limited way for some vehicles, but much more for others. This shows the need to carefully define the pool of structural effects/elements to be investigated. Within the framework of the FALCON project, its shows the importance of the definition of the infrastructure catalogue [6].

### 5.2.3. Normalizing the effects of the complete fleet with respect to GCM

Figure 37 and Figure 38 show the Effects as normalized with respect to the total vehicle weight (GCM). It can be seen that the value of a given Effect is less scattered when made proportional to the weight of the vehicle. Further, it can be seen that some vehicles will often have one of the highest normalised Effects, while others consistently have one of the lowest Effects. One of the vehicles with one of the highest Effects is vehicle 2.3, while vehicles 6.5 (especially for small spans, less than 20 meter) or 6.4 have generally some of the smallest Effects. Therefore, comparing all the vehicles based on these plots may not be conclusive, and so we will hereafter focus on a smaller sample to better explain the methodology.

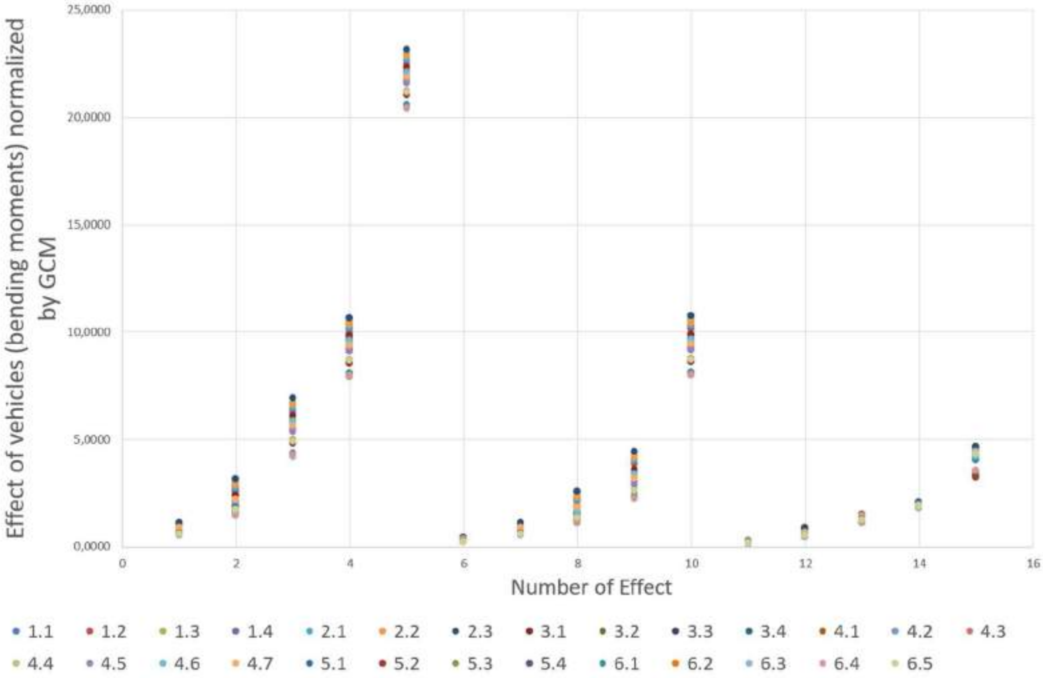



*Figure 37: Effects (bending moments) by the various vehicles normalized by GCM*

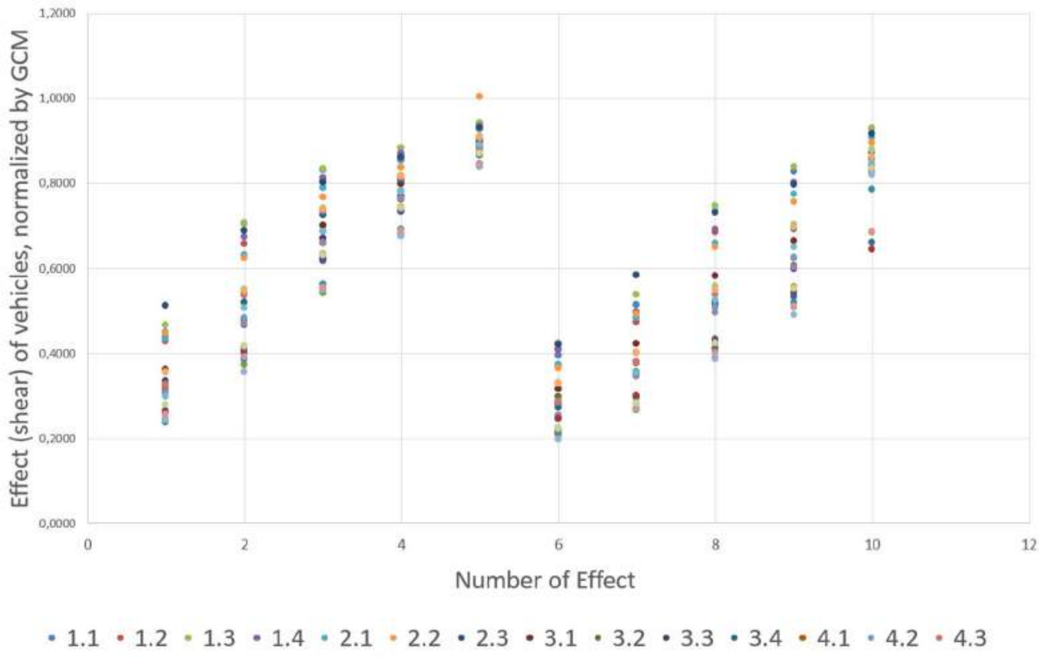



*Figure 38: Effects (shear forces) by the various vehicles normalized by GCM*

## 5.3. Comparison of methods to normalise the Effects of a limited fleet, for normal loading

Several types of normalization are possible in order to better capture the relative Effects of the vehicles. We investigated the following normalizations:

- Normalization with total length between the first and last axle (Figure 39)
- Normalization with volume (Figure 40)
- Normalization with cargo mass (payload) (Figure 41),
- Normalization with total mass (GCM) (Figure 42)

From these graphs, several comments can be made. Each normalisation method results in quite similar trends. Therefore, each of these normalisation parameters must be considered when developing a formula. Some Effects make it possible to discriminate clearly between vehicles, e.g. separating vehicles with high Effect from those with low Effect. These are the Effects of long bridge spans. This is not surprising, as smaller spans only encounter parts of the vehicle, which means that the Effect of the vehicle is only the Effect of certain axles or axle groups. For longer spans, the load model to design the structure would be a queue of vehicles (traffic jam), which is the case in the Eurocodes (uniformly distributed load of LM1 of Eurocode 1). Therefore, the most important structural models might be spans between 25 and 50 meters.

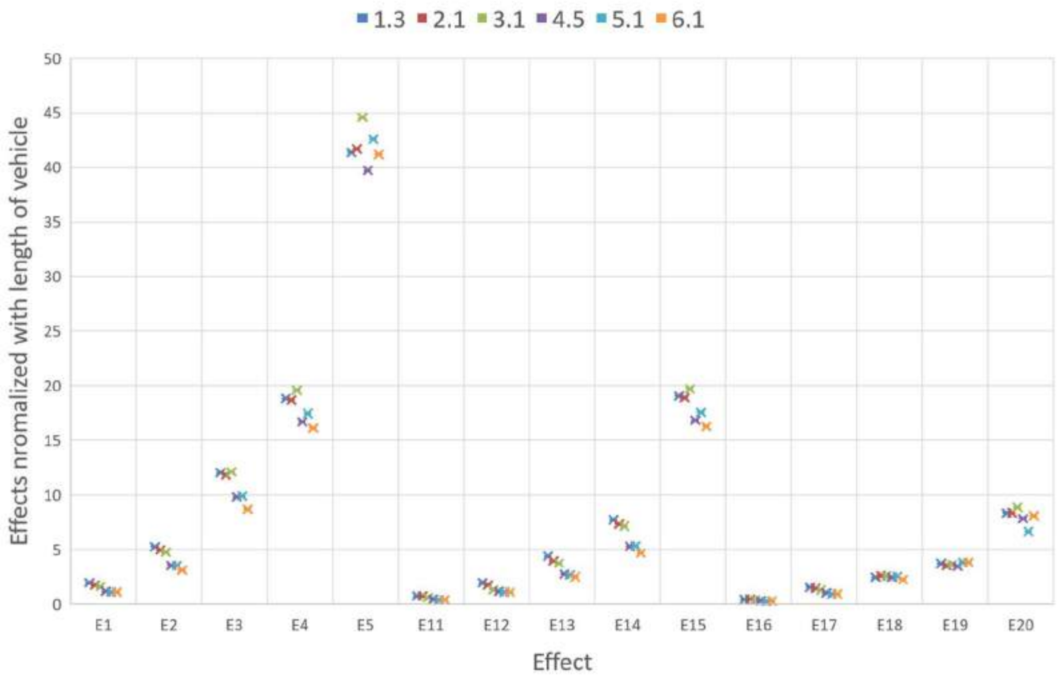



*Figure 39: Normalization for Effects (bending moments) with length*

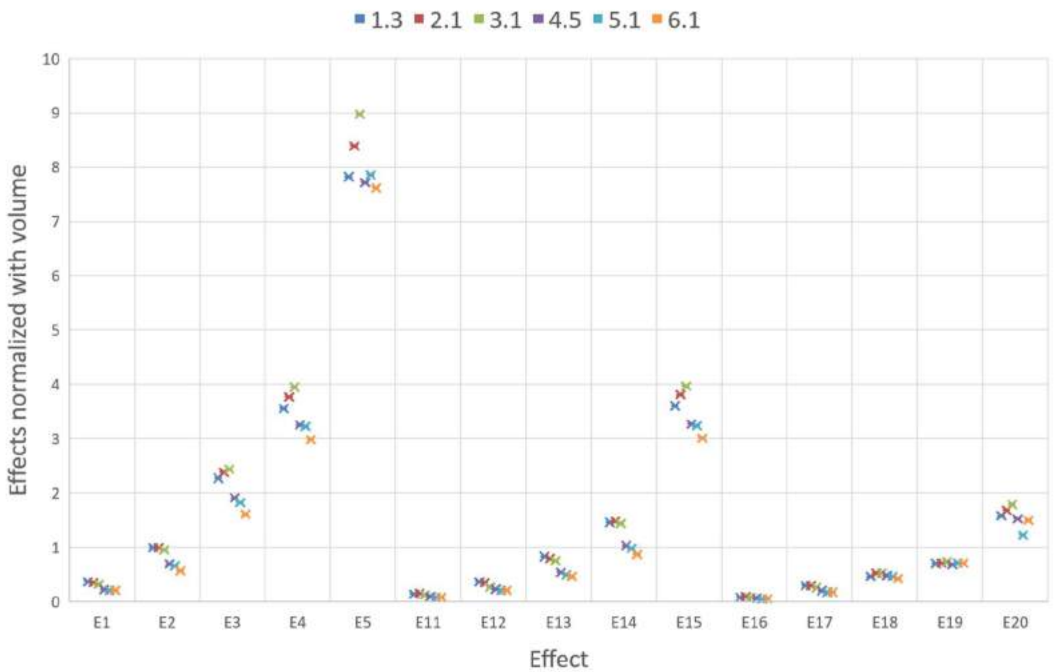



*Figure 40: Normalization for Effects (bending moments) with volume*

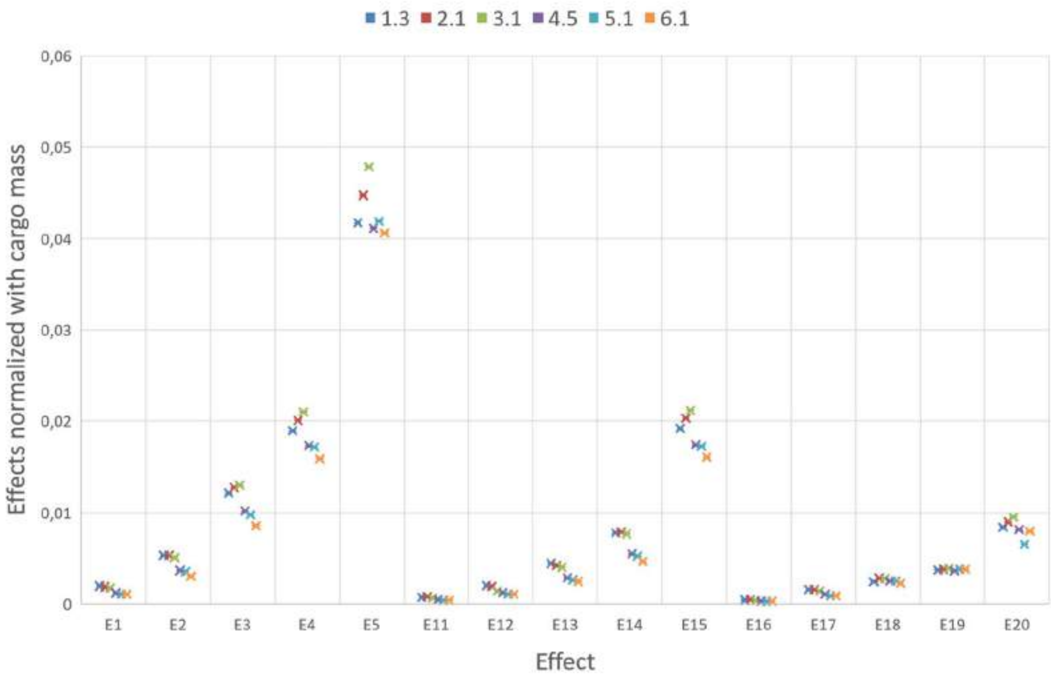



*Figure 41: Normalization for Effects (bending moments) with cargo mass*

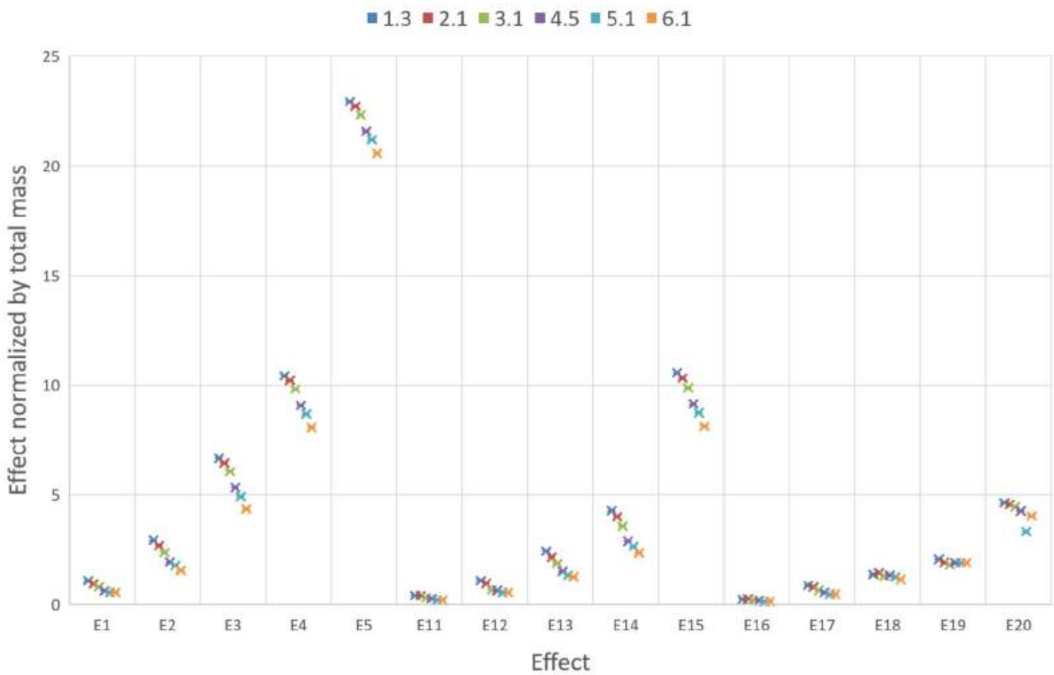



*Figure 42: Normalization for Effects (bending moments) with total mass*

### 5.4. Comparison of Effect of vehicles with normal load and high load

The Effect of this limited fleet is compared for both normal and high load, once again normalising either by length (Figure 43), by volume (Figure 44) or by GCM (Figure 45). The same pattern as before appears: some Effects seem to better differentiate between low and high damaging vehicles. Nevertheless, one specific conclusion may be: if normalizing the damage with the characteristics of the vehicle (length, volume, total mass or payload), high capacity vehicles do not exhibit more damage than standard vehicles.

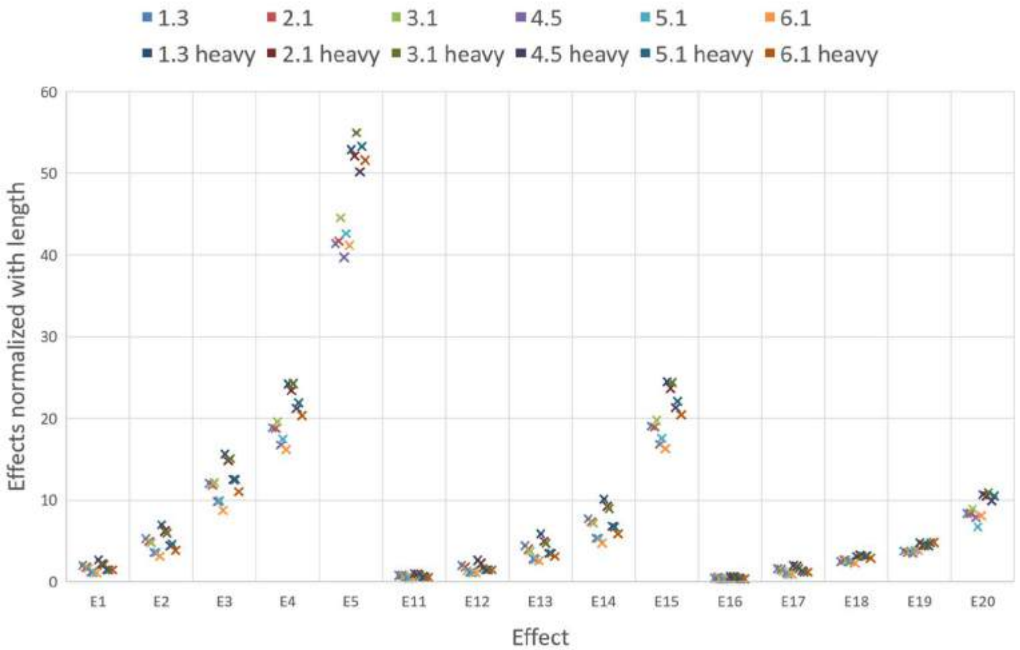



*Figure 43: Effects (bending moments) of normal and heavy loaded vehicles, normalization with length*

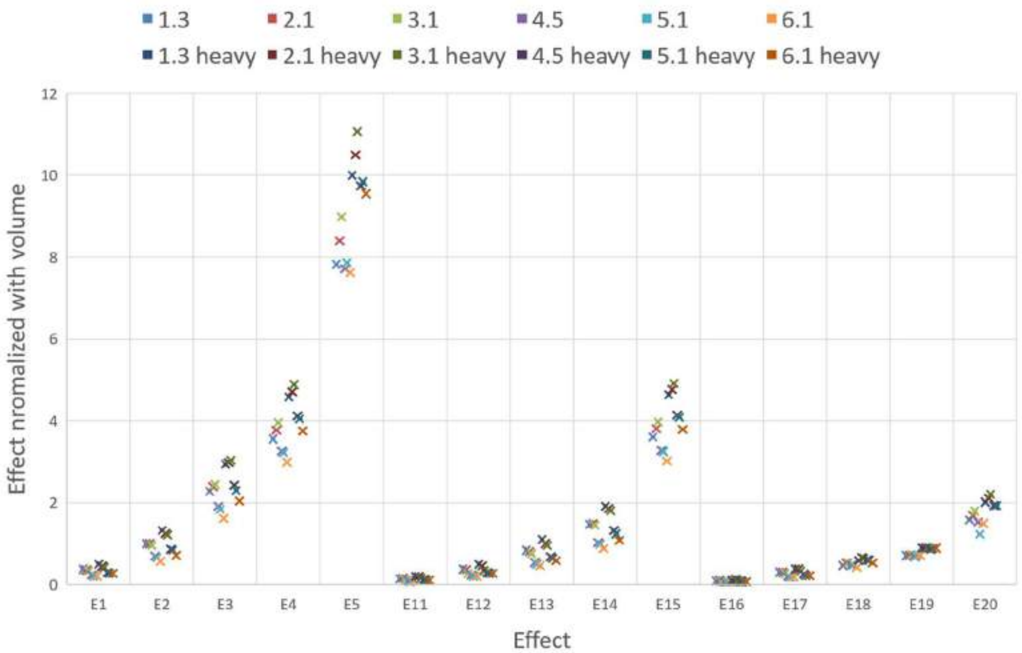



*Figure 44: Effects (bending moments) of normal and heavy loaded vehicles, normalization with volume*

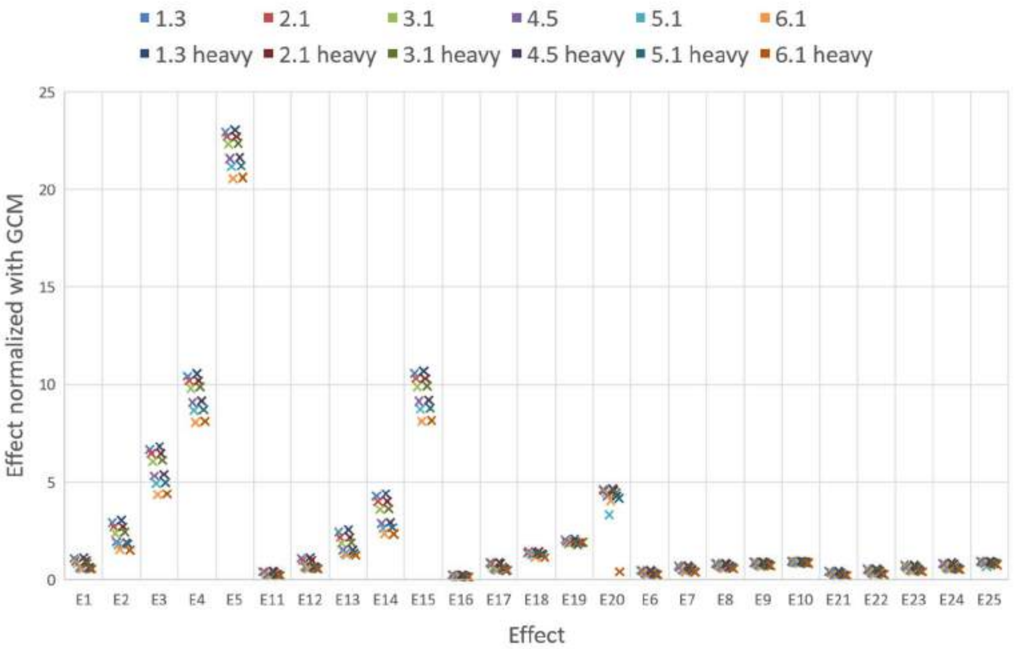



*Figure 45: Effects (bending moments) of normal and heavy loaded vehicles, normalization with cargo mass.*

## 5.5. Synthesis of the results

If vehicle 2.1 is considered to be the reference vehicle, we can classify the vehicles according to their Effects. If all their Effects are higher than those of vehicle 2.1, the vehicles will be considered to be “aggressive” (marked as red, see Table 12). If they are lower, they will be classified as “non-damaging” vehicles (marked as green). When all the Effects are of similar value, the vehicle is marked in yellow. Two comments are necessary here:

- It should be noted here that we used a 10% margin to decide what value is “similar”, “higher”, “lower”. This is also a threshold which can be studied and fixed in an adapted way.
- The various Effects of a given structure may not give the same classification (for a given vehicle, one Effect may be higher than the Effect of vehicle 2.1, whereas another will be lower). In this case, we classified this vehicle as more aggressive than the reference vehicle (in red). But here, also one could decide to classify it in the lowest category (in any case) or decide a hierarchy between the Effects (the result of one Effect would decide on the classification, over the result over another Effect.

We will do that for the structures that have been studied, namely:

- **Structure 1: single-span** structure, span length equal to **10m**, structure verified through bending moment at midspan and shear on support
- **Structure 2: single-span** structure, span length equal to **20m**, structure verified through bending moment at midspan and shear on support
- **Structure 3: single-span** structure, span length equal to **35m**, structure verified through bending moment at midspan and shear on support
- **Structure 4: single-span** structure, span length equal to **50m**, structure verified through bending moment at midspan and shear on support
- **Structure 5: single-span** structure, span length equal to **100m**, structure verified through bending moment at midspan and shear on support

- **Structure 6: two-span** structure, span lengths identical and equal to **5m**, structure verified through bending moment at midspan, bending moment at central support and shear on support,
- **Structure 7: two-span** structure, span lengths identical and equal to **10m**, structure verified through bending moment at midspan, bending moment at central support and shear on support,
- **Structure 8: two-span** structure, span lengths identical and equal to **17.5m**, structure verified through bending moment at midspan, bending moment at central support and shear on support,
- **Structure 9: two-span** structure, span lengths identical and equal to **25m**, structure verified through bending moment at midspan, bending moment at central support and shear on support,
- **Structure 10: two-span** structure, span lengths identical and equal to **50m**, structure verified through bending moment at midspan, bending moment at central support and shear on support.

*Table 12: Comparison of damaging effect of vehicles, compared to the reference vehicle 2.1*

| Structure | Normalization with volume† | Normalization with mass† |
|---|---|---|
| 1 | 4.5, 5.1, 6.1<br>2.1, 3.1<br>1.3 | 4.5, 5.1, 6.1<br>2.1, 3.1<br>1.3 |
| 2 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 | 4.5, 5.1, 6.1<br>3.1<br>1.3, 2.1 |
| 3 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 |
| 4 | 4.5, 5.1, 6.1<br>1.3, 2.1<br>3.1 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 |
| 5 | 4.5<br>1.3, 2.1, 5.1, 6.1<br>3.1 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 |
| 6 | 4.5, 5.1, 6.1<br>3.1<br>1.3, 2.1 | 5.1, 6.1<br>3.1, 4.5<br>1.3, 2.1 |
| 7 | 4.5, 5.1, 6.1<br>3.1<br>1.3, 2.1 | 3.1, 4.5, 5.1, 6.1<br>1.3, 2.1 |
| 8 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 | 6.1<br>5.1<br>1.3, 2.1, 3.1, 4.5 |
| 9 | 4.5<br>1.3, 2.1, 3.1, 5.1, 6.1 | 4.5, 5.1, 6.1<br>1.3, 2.1, 3.1 |
| 10 | 5.1<br>1.3, 2.1, 4.5, 6.1 | 5.1<br>6.1<br>1.3, 2.1, 3.1, 4.5 |

| | | |
|---|---|---|
| | 3.1 | |
| † Vehicles more damaging than vehicle 2.1 are in red, vehicles damaging approximately in the same amount than vehicle 2.1 are in yellow, and vehicles less damaging are in green) | | |

It should be noted here that we compare the Effects of the individual vehicles, which means that fatigue is taken into account. For the assessment of the extreme effects induced by these vehicles, this work would have to be completed by traffic jams composed only by the various vehicles.

We can conclude on the following points:

- High-capacity vehicles are generally less aggressive than the reference vehicle (or other conventional European vehicles, such as 1.3 and 2.1),
- A finer classification between the damaging Effect of the various vehicles can be done, but decisions should be made on the type of normalization, the thresholds for considering effects to be higher/similar/lower than the reference, the type of structures and Effects to be analysed etc.

In the following, we will focus on short- and medium-span bridges, for several reasons:

- These are the main issue for bridges [43].
- Moreover, for long span bridges, the governing case is congestion (meaning a queue of vehicles covering the whole bridge), and not just one vehicle.
- Finally, the Eurocodes are not valid for spans longer than 200 meters (which is a value not studied here).

To deal with these issues, two approaches are possible and should be combined:

1. <u>Development of (at least) one bridge formula</u>. This formula then limits the weights on axles, being single axles or in a group, depending on the distance to the adjacent axles, the total length of the vehicle and the total number of axles. Some countries have developed a bridge formula for "usual" vehicles (driving without special limits) and abnormal loads.

2. <u>Limitation of traffic load effect for all types of vehicles</u>. Traffic load models induce responses in the structure, which should not be exceeded by any vehicle driving on the structure (abnormal or normal load) or any combination of these loads. In order to take into account the uncertainties in the whole phenomenon, linked to the structure, to the vehicle, the driving conditions, the environmental conditions, this threshold of possible Effects within the structure should be lowered by a given coefficient (inferior to 1). This updated threshold is then a limit to which the Effects by all the allowed vehicles should be verified.

These two methods will be investigated in turn in the following sections.

## 5.6. Considerations for the development of a bridge formula

It was decided to focus on short- and medium-span bridges. This means that we will focus on effects 1, 2, 3, 6, 7, 8, 11, 12, 13, 14, 16, 17, 18, 19, 21, 22, 23, 24. The considered structures are 1, 2, 3, 6, 7, 8. The allowed gross weight, on the whole vehicle (GVW), on single axles or on groups of axles, should have the following shape:

$$W = f(L, N), \tag{1}$$

where:

- L is the length between the extreme axles of the considered combination of loads (the distance between first and last axle of a vehicle, or the first and last axle of the axle group),
- N is the number of axles.

### 5.6.1. Bridge-formula literature review

A "bridge formula" is a type of semi-performance-based standard, where it regulates parameters (axle spacing and number of axles) that are related to the performance of the vehicle in terms of the load effect imposed on bridges and pavements. Bridge formulae provide an efficient method to help with the regulation of truck weights while ensuring the sustainability of the infrastructure by allowing vehicle configurations that have an acceptable effect on structures.

Several countries utilise bridge formulae, including: the United States, Mexico, Canada, South Africa, Australia, and New Zealand. The most well-known bridge formula is the federal U.S. Bridge Formula B (BFB) that has been regulating truck size and weight on the Interstate highways in the U.S. since 1974. The formula determines the maximum allowable weight on any series of consecutive axles as a function of axle spacing and number of axles, and must be applied to every axle combination:

$$W = 500 * \left(\frac{LN}{N-1}\right) + 12N + 36, \tag{2}$$

where:

- W is the maximum allowable weight, in lb,
- L is the distance between extreme axles, in ft,
- N is the number of axles.

In addition, there exist limits on:

- Gross Vehicle Weight: 80 000 lbs,
- Single axle: 20 000 lbs,
- Tandem axle: 34 000 lbs.

In addition to the BFB, other weight regulations have been implemented that limit the gross vehicle weight to 80,000 lbs and axle weights to other limits depending on the axle configuration (i.e. single, tandem, tridem). The BFB was developed separately from the gross and axle weight limits, therefore the "capped BFB" refers to the BFB allowable weights limited at the 80,000 lbs gross vehicle weight limit. Due to criticisms of the current BFB on its inadequacy to fairly limit gross and axle weights of different truck configurations, alternative bridge formulae have been developed to overcome some of the limitations. However, none of the proposed bridge formulae have been implemented and the BFB still governs.

*Table 13: Characteristics of existing bridge formulae.*

| **Bridge Formulae** | **Characteristics** |
|---|---|
| U.S. Bridge Formula B | • Depends on axle spacing and number of axles<br>• Applied to every axle combination<br>• GVW limit of 36.4 tonnes (80 kips) |

| | |
|---|---|
| Mexico | • Similar format to U.S. BFB<br>• Allowable weight varies depending on the route classification (Class A, B-primary, C-secondary, or D-feeder)<br>• Applied only to the extreme outer axles to determine allowable gross vehicle weight |
| Canada | • Developed by and used in Ontario<br>• Depends on Equivalent Base Length (EBL)<br>• Applied to all axle combinations<br>• GVW limit of 63.5 tonnes |
| South Africa | Two different bridge formulae, applied to every possible axle combination:<br>• Legal loads (up to 56 tonnes and length limit of 22 meters): depends on axle spacing only<br>• Abnormal loads: depends on axle spacing and Effective Width (EW) of the axle groups |
| Australia | Current:<br>• Different formulae used by different states<br>• Depends on axle spacing only<br>• In most states applied to outer axles only to determine allowable gross vehicle weight<br>Proposed:<br>• Depends on route and vehicle classification<br>• Applied to all axle combinations<br>• GVW limit of 42.5 tonnes for general access vehicles |
| New Zealand | • Bridge formula table<br>• Limited to 44 tonnes |

So, we see that several parameters may be involved in the description of a bridge formula:

- Parameters linked to the vehicle: GVW, axle loads, wheelbase, distance between two consecutive axles or axles in a group, number of axles (total number or number in the group),
- Parameters linked with the type of structure: typically, these parameters define the limits of application of the bridge formula.

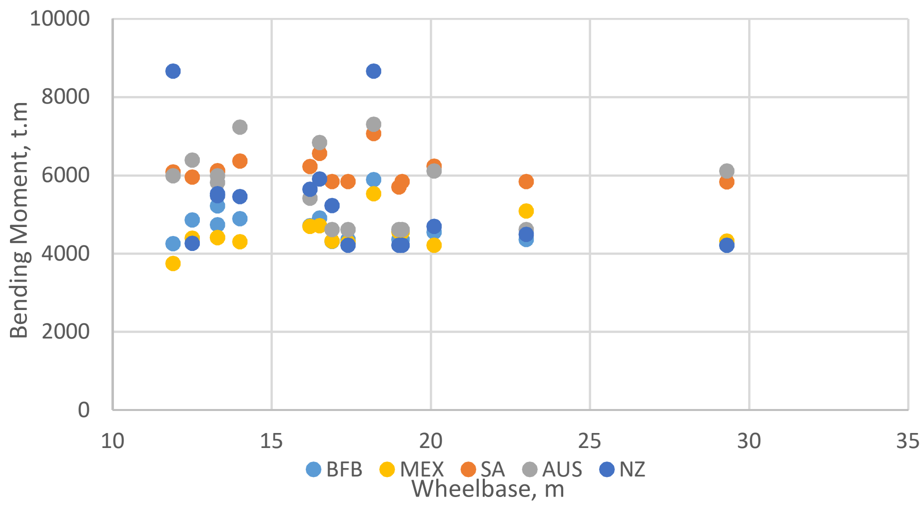



*Figure 46: Bending moment induced at mid-span of a 20m-simply supported bridge by trucks with various wheelbases and complying with different Bridge Formulae.*

### 5.6.2. Proposed methodology for development of a deterministic bridge formula

We assume here that a deterministic bridge formula is being developed (a probabilistic bridge formula would need to consider the uncertainties of structure/materials and of actions/loads through for example reliability calculations). The following methodology is proposed for developing a suitable bridge formula:

- Create a catalogue of vehicles structures to assess:
    - The vehicle fleet should reflect the vehicles that already exist in Europe, that exist in other countries and those for which authorizations are interested in,
    - The pool of structures (or structural effects) should reflect the bridges existing in Europe. But generally, it would be similar to the structures that have been used in this report, and also in other linked works [43].
- Calculate the effects of the vehicles of the vehicle fleet, and the traffic load models that are applicable, for each structural effect. Then, a limit value must be chosen for each effect, for example as a fraction of the effect of the load model, a fraction of the effects of the vehicles of the fleet or depending on the acceptability (or not) of given vehicles.
- For each structural effect, the outcome would be a limit that should not be overpassed. Then a bridge formula can be fitted:
    - A first solution may be a linear fit for equation $W = f(L, N)$ as:

$$W = a_0 L \times N + a_1 L + a_2 N + a_3, \tag{3}$$

where: $a_0, a_1, a_2, a_3$ are constant numerical values.

This equation must fit the envelope of effects for each vehicle, axle and group of axles.

    - A second solution is to fit higher order equations to the envelope of the most aggressive effect. To do that, as the effect is linked to the influence line which is a polynomial function of given order (for example, for a single span structure, the polynomial is liner for shear force, and of degree 2 for bending moment, etc.), the degree of the fitted curve can be fixed a priori as the highest degree of the influence lines.

## 5.7. Traffic load effect limitation

As highlighted in FALCON deliverables D3.2 and D3.4, bridges in Europe are designed according to the Eurocodes. These European standards define the traffic load models to be used for designed bridge structures. The load models induce stresses, and the structure is designed in order for these stresses to stay below the design stresses of the materials. Therefore, the stresses induced by traffic load models should never be exceeded by any vehicle driving over the structure, or any combination of these vehicles on the structure. Moreover, in order to account for all the uncertainties around these calculations, this threshold should be lowered by a given coefficient β. This approach has been adopted in South Africa for example, where β is a constant (around 0.7 for abnormal loads). But it could also be a variable which depends on the type of structure, its age, its level of damage (and would be below 1).

This method has an additional complicating feature in Europe, where the load models from the Eurocodes are nationally specific by the introduction of the so-called α-factors. Therefore, in Europe, contrary to the South African case, a first step would be to determine the “weakest” design code for each structure, meaning the code allowing the lowest design stresses.

### 5.7.1. Determination of the decisive design load model

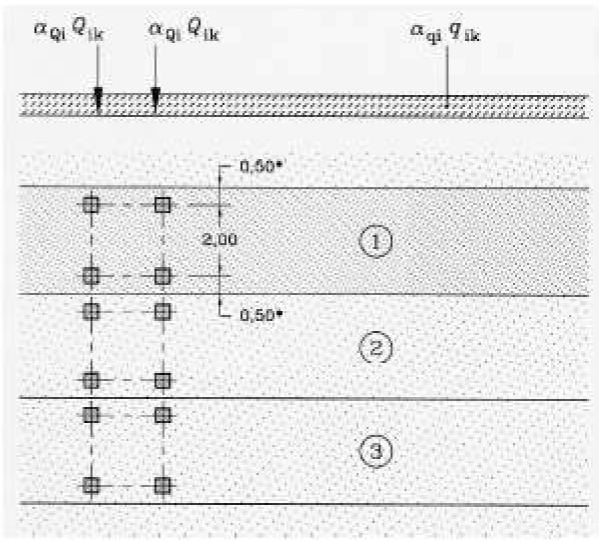
In principle, finding the most restrictive load models would require assessing all European national annexes for Eurocode 1 (all variations of Eurocode 1, depending of the various countries). At the very least, it should be done for all countries covered by the route of interest. Here we present a case study of how this might be done.

*Assumption 1: The route crosses the Netherlands and Germany.*

The comparison of the design codes would have to be done for each type of structure and each type of Effect. Here, as an example, we will focus on one single Effect (Bending moment at midspan, of a single span bridge).

*Assumption 2: The investigated Effect is the bending moment at midspan of a simply supported, single span bridge (previously named "Effect 2" in "Structure 2").*

The load model 1 of Eurocode 1 is given by a uniformly distributed load, plus additional concentrated loads (see Figure 47).




**Key**
(1) Lane Nr. 1 : $Q_{1k} = 300$ kN ; $q_{1k} = 9$ kN/m$^2$
(2) Lane Nr. 2 : $Q_{2k} = 200$ kN ; $q_{2k} = 2{,}5$ kN/m$^2$
(3) Lane Nr. 3 : $Q_{3k} = 100$ kN ; $q_{3k} = 2{,}5$ kN/m$^2$
* For $w_l = 3{,}00$ m

*Figure 47: Load model 1 of Eurocode 1.*

*Assumption 3: The annual traffic is above 2 000 000 trucks and the span length is L=20m.*

The national α-factors for each country (the Netherlands and Germany) are given by Table 14, assuming that the annual traffic is above 2 000 000 trucks and the span length is L=20m. The Eurocode 1 states that these loads are applied to various traffic lanes of a given width, and the position of these lanes is investigated to be the worst in terms of stresses of traffic. Here, for this example, we will simplify the problem to have to assess only one case of transversal positioning of the loads.

*Table 14: National α-factors in the Netherlands and Germany, for an annual traffic volume higher than 2 million vehicles and a span length of 20m.*

| | **The Netherlands** | **Germany** |
|---|---|---|
| α-factors | $\alpha_{Q1} = 1.0$ for N > 2 000 000 and L =20 m (as in the Netherlands, this coefficient depends on the volume of traffic and the span length)<br><br>$\alpha_{q1} = 1.15$<br><br>$\forall i > 1, \alpha_{qi} = 1.40$ | $\alpha_{Q1} = 0.8$<br><br>$\alpha_{Q2} = 0.8$<br><br>$\forall i > 2, \alpha_{Qi} = 0$<br><br>$\forall i, \alpha_{qi} = 1.00$ |

*Assumption 4: The transversal positioning of the application of the punctual forces is simplified by the following statements:*

- There is only one lane.
- The lane width is 1 meter.
- This lane covers the whole surface of the deck.
- The application of the concentrated loads is solely a point load (not distributed in tyre contact patches for example).

The bending moment at midspan is assessed through the formula: $M_{uni} = \frac{pL^2}{8}$, whereas the highest bending moment induced by the punctual loads is obtained a sumetric application of the forces to midspan. In this case, the bending moment at midspan is $M_{punctual} = \frac{P(\frac{L}{2}-\frac{w}{2})(L:2+\frac{w}{2})}{L}$, where $w$ is the distance (in the longitudinal direction) of the punctual loads.

In this case the German load model copes for lower stresses, therefore for this structure and with these assumptions, the effects to be considered are those created by the German version of Load Model 1 of Eurocode 1. This is shown in Table 15.

*Table 15: Bending moment at midspan calculated in this case study, with the chosen assumptions.*

| | **The Netherlands** | **Germany** |
|---|---|---|
| $M_{uni}$ | 517.5 kN.m | 450 kN.m |
| $M_{punctual}$ | 2932.5 kN.m | 2346 kN.m |
| $M_{total}$ | 3450 kN.m | 2796 kN.m |

### 5.7.2. Comparison of the Effects of the individual vehicles with the Effect of the load model

The Effects of individual vehicles have to be compared with the same Effect induced by the weakest load model, as shown in Figure 48. This same procedure must be applied for all types of traffic situations: traffic jam on all lanes, traffic jam only on slow lanes, traffic jam only on the lanes of one side, etc. Then, for all these values, a threshold has to be chosen, mainly in terms of acceptability of the loadings and required safety margins, as in the South African case.


*Figure 48: Effect 2 for all vehicles, to be compared with Effect 2 of the German load model 1 (value of 2796 kN.m, not represented here it is ten times higher than the highest effect here).*

### 5.7.3. Effects of platooning and other (semi-) autonomous driving on bridge loading

It is worth giving consideration to the impact of truck platooning, giving the growing interest in this field worldwide. The bridge loading imposed by platooning trucks is a more uniformly distributed load along the length of the platoon than in the case of isolated vertical loads when the traffic is freely flowing with the recommended following distances between vehicles. The impact of this will differ for different bridge span lengths.

From a longitudinal point of view, a truck platoon may resemble a traffic jam. The load models of Eurocode 1, and especially LM1, include a uniform load to take into account traffic jams. But it should be noted that these load models have been calibrated based on traffic data from the 1980s (limit of GVW generally of 37 tons). Therefore, some re-assessment may be needed.

From a transversal point of view, platoons induce that the vehicles travel on a given lateral position in the lane. As for pavements, this may be an issue for some type of bridges (as for example steel bridges with orthotropic decks). Currently, bridge codes plan 50% of the trucks centred in the lane, 17% displaced 10 centimetres to the left and to the right, and 8% displaced 20 centimetres to the left and the right. This might represent an issue and induce different bridge deck designs.

**Short-span bridges (L < 15 meters)**, which will typically only be exposed to the load of one vehicle or axle group at a time, will not experience any additional damage due to platooning. This type of bridge is very common, making up a large proportion of the bridge network in Europe. Note that long-span bridges with orthotropic decks have influence lines with small supports, and so are considered to belong to the “short-span” category of bridges.

**Medium- and long-span bridges** will experience increased loading when subjected to platooning trucks, compared to regular truck traffic. Although the overall loads may be below the Eurocode 1 load models, the damage caused by platooning will be in excess of that cause by the same truck traffic maintaining standard following distances. Medium-span bridges will be most highly at risk, because long-span bridges are generally well monitored and maintained. In the bridge loading analyses presented in this report, the impact of single vehicles was assessed and compared; the impact of a platoon of trucks, or other combination of trucks, was not considered. Such a study would need to take into account the number of trucks and following distances in platoons relative to usual truck traffic. This will be studies in the Horizon 2020 project: H2020 ENSEMBLE.

## 5.8. Conclusions and recommendations

### 5.8.1. Conclusions

1. Strictly speaking, it cannot be said that one vehicle is more/less aggressive than another in terms of bridge loading, because it depends on the structures that are studied. Indeed, vehicle A may be more aggressive than vehicle B for structure 1 but less aggressive for structure 2. This is not necessarily the case for road wear impact (see Section 6).

2. In general, however, when normalised by loading capacity both in terms of volume (or loading length) or mass (total mass or cargo mass), high capacity vehicles are not more aggressive than more conventional vehicles. Indeed, the European semi-trailer is generally more aggressive when compared to the loading possibilities.

3. The development of a bridge formula involves several assumptions which are of regulatory/political nature and which have to answered, the most important being: what vehicle or fraction of load model should be supported by the structures, during their lifetime? This leads to future work.

4. It should be noted that in the calculations/simulations performed in this section, the considered reliability indexes are set to account for overloading. However, in an envisaged PBS framework in which vehicles are equipped with on-board load cells, relaying mass data to a compulsory IAP, then it may be possible to consider reduced reliability indexes in the bridge loading calculations.

### 5.8.2. Future work

1. As the sections on the development of bridge formula and on development of Effect threshold values indicate, the work proposed here should be refined. Indeed, the assumptions that have been taken are quite coarse in order to obtain easily understandable results and confirm the validity of the method.

2. These assumptions, of course, need to be refined/changed, discussed and agreed on by bridge experts all over Europe.

# 6. Simulations: Road Wear Impact

## 6.1. Methodology and assumptions

Road structures comprise several layers of different materials. The bearing capacity of the structure depends on the specific materials, their combination and of the thickness of each layers. Usually, road structures are designed for the (heavy) traffic expected to make use of them in the forthcoming 20 to 40 years. When introducing new truck configurations that were not taken into account during the initial design of the road structures, an evaluation of the impact of these new loads on the existing road structures is important for the preservation of the pavements. Such an evaluation can make use of a multi-layer model of the road structure and a model of the truck combinations, allowing the estimation of the stresses and strains that will occur in the road structure when the truck applies its load at the top of the pavement. Additional details and a review of the pertinent literature is provided in Appendix G. Appendix H gives an overview of some of the software available currently for the modelling of road structures

In the current work, we perform a road wear impact assessment of the representative fleet of trucks on a selection of representative road structures. From the analysis of the results, we formulate a proposal for a uniform method of assessing the road wear impact of high capacity vehicles throughout Europe, which could form part of the proposed PBS framework.

The impact of the representative fleet on roads was assessed by BRRC in Belgium. Axle loads were provided by CSIR from the vehicle models. Four pavement structures were evaluated:

- a flexible pavement (designed for low traffic loading),
- a thick bituminous pavement (designed for medium traffic),
- a semi-rigid pavement (designed for medium traffic), and
- a concrete pavement (designed for medium traffic).

Stresses and strains were computed using the software Alizé-LCPC, modelling the road structures with a linear elastic multi-layer model. Material properties were obtained from the Alizé-LCPC database. A standard axle of 10kN was modelled and used as a reference. From the stresses and strains, the number of repetitions of the loads applied by the axle groups before failure of the pavement were calculated. The vehicle combinations were then ranked according to aggressiveness. Additional rankings were carried out according to aggressiveness normalised by payload volume, payload mass, and combination mass. Combinations 1.3 and 2.1 were used as the reference vehicles.

### 6.1.1. Vehicle combinations considered

Due to limited resources, six vehicle combinations were selected from the representative fleet for analysis: trucks 1.3 and 2.1 which represent existing conventional European combinations were considered the “reference trucks” and the trucks 3.1, 4.5, 5.1 and 6.1 were selected as the representative high capacity vehicles. All six trucks were first assessed under representative loading. A second set of simulations was then conducted on a subset of these with the critical loading scenario, with 2.1 representing the reference truck, and 3.1 and 6.1 representing the high capacity vehicles. The input data used are summarised in Table 16 and Table 17 (representative and critical loading simulations respectively). Table 18 summarises the freight volume and mass per truck in each case.

*Table 16: Input data for road impact simulations (first series of computations, representative loading)*

| Vehicle | Vehicle description | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Axle 1 | Axle 2 | Axle 3 | Axle 4 | Axle 5 | Axle 6 | Axle 7 | Axle 8 | Axle 9 | Axle 10 | Axle 11 | Axle 12 | GCM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 | TR4x2-ST3 (13.6m) | TR4x2 | ST3 13.6 | | | steer LD | drive | trailer | trailer | trailer | | | | | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 3,6 | 9,335 | 10,645 | 11,955 | | | | | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 2,14 | 2,14 | 2,14 | | | | | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | | | | | | | | |
| | Dual/single tyres? | | | | | single | dual | single | single | single | | | | | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | - | - | - | | | | | | | | |
| | Axle load (kg) | | | | | 6.301 | 7.511 | 5.289 | 5.289 | 5.289 | | | | | | | | 29.678 |
| 2.1 | TK6x2-CT2 (2x7.8m) | TK6x2 | CT2 | | | steer LD | drive | tag | trailer | trailer | | | | | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 4,8 | 6,15 | 12,976 | 14,786 | | | | | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 2 | 2,14 | 2,14 | | | | | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | | | | | | | | |
| | Dual/single tyres? | | | | | single | dual | single | single | single | | | | | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | - | - | - | | | | | | | | |
| | Axle load (kg) | | | | | 5.973 | 9.665 | 5.203 | 7.285 | 7.285 | | | | | | | | 35.412 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | TR6x4 | ST3 45ft | CT3 | | steer HD | drive | drive | trailer | trailer | trailer | trailer | trailer | trailer | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 3,3 | 4,65 | 9,595 | 11,005 | 12,315 | 17,92 | 19,22 | 20,52 | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | | | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | single | single | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | - | - | | | | |
| | Axle load (kg) | | | | | 6.174 | 5.326 | 5.326 | 6.345 | 6.345 | 6.345 | 3.806 | 3.806 | 3.806 | | | | 47.280 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | TK6x4 | CT2 | CT2 | | steer HD | drive | drive | trailer | trailer | trailer | trailer | | | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 4,8 | 6,15 | 13,03 | 14,84 | 21,62 | 23,43 | | | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | | | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | | | | | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | | | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | | | | | | |
| | Axle load (kg) | | | | | 6.627 | 7.519 | 7.519 | 7.638 | 7.638 | 7.232 | 7.232 | | | | | | 51.405 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | TR6x4 | ST3 45ft | DY2 | ST3 45ft | steer HD | drive | drive | trailer | trailer | trailer | dolly | dolly | trailer | trailer | trailer | | |
| | Distance behind axle 1 (m) | | | | | 0 | 3,3 | 4,65 | 9,595 | 11,005 | 12,315 | 17,225 | 18,625 | 23,995 | 25,405 | 26,715 | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | single | single | single | single | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | - | - | - | - | | |
| | Axle load (kg) | | | | | 6.208 | 5.547 | 5.547 | 5.735 | 5.735 | 5.735 | 5.359 | 5.548 | 5.723 | 5.723 | 5.723 | | 62.581 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | TK6x4 | DY2/s1 | LT2 | ST3/s3 2x7.8 | steer HD | drive | drive | dolly | dolly | dolly | dolly | trailer | trailer | trailer | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 4,8 | 6,15 | 10,55 | 11,95 | 18,255 | 20,065 | 28,32 | 29,63 | 30,94 | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | single | single | single | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | - | - | - | | | |
| | Axle load (kg) | | | | | 6.767 | 7.248 | 7.248 | 6.007 | 6.007 | 9.225 | 9.225 | 6.422 | 6.422 | 6.422 | | | 70.993 |

*Table 17: Input data for road impact simulations (second series of computations, critical loading)*

| Vehicle | Vehicle description | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Axle 1 | Axle 2 | Axle 3 | Axle 4 | Axle 5 | Axle 6 | Axle 7 | Axle 8 | Axle 9 | Axle 10 | Axle 11 | Axle 12 | GCM (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.1 | TK6x2-CT2 (2x7.8m) | TK6x2 | CT2 | | | steer LD | drive | tag | trailer | trailer | | | | | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 4,8 | 6,15 | 12,976 | 14,786 | | | | | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 2 | 2,14 | 2,14 | | | | | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | | | | | | | | |
| | Dual/single tyres? | | | | | single | dual | single | single | single | | | | | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | - | - | - | | | | | | | | |
| | Axle load (kg) | | | | | 6.439 | 12.052 | 6.731 | 9.526 | 9.526 | | | | | | | | 44.273 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | TR6x4 | ST3 45ft | CT3 | | steer HD | drive | drive | trailer | trailer | trailer | trailer | trailer | trailer | | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 3,3 | 4,65 | 9,595 | 11,005 | 12,315 | 17,92 | 19,22 | 20,52 | | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | | | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | single | single | | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | - | - | | | | |
| | Axle load (kg) | | | | | 6.499 | 6.620 | 6.620 | 7.990 | 7.990 | 7.990 | 4.808 | 4.808 | 4.808 | | | | 58.132 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | TK6x4 | DY2/s1 | LT2 | ST3/s3 2x7.8 | steer HD | drive | drive | dolly | dolly | dolly | dolly | trailer | trailer | trailer | | | |
| | Distance behind axle 1 (m) | | | | | 0 | 4,8 | 6,15 | 10,55 | 11,95 | 18,255 | 20,065 | 28,32 | 29,63 | 30,94 | | | |
| | Axle track width (m) | | | | | 2,05 | 1,84 | 1,84 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | 2,14 | | | |
| | Tyre width (m) | | | | | 0,315 | 0,315 | 0,315 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | 0,385 | | | |
| | Dual/single tyres? | | | | | single | dual | dual | single | single | single | single | single | single | single | | | |
| | Dual tyre spacing (m) | | | | | - | 0,35 | 0,35 | - | - | - | - | - | - | - | | | |
| | Axle load (kg) | | | | | 7.300 | 9.190 | 9.190 | 7.398 | 7.398 | 11.662 | 11.662 | 8.304 | 8.304 | 8.304 | | | 88.714 |

*Table 18: Freight (volume and cargo mass) for each truck under consideration*

| Truck | Internal Volume *V* (usable for transport) [$m^3$] | Cargo mass [kg] First series of computations | Cargo mass [kg] Second series of computations |
|---|---|---|---|
| 1.3 | 87.0 | 16317.7 | - |
| 2.1 | 95.8 | 17968.2 | 26829.7 |
| 3.1 | 117.5 | 22038.3 | 32890.3 |
| 4.5 | 143.7 | 26952.4 | - |
| 5.1 | 168.6 | 31622.7 | - |
| 6.1 | 191.6 | 35936.5 | 53657.5 |

### 6.1.2. Road structures considered

The four road structures under investigation are presented in deliverable D3.2 of the FALCON project [6]. In that deliverable, the following seven pavement structures were considered, chosen to represent the most common European road structures:

1. One flexible, low traffic pavement (granular base, bituminous wearing course) designed for a level of traffic T5, according to the French pavement design guide [44]. This level corresponds to 25 heavy vehicles per day over 20 years.
2. Two thick bituminous pavements designed for two different levels of traffic (medium and high): T0, which corresponds to 1200 heavy vehicles per day over 30 years, and T1, which corresponds to 500 heavy vehicles per day over 20 years.
3. Two semi rigid pavements (cement treated base, bituminous wearing course), designed for T0 and T1 traffic loading.
4. Two concrete pavements designed for both T0 and T1 traffic loading.

These pavements are defined in detail in Table 19 and Table 20. The three designs for dense traffic level T0 were not further considered since they are more performant under traffic loads than the similar designs for the lesser dense traffic level T1.

*Table 19: Motorway pavement structures under consideration*

| Traffic | Pavement structures | | |
|---|---|---|---|
| | Thick Bituminous | Semi-rigid | Concrete |
| T0<br>1200 HV/day during 30 years | 8.5 cm BBSG (bituminous concrete)<br>13 cm GB3 (base course asphalt material)<br>13 cm GB3<br>Subgrade E = 120 MPa | 10.5 cm BBSG (bituminous concrete)<br>19 cm GC3 (cement treated gravel)<br>18 cm GC3<br>Subgrade E = 120 MPa | 21 cm BC5 concrete<br>15 cm BC2 concrete<br>Subgrade E = 120 MPa |
| T1<br><br>500 HV/day during 20 years | 8.5 cm BB (bituminous concrete)<br>10 cm GB3 (base course asphalt material)<br>11 cm GB3<br>Subgrade E = 50 MPa | 8.5 BB (bituminous concrete)<br>22 cm GC3 (cement treated gravel)<br>20 cm GC3<br>Subgrade E = 50 MPa | 20 cm BC5 concrete<br>18 cm BC2 concrete<br>Subgrade E = 50 MPa |

*Table 20: Pavement structure of main road under consideration*

| Traffic | Pavement structure |
|---|---|
| | Flexible |
| T5<br>25 HV/day<br>during 20 years | 5 cm BBSG (bituminous concrete)<br>25 cm UGM (unbound granular material)<br>Subgrade E = 40 MPa |

The different pavement material characteristics correspond to standard material classes widely used in France. For the current simulations, we used the standard values as available in the materials library of the software Alizé-LCPC, as illustrated in Figure 49. The typical characteristics with which the computations were done are summarized in Table 21, Table 22, Table 23 and Table 24 for the different pavements. The thickness of each layers is as given in Table 19 and Table 20.

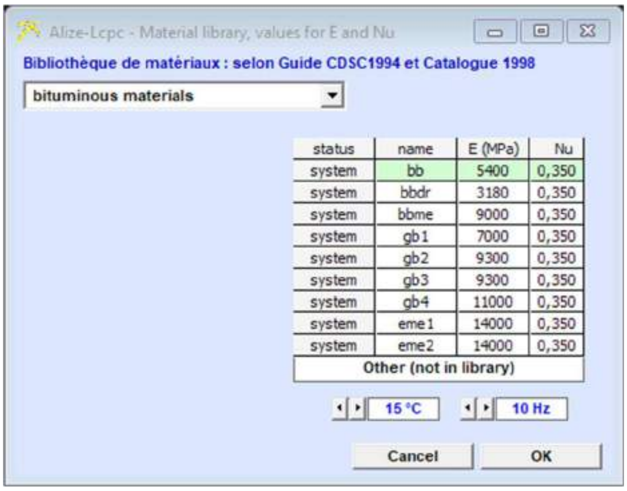



*Figure 49: Values for E and ν (Nu) defined in the materials library of Alizé-LCPC*

*Table 21: T1 concrete pavement (E = elastic modulus, ν = Poisson ratio)*

| Material | E (MPa)<br>At 15 °C, 10 Hz | ν |
|---|---|---|
| BC5 (concrete) | 35000 | 0,25 |
| BC2 (concrete) | 20000 | 0,25 |
| PF2 (subgrade) | 50 | 0,35 |

*Table 22: T1 semi-rigid pavement (E = elastic modulus, ν = Poisson ratio)*

| Material | E (MPa)<br>At 15 °C, 10 Hz | ν |
|---|---|---|
| BBSG (bituminous concrete) | 5400 | 0,35 |
| GC3 (cement treated gravel) | 23000 | 0,25 |
| GC3 (cement treated gravel) | 23000 | 0,25 |
| PF2 (subgrade) | 50 | 0,35 |

*Table 23: T1 thick bituminous pavement (E = elastic modulus, ν = Poisson ratio)*

| Material | E (MPa)<br>At 15 °C, 10 Hz | ν |
|---|---|---|
| BBSG (bituminous concrete) | 5400 | 0,35 |
| GB3 (base course asphalt material) | 9300 | 0,35 |
| GB3 (base course asphalt material) | 9300 | 0,35 |
| PF2 (subgrade) | 50 | 0,35 |

*Table 24: T5 flexible pavement (E = elastic modulus, ν = Poisson ratio)*

| Material | E (MPa)<br>At 15 °C, 10 Hz | ν |
|---|---|---|
| BBSG (bituminous concrete) | 5400 | 0,35 |
| GNT3 (untreated granular material) | 200 | 0,35 |
| PF2 (subgrade) | 50 | 0,35 |

### 6.1.3. Pavement modelling and boundary conditions

#### 6.1.3.1. Models in Alizé-LCPC

Deliverable D3.2 (a representative infrastructure catalogue) [6] described seven different road structures: a concrete, a semi-rigid and a thick bituminous structure with different layer thicknesses for roads designed for traffic classes T0 or T1, and a fully flexible road structure designed for the lower traffic class T5. We considered four of these road structures (T1 concrete, T1 semi-rigid, T1 thick bituminous, T5 flexible) and six of the truck combinations (1.3 and 2.1 as references, and LHVs 3.1, 4.5, 5.1 and 6.1). The software Alizé-LCPC was used for the analysis [45]. A linear elastic multi-layer model for each road structure was modelled in Alizé-LCPC, together with full load models of each of the six trucks under consideration. A "standard axle" of 100kN was modelled and intended as a reference. Standard axle loads are often used as a reference load when designing or evaluating the performance of pavements. The use of a linear elastic multi-layer model is common in the design of new pavements and for the evaluation of existing pavements. However, by doing so, this analysis neglects the viscous properties of the pavements. Some commercial software includes the ability to model viscosity, but the use of such tools is not yet common practice in most countries. Also, not all pavements exhibit viscoelastic behaviour.

#### 6.1.3.2. Temperature and climate

Variations in temperature between seasons were not considered. The computations were based on Young's Moduli taken at 15°C and assumed here as being the average temperature over the year. Climatic conditions vary greatly throughout Europe, and this disparity could not be taken fully into account within the frame of this task in the FALCON project. The particular case of frost actions including thaw cycles would need additional consideration and were not accounted for here. However, the main goal of the exercise presented here was the comparison between different trucks under the same conditions, such as road structures and local climate conditions, not their overall performance all over Europe under all possible conditions. As such, these simplifications were assumed reasonable.

#### 6.1.3.3. From stresses and strains to aggressiveness

With the Alizé-LCPC software, the strains and stresses were computed according to the Burmister layer model [46]. The strains and stresses were also computed for a standard axle of 100kN, as a reference. The models consider wheels on both sides of the truck for all the axles so that it is possible to compute the strains and stresses resulting from the axle groups. The road was represented as a multi-layer linear-elastic model. The loads were applied through several circular contact surfaces, each representing the contact area between a tyre and the road surface. Tyre pressures were arbitrarily set to 707 kPa.

From the options available in Alizé-LCPC, the strains or stresses "under the road surfacing layer" were selected for inspection. These were used for the computation of the aggressiveness $A_i$ of each of the axle groups of the trucks, using the approach of [47], and taking into account the intermediate partial relaxations. The total aggressiveness $A$ of the truck is then the sum of the aggressiveness of all axles of the truck. The aggressiveness depends both on the road structure and on the truck. For each road structure, all six trucks can be compared with their value for $A$.

#### 6.1.3.4. Truck loads

From a high-level perspective of transport logistics, comparing the value of high capacity vehicles and conventional trucks, consideration must be given to the road wear *per tonne of transported goods* or the wear *per unit of volume of transported goods*. In Europe, it is often the case that 80–90% of the available load volume is used, without approaching the maximum allowed mass, as observed in the statistical data obtained in the ARTEMIS European research project [48]. The internal cargo volume $V$ for each of the vehicles considered in the computations was given in Table 18.

First, the representative loading case was considered (Table 16). The aggressiveness obtained from these strains or stresses indicates the impact of each of the considered LHVs compared to the two reference trucks. From these, we can conclude whether or not an individual LHVs causes more or less damage to the road structure than the conventional truck. From the perspective of the road administrator, this evaluation is critical for the preservation of the roads: if the LHVs would be more demanding to the road structures, these would have to be reinforced.

In some specific cases, some LHVs or other vehicles may occasionally be heavier than was considered in the computations presented here. For such specific cases it is recommendable to study the impact of the exceptional heavier loads on the particular road structures in place. It was hypothesised that the impact of this on the comparative result would be minimal. To confirm this hypothesis, a second iteration of computations was conducted using the critical loading case, considering only the conventional truck 2.1 and HCVs 3.1 and 6.1, on the "T1 thick bituminous" pavement.

#### *6.1.3.5. Lateral wander*

Especially for bituminous pavements (both for flexible and semi-rigid structures) lateral wander of traffic influences the stresses' and strains' distributions in the pavement structure as well as surface rutting. Lateral wander distributes pavement loading, and hence pavement wear, over a larger area of the pavement. This prolongs the pavement service life.

The effects of lateral wander are different for the different distress modes. They also may differ between dual tyres and wide base singles. These effects are important: COST 334 reported that the distress reduction factor of lateral wander on primary rutting compared to non-wandering loading were in the range 0.67 – 0.87, using different road structures and a range of tyres [49]. A recent review on lateral wander can be found in [50]. Therefore lateral wander is thoroughly studied and accelerated load testing equipment usually allows parameterising the lateral wander during experiments, for instance as in the systems described in [51].

Recent European contributions to the topic are the examination of the lateral distribution of wheel wander by [52], a recent paper on the influence on rutting is [53] exploited in VTI report on the prediction of asphalt layer rutting [54]. The effects of wander are of secondary importance for rigid (concrete) pavements since these are much stiffer.

In this exercise, lateral wander was not taken into account. However, the influence of platooning and longer vehicles on reduction of lateral wander and its impact on faster wear and reduced service life of pavements should certainly be further investigated.

### 6.1.4. Simulation approach

From the strains $\varepsilon_i$ or stresses $\sigma_i$ computed with Alizé-LCPC, we determine the number of repetitions $N_{gr,i}$ of the loads applied by the axle groups before the pavement structure will fail. $N_{ref}$ is the number of load repetitions of the reference axle required to cause the pavement to fail.

We define the aggressiveness $A_{gr,i}$ of the *i*-th axle group as the ratio between $N_{ref}$ and $N_{gr,i}$:

$$A_{gr,i} = \frac{N_{ref}}{N_{gr,i}} \tag{4}$$

We then define the aggressiveness $A$ of a truck as the sum of the aggressiveness's $A_{gr,i}$ of all $m$ axle groups of the truck:

$$A = \sum_{i=1}^{m} A_{gr,i} \tag{5}$$

The values for $N_{gr,i}$ (and $N_{ref}$) were computed with the formulas given in [47] and these use only the strain $\varepsilon_i$ or stress $\sigma_i$ at one particular depth in the road structure.

For bituminous materials, the fatigue law used in [47] takes the following form:

$$N_i = \left(\frac{0.0016}{\varepsilon_i}\right)^{\alpha} \tag{6}$$

where

$N_i$: the number of repetitions of load $P_i$ before breaking of the sample;
$\varepsilon_i$: the strain (dimensionless) under load $P_i$;

$\alpha$: the slope coefficient of the fatigue curve, equal to 4.76.

For hydraulically-bound materials, the fatigue law used in [47] is a logarithmic function:

$$\log N_i = b\left(1 - \frac{\sigma_i}{f_{frts}}\right) \tag{7}$$

where

$N_i$: the number of repetitions of load $P_i$ before breaking of the sample;

$\sigma_i$: the stress (in *MPa*) under load $P_i$;

$f_{frts}$: average flexural (bending) resistance from tensile stress ($f_{frts}$ = *2.07 MPa*, cf. [55]);

$b$: the coefficient of the fatigue curve (*b = 12* is used in the computations).

The formula used in the computation is based on the materials and the layer thicknesses in each of the road structures. The following choices were made for the four road structures under consideration:

- For the concrete pavement, we considered tensile stress $\sigma_i$ at a depth of 0,200 m at the bottom of the concrete layer.
- For the semi-rigid pavement, we considered tensile stress $\sigma_i$ at a depth of 0,305 m under the first layer of "gc".
- For the thick bituminous pavement, we considered the strain $\varepsilon_i$ in the direction of the movement of the truck at a depth of 0,185 m at the bottom of the first layer of "gb".
- For the flexible pavement, we considered the strain $\varepsilon_i$ in the direction of the movement of the truck at a depth of 0,050 m at the bottom of the bituminous layer.

These choices were motivated by the stability and the coherence of the results obtained with Alizé-LCPC, when the results were compared between the different road structures and for the different trucks. Hence, for the concrete and semi-rigid pavements, only the fatigue law for hydraulically bound materials was used in the computations; for the thick bituminous and flexible pavements only the fatigue law for bituminous materials was used in the computations. In the computations we only consider one failure criterion: the stress or the strain at one particular depth in the road structure.

For single axles the fatigue laws can be applied directly. However, tandem and tridem axle groups consist of two or three consecutive axles positioned close to each other so that the strains and stresses imposed by the load of first axle are not relaxed before the next axle applies its load. Therefore, for tandem and tridem axle groups, stresses or strains are taken into consideration under each axle of the axle group and in the middle between two consecutive axles of the axle group. For instance, when we consider a tridem axle combination on a rigid pavement, the effect of the passage of the tridem axle group is a sequence of three high stress values ($\sigma_b$, $\sigma_d$ and $\sigma_f$) with intermediate partial relaxations ($\sigma_c$ and $\sigma_e$) as illustrated in Figure 50. In order to compute the aggressiveness of the axle group, we must get the three values for $\sigma_b$ (= $\sigma_f$), $\sigma_c$ (= $\sigma_e$) and $\sigma_d$ from the computations with Alizé-LCPC. More details on the approach of [47] are given in Appendix G.

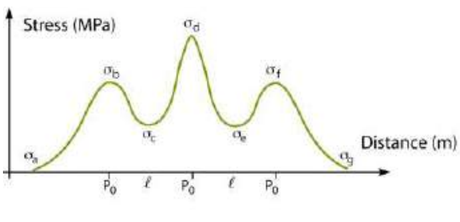



*Figure 50: Example of the shape of the stresses generated by a tridem axle*

A similar approach was used for tandem axles. For flexible and thick bituminous pavements we proceed in an analogous way, considering strains rather than stresses.

We therefore compute with Alizé-LCPC the strains and stresses at a given depth in the road structure and at different positions under the truck: underneath every axle and in the middle in between two consecutive axles of an axle group (tandem or tridem). We assume full relaxation between different axle groups: $\sigma_a = \sigma_g = 0$.
For example, with the values in Table 25 obtained with Alizé-LCPC for a tridem axle on a concrete pavement (with notations as in Figure 50) and by applying formulas:

$$\log N_d = b\left(1 - \frac{\sigma_d}{f_{frts}}\right) \quad (8)$$

$$\log N_b = b\left(1 - \frac{\sigma_b - \sigma_c}{f_{frts}}\right) \quad (9)$$

$$\log N_f = b\left(1 - \frac{\sigma_f - \sigma_e}{f_{frts}}\right) \quad (10)$$

with $b = 12$ and $f = 2.07\ MPa$, and

$$3\ N_{TR} = \frac{1}{\frac{1}{3}\frac{1}{N_b} + \frac{1}{3}\frac{1}{N_d} + \frac{1}{3}\frac{1}{N_f}} \quad (11)$$

we obtain the values $N_d$, $N_b$ and $N_f$ (one for each of the individual axles in the tridem axle group) and $N_{TR}$ (for the tridem axle group as a whole) presented in Table 26.

*Table 25: Example of output from Alizé-LCPC for tridem axle on concrete pavement*

| | (in *MPa*) |
|---|---|
| $\sigma_d$ | 0.501 |
| $\sigma_b$ (= $\sigma_f$) | 0.438 |
| $\sigma_c$ (= $\sigma_e$) | 0.167 |

*Table 26: obtained values for $N_i$ and $N_{TR}$ for tridem axle on concrete pavement*

| | |
|---|---|
| $N_d$ | $1.25 \cdot 10^9$ |
| $N_b$ and $N_f$ | $26.9 \cdot 10^9$ |
| $N_{TR,concrete}$ | $1.14 \cdot 10^9$ |

From $N_{TR}$ we then can compute aggressiveness $A_{TR}$ of the tridem axle group:

$$A_{TR,concrete} = \frac{N_{ref}}{N_{TR,concrete}} \quad (12)$$

where $N_{ref}$ is the total number of repetitions of the load applied by the reference axle before failing of the pavement.

## 6.2. Results

Table 27 shows the synthesis of the results of the computations for the trucks listed in Table 16 expressed in total aggressiveness (*A*) of each truck on the different road structures and as ratio between aggressiveness *A* with respect to the aggressiveness (*A1.3*) of truck 1.3 or with respect to the aggressiveness (*A2.1*) of truck 2.1.

*Table 27: Aggressiveness computed from Alizé-LCPC results for 6 different trucks and 4 different pavements*

| Truck | T1 - Thick bituminous | | | T1 - Semi rigid | | | T1 - Concrete | | | T5 - Flexible | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **A/A1.3** | **A/A2.1** | **A** | **A/A1.3** | **A/A2.1** | **A** | **A/A1.3** | **A/A2.1** | **A** | **A/A1.3** | **A/A2.1** |
| 1.3 | **0.68** | (1) | 0.4 | **0.09** | (1) | 0.2 | **0.39** | (1) | 0.4 | **2.45** | (1) | 0.8 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.1 | **1.93** | 2.8 | (1) | **0.55** | 6.0 | (1) | **1.00** | 2.6 | (1) | **3.20** | 1.3 | (1) |
| 3.1 | **1.12** | 1.6 | 0.6 | **0.10** | 1.1 | 0.2 | **0.37** | 0.9 | 0.4 | **3.44** | 1.4 | 1.1 |
| 4.5 | **2.31** | 3.4 | 1.2 | **0.09** | 1.0 | 0.2 | **1.00** | 2.6 | 1.0 | **4.34** | 1.8 | 1.4 |
| 5.1 | **1.60** | 2.3 | 0.8 | **0.12** | 1.3 | 0.2 | **0.67** | 1.7 | 0.7 | **4.94** | 2.0 | 1.5 |
| 6.1 | **3.03** | 4.4 | 1.6 | **0.83** | 9.2 | 1.5 | **1.65** | 4.2 | 1.7 | **5.85** | 2.4 | 1.8 |

Aggressiveness *A* is expressed as a multiple of the aggressiveness of the reference axle of 100kN (a 50kN single).
Table 28 presents the synthesis of the results of the computations for the trucks listed in Table 17 (more heavily loaded) expressed in total aggressiveness (*A*) of each truck on the “T1 thick bituminous” pavement. As expected, aggressiveness *A* increases with increased (freight-) load. But by comparing the results in Table 28 with the same trucks in Table 27, we observe hardly any difference in the relative aggressiveness of LHVs 3.1 and 6.1 with respect to truck 2.1.

*Table 28: Aggressiveness computed from Alizé-LCPC results for 3 of the more heavily loaded trucks on 1 of the pavements*

| Heavy loaded trucks | T1 - Thick bituminous | | | |
|---|---|---|---|---|
| | **A** | **A/A1.3** | **A/A2.1** | **A/A2.1 Heavy** |
| 2.1 TK6x2-CT2 (2x7.8m - REF Heavy loaded) | **3.85** | 5.6 | 2.0 | (1) |
| 3.1 TR6x4-ST3-CT3(45ft+20ft Heavy loaded) | **1.99** | 2.9 | 1.0 | 0.5 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m Heavy loaded) | **5.76** | 8.4 | 3.0 | 1.5 |

## 6.3. Possible interpretations of results

### 6.3.1. Aggressiveness ranking

Since the absolute value of the aggressiveness (*A*) also depends on the road structure, these absolute values cannot be compared between different road structures. Therefore, we only consider the values of aggressiveness for each road structure separately. We also indicate the ranking of the trucks for each of the evaluations per road structure. Table 29, Table 30, Table 31 and Table 32 revisit aggressiveness *A* from Table 27 and show the ranking (*R1* to *R4*) of each truck.

*Table 29: Aggressiveness and ranking for T1 concrete road structure*

| Truck type / road structure | *A* | Ranking *(R1)* |
|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0.391 | 2 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0.999 | 4 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0.366 | 1 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 1.000 | 5 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0.666 | 3 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 1.651 | 6 |

*Table 30: Aggressiveness and ranking for T1 semi-rigid road structure*

| Truck type / road structure | *A* | Ranking (*R2*) |
|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0.091 | 2 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0.548 | 5 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0.102 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0.089 | 1 |

| | | |
|---|---|---|
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0.116 | 4 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0.835 | 6 |

*Table 31: Aggressiveness and ranking for T1 thick bituminous road structure*

| Truck type / road structure | *A* | Ranking (*R3*) |
|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0.684 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 1.932 | 4 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 1.119 | 2 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 2.310 | 5 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 1.600 | 3 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 3.031 | 6 |

*Table 32: Aggressiveness and ranking for T5 flexible road structure*

| Truck type / road structure | *A* | Ranking (*R4*) |
|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 2.454 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 3.199 | 2 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 3.440 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 4.343 | 4 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 4.939 | 5 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 5.849 | 6 |

The rankings of the trucks for different pavement structures are quite similar, as illustrated in Figure 51 and Figure 52 where the computed values for *A* are presented per road structure and per truck.

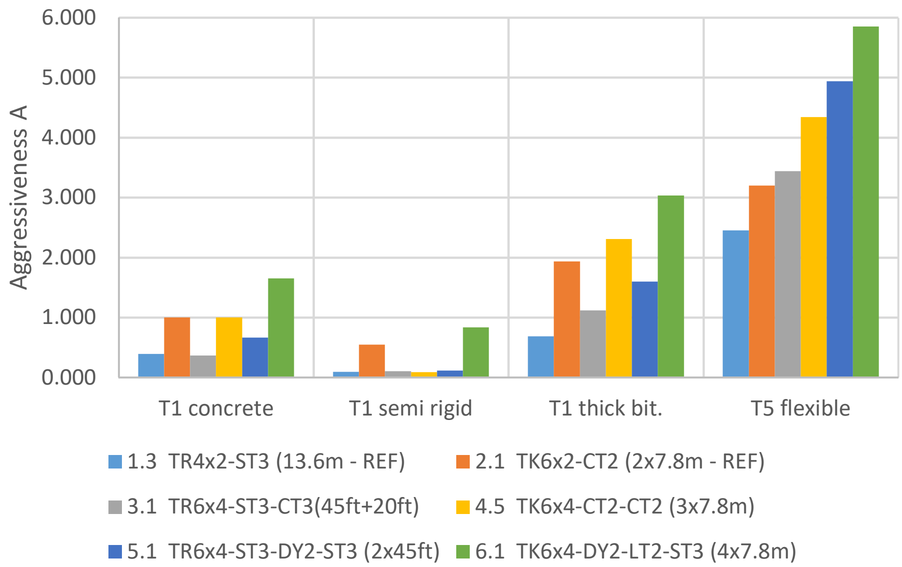



*Figure 51: Aggressiveness road structures (A): 6 trucks presented for each of the pavement structures*

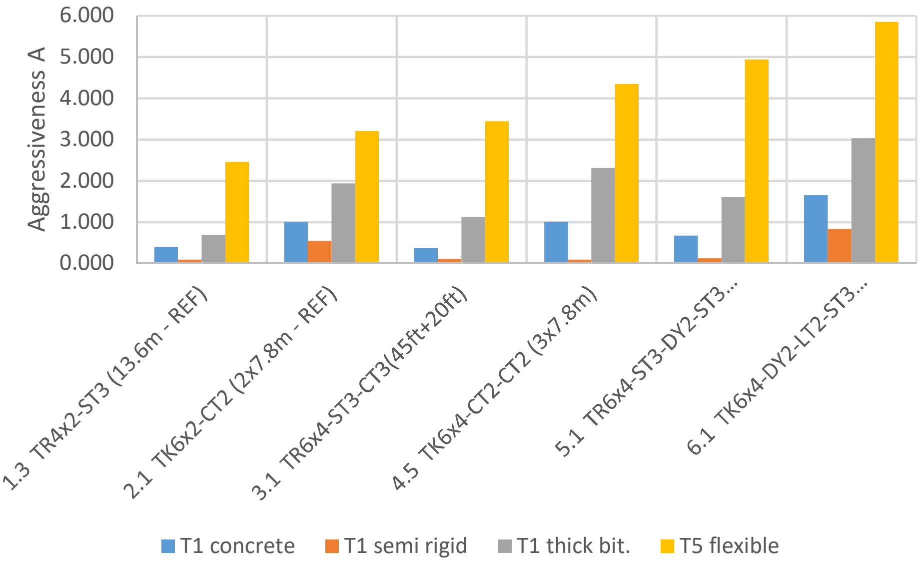



*Figure 52: Aggressiveness road structures (A): 4 pavement structures presented for each of the trucks*

### 6.3.2. Aggressiveness ranking relative to freight volume

In order to take the internal volume *V* for cargo for each of the vehicles into account, we first divided aggressiveness *A* by *V* for each of the trucks:

$$AperV(truck) = \frac{A(truck)}{V(truck)} \quad (13)$$

and then we computed the ratio with respect to truck 1.3:

$$AperVrel1.3(truck) = \frac{AperV(truck)}{AperV(truck\ 1.3)} \quad (14)$$

Table 33, Table 34, Table 35 and Table 36 show for the four different road structures the values for "*AperV*" and "*AperVrel*1.3" for each of the trucks and their ranking (*RV1* to *RV4*).

*Table 33: Aggressiveness per transported volume unit for T1 concrete road structure*

| Truck type / road structure | *AperV* | *AperVrel1.3* | Ranking (*RV1*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0045 | 1.000 | 3 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0104 | 2.321 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0031 | 0.693 | 2 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0070 | 1.549 | 4 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0040 | 0.879 | 1 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0086 | 1.917 | 5 |

*Table 34: Aggressiveness per transported volume unit for T1 semi-rigid road structure*

| Truck type / road structure | *AperV* | *AperVrel1.3* | Ranking (*RV2*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0010 | 1.000 | 4 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0057 | 2.015 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0009 | 0.932 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0006 | 0.753 | 1 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0007 | 0.851 | 2 |

| | | | |
|---|---|---|---|
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0044 | 1.571 | 5 |

*Table 35: Aggressiveness per transported volume unit for T1 thick bituminous road structure*

| Truck type / road structure | *AperV* | *AperVrel1.3* | Ranking (*RV3*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0079 | 1.000 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0202 | 2.567 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0095 | 1.212 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0161 | 2.046 | 5 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0095 | 1.208 | 2 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0158 | 2.013 | 4 |

*Table 36: Aggressiveness per transported volume unit for T5 flexible road structure*

| Truck type / road structure | *AperV* | *AperVrel1.3* | Ranking (*RV4*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0282 | 1.000 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0334 | 1.184 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0293 | 1.038 | 2 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0302 | 1.071 | 4 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0293 | 1.039 | 3 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0305 | 1.082 | 5 |

The same can be done with respect to truck 2.1, using the formula:

$$AperVrel2.1(truck) = \frac{AperV(truck)}{AperV(truck\ 2.1)} \tag{15}$$

but obviously this does not change anything about the ranking of the 6 trucks under consideration.

The rankings of the trucks for different pavement structures are quite similar, as illustrated in Figure 53 and Figure 54. These figures present the value for *A/V*, also summarized in Table 37. We can clearly see that on all four road structures the currently used Truck 2.1 has the highest value for *A/V*.

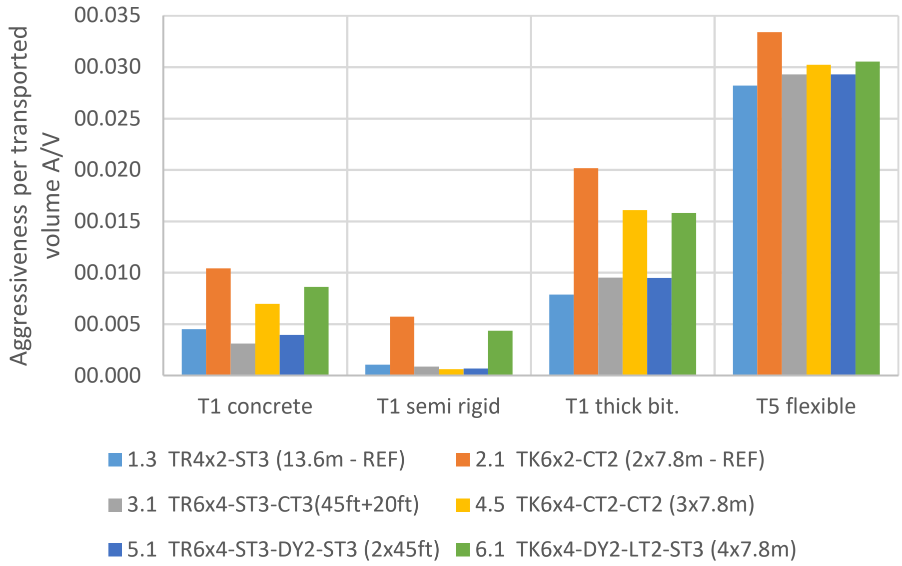



*Figure 53: Aggressiveness road structures per transported volume (A/V): 6 trucks presented for each of the pavement structures*

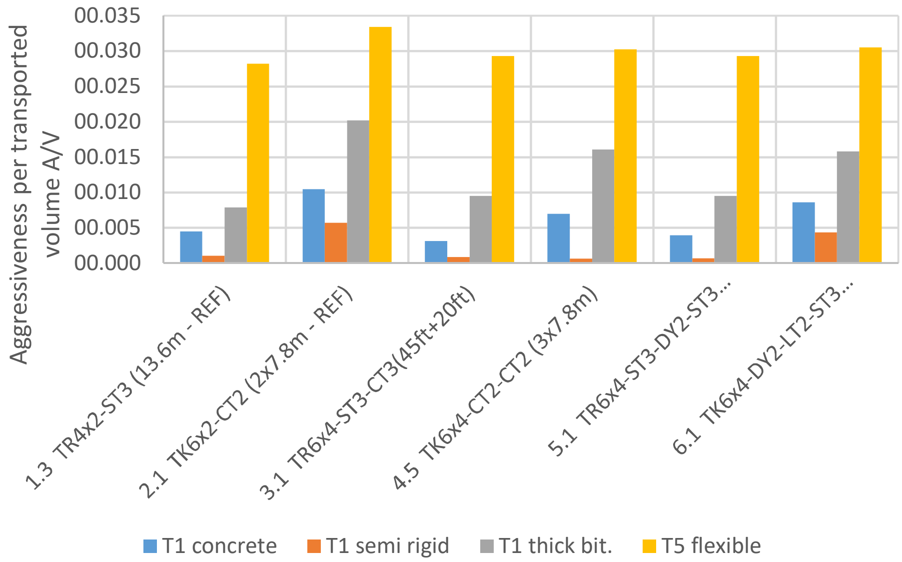



*Figure 54: Aggressiveness road structures per transported volume (A/V): 4 pavement structures presented for each of the trucks*

*Table 37: Aggressiveness road pavements per transported volume (A/V)*

| Truck type / road structure | T1 concrete | T1 semi-rigid | T1 thick bit. | T5 flexible |
|---|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0045 | 0,0010 | 0,0079 | 0,0282 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0104 | 0,0057 | 0,0202 | 0,0334 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0031 | 0,0009 | 0,0095 | 0,0293 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0070 | 0,0006 | 0,0161 | 0,0302 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0040 | 0,0007 | 0,0095 | 0,0293 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0086 | 0,0044 | 0,0158 | 0,0305 |

### 6.3.3. Aggressiveness ranking relative to the ratio of cargo mass to GCM

The ratio between cargo mass and GCM is not identical: it depends on the truck. By taking this ratio into account we can differentiate between carried volume and carried weight at constant density. We could say that the "bigger" the ratio the "better" it is (e.g. less fuel consumption if that only would depend on weight), although this is an over-simplified view of reality. Generally speaking, it would be best to have lowest possible weight of the vehicle combination including empty loading units, by light-weight structural design of the vehicles. However, the empty weight of container and swap bodies, which were both considered in the fleet of the studies in FALCON, differs considerably. Containers are heavier due to two facts: they are stackable, and they can be loaded more with respect to weight (as they are more robust). Therefore, for the vehicle operator it also matters what sort of loading units he prefers for the entire multimodal trip, because containers can be generally accommodated on the ship, road and rail, whereas the swap bodies can be used only on rail and road.
We used the ratio *R* between cargo mass and GCM for yet another comparison between the 6 trucks for which we have computed aggressiveness *A*. We divided cargo mass expressed in tonnes by GCM expressed in tonnes and we divided the values for "*AperV*" and "*AperVrel*1.3" by this ratio. This gives us the results presented in Table 38, Table 39, Table 40 and Table 41 (each one for another road structure) for the 6 trucks and their ranking (*RM1* to *RM4*).

*Table 38: Aggressiveness relative to freight volume and ratio of cargo mass and GCM for T1 concrete road structure (T1 concrete)*

| Truck type / road structure | AperV/R | AperVrel1.3/R | Ranking (*RM1*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0082 | 1.819 | 3 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0206 | 4.575 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0067 | 1.487 | 1 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0133 | 2.954 | 4 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0078 | 1.740 | 2 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0170 | 3.787 | 5 |

*Table 39: Aggressiveness relative to freight volume and ratio of cargo mass and GCM for T1 semi-rigid road structure (T1 semi-rigid)*

| Truck type / road structure | AperV/R | AperVrel1.3/R | Ranking (*RM2*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0019 | 1.819 | 4 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0113 | 10.819 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0019 | 1.794 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0012 | 1.138 | 1 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0014 | 1.304 | 2 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0086 | 8.262 | 5 |

*Table 40: Aggressiveness relative to freight volume and ratio of cargo mass and GCM for T1 thick bituminous road structure (T1 thick bitumen)*

| Truck type / road structure | AperV/R | AperVrel1.3/R | Ranking (*RM3*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0143 | 1.82 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0398 | 5.06 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0204 | 2.60 | 3 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0307 | 3.90 | 4 |

| | | | |
|---|---|---|---|
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0188 | 2.39 | 2 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0313 | 3.98 | 5 |

*Table 41: Aggressiveness relative to freight volume and ratio of cargo mass and GCM for T5 flexible road structure (T5 flexible)*

| Truck type / road structure | AperV/R | AperVrel1.3/R | Ranking (*RM4*) |
|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0513 | 1.82 | 1 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0658 | 2.33 | 6 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0628 | 2.23 | 5 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0576 | 2.04 | 2 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0580 | 2.06 | 3 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0603 | 2.14 | 4 |

The rankings of the trucks for different pavement structures are quite similar, as illustrated in Figure 55 and Figure 56. These figures present the value for (A/V)/(cargo mass/GCM), also summarized in Table 42. We can clearly see that on all four road structures the currently used Truck 2.1 has the highest value for *(A/V)/(cargo mass/GCM)*.

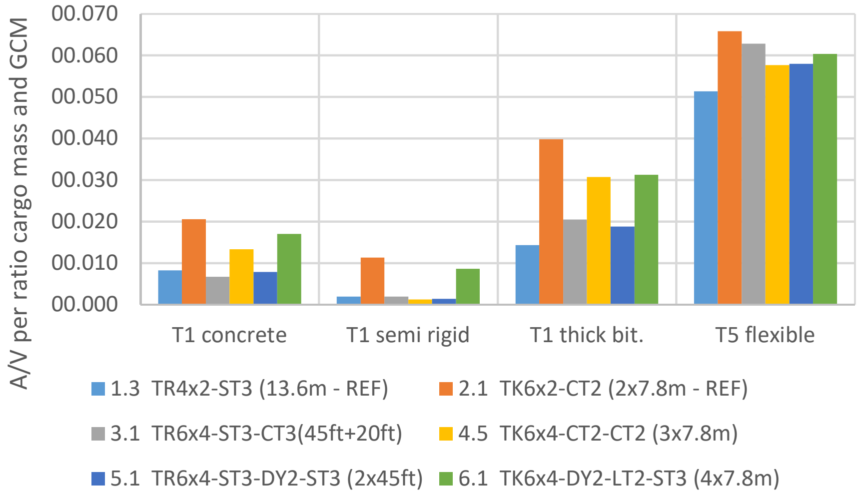



*Figure 55: Aggressiveness per transported volume per ratio cargo mass and GCM ((A/V)/(cargo mass/GCM)): 6 trucks presented for each of the pavement structures*

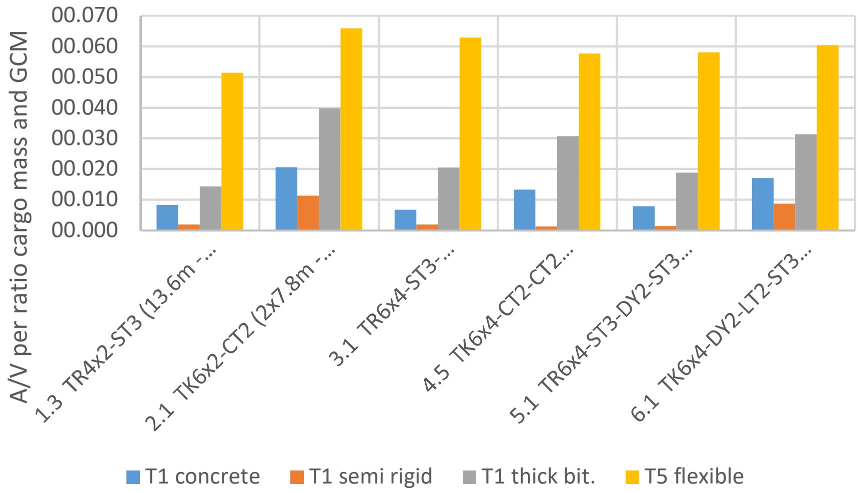



*Figure 56: Aggressiveness per transported volume per ratio cargo mass and GCM ((A/V)/(cargo mass/GCM)): 4 pavement structures presented for each of the trucks*

*Table 42: Aggressiveness per transported volume per ratio cargo mass and GCM ((A/V)/(cargo mass/GCM))*

| Truck type \ road structure | T1 concrete | T1 semi-rigid | T1 thick bit. | T5 flexible |
|---|---|---|---|---|
| 1.3 TR4x2-ST3 (13.6m - REF) | 0,0082 | 0,0019 | 0,0143 | 0,0513 |
| 2.1 TK6x2-CT2 (2x7.8m - REF) | 0,0206 | 0,0113 | 0,0398 | 0,0658 |
| 3.1 TR6x4-ST3-CT3(45ft+20ft) | 0,0067 | 0,0019 | 0,0204 | 0,0628 |
| 4.5 TK6x4-CT2-CT2 (3x7.8m) | 0,0133 | 0,0012 | 0,0307 | 0,0576 |
| 5.1 TR6x4-ST3-DY2-ST3 (2x45ft) | 0,0078 | 0,0014 | 0,0188 | 0,0580 |
| 6.1 TK6x4-DY2-LT2-ST3 (4x7.8m) | 0,0170 | 0,0086 | 0,0313 | 0,0603 |

### 6.3.4. Aggressiveness of individual axle groups

In order to analyse the impact of a particular axle group of a particular truck, the aggressiveness of each individual axle group can be considered. One way could be to compare the number of repetitions $N_i$ of the load applied by the axles group before failing of the pavement with respect to the number of repetitions $N_{ref}$ of the load applied by a reference load. In the previous, we considered the aggressiveness's $A_i$ of all $m$ axle groups of the truck, where $A_i$ was defined as the ratio between $N_{ref}$ and $N_i$, both computed with Alizé-LCPC:

$$A_i = \frac{N_{ref}}{N_i} \quad (16)$$

where $N_{ref}$ is the number of repetitions of the standard load (a 50kN single wheel of a 100kN reference axle) before failing of the pavement.

We now proceed as follows:

- for each of the four road structures ($pav$ = 1, ..., 4) considered here, we determine the smallest value $N_{pav}$ amongst the values for $N_i$ for the axle groups of trucks 1.3 and 2.1,
- for road structure $pav$ (= 1, ..., 4), we use $N_{pav}$ as the reference value and we compute $N_{pav}/N_i$ for each of the axle groups of LHVs 3.1, 4.5, 5.1 and 6.1.

If $N_{pav}/N_i > 1$ then the corresponding axle group of the LHV is more aggressive than any of the axles groups of trucks 1.3 and 2.1.

Figure 57 illustrates the axle groups of truck 1.3 and Figure 58 does so for truck 2.1. According to the computations performed with Alizé-LCPC, the most aggressive axle group of either truck

1.3 or 2.1 is axle group B of truck 2.1 for pavements “T1 concrete”, “T1 semi-rigid” and “T1 thick bituminous” and axle group C of truck 2.1 for pavement “T5 flexible”. This defines $N_{pav}$ for each of the pavements.

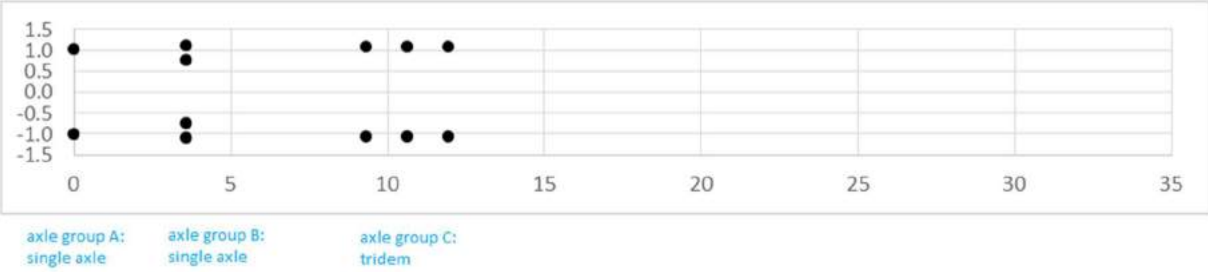



*Figure 57: Axle groups of truck 1.3 (the dots represent the positions of the tyres on the road surface, distances in m)*

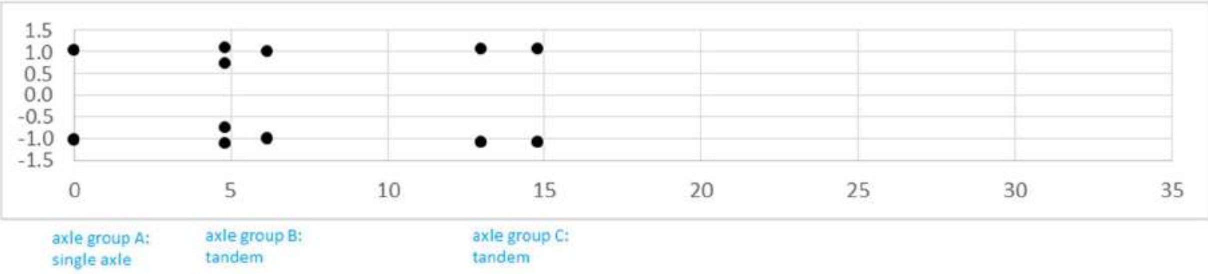



*Figure 58: Axle groups of truck 2.1 (the dots represent the positions of the tyres on the road surface, distances in m)*

For the LHVs, Figure 59, Figure 60, Figure 61 and Figure 62 illustrate the axle groups. According to the computations, axle group D of truck 6.1 is more aggressive than the reference axle group for all pavements. For the pavements “T1 concrete” and “T1 semi-rigid”, the other three LHVs (3.1, 4.5 and 5.1) have no axle group more aggressive than the reference axle group. For pavement “T1 thick bituminous”, LHVs 3.1 and 5.1 have no axle group more aggressive than the reference axle group but axle group C of LHV 4.5 turns out to be slightly more aggressive. For pavement “T5 flexible”, all four LHVs have some axle group more aggressive than the reference axle group. The most aggressive axle groups of LHVs 4.5 and 5.1 are only slightly more aggressive than the reference axle group. But it is noteworthy that LHV 6.1 is particularly more aggressive due to the presence of its axle group D: a tandem axle with quite a heavy load. Wear of a pavement increases exponentially with increasing axle loads through the “fatigue laws”. Table 43, Table 44, Table 45 and Table 46 give the results of this analysis for all axle groups (one table per pavement).

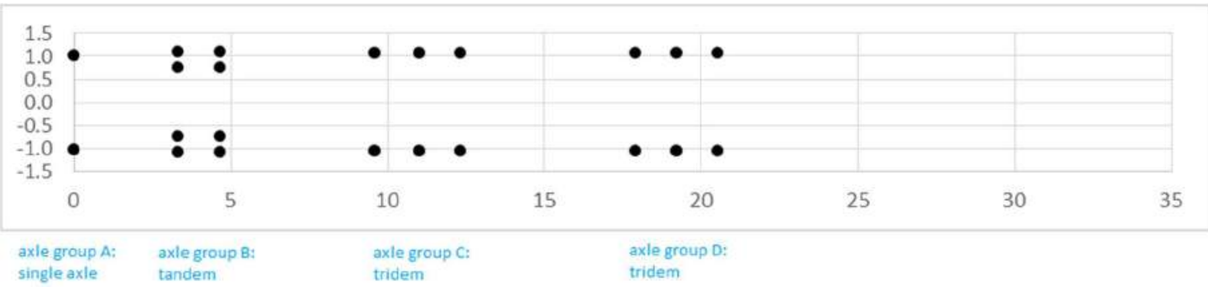



*Figure 59: Axle groups of LHV 3.1 (the dots represent the positions of the tyres on the road surface, distances in m)*

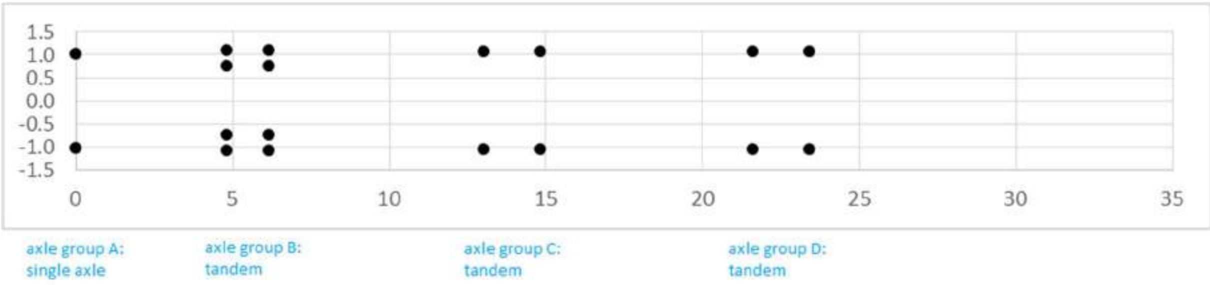



*Figure 60: Axle groups of LHV 4.5 (the dots represent the positions of the tyres on the road surface, distances in m)*

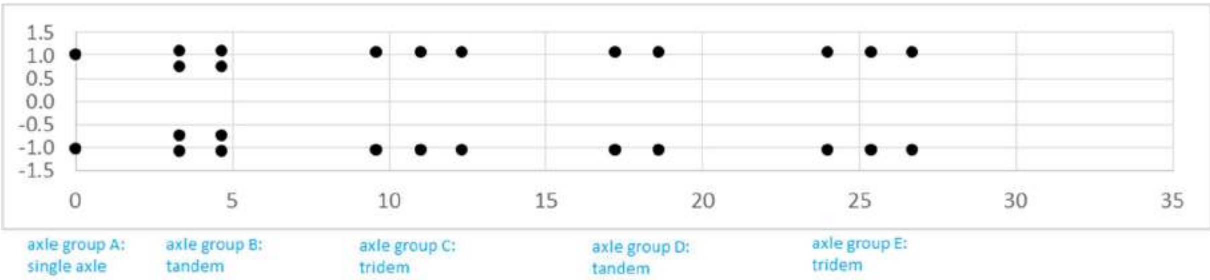



*Figure 61: Axle groups of LHV 5.1 (the dots represent the positions of the tyres on the road surface, distances in m)*

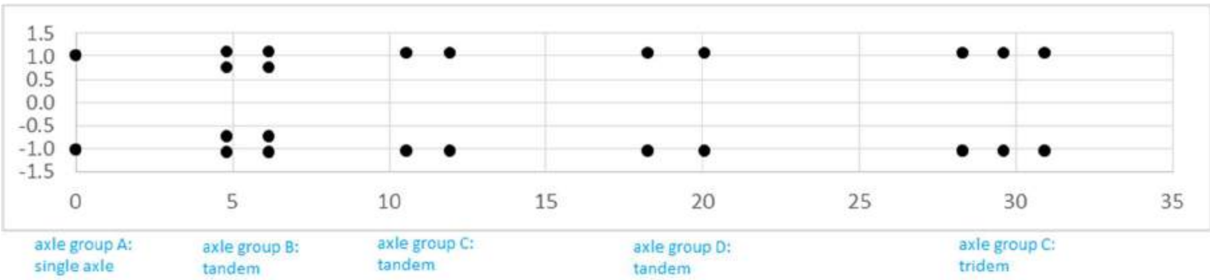



*Figure 62: Axle groups of LHV 6.1 (the dots represent the positions of the tyres on the road surface, distances in m)*

*Table 43: Aggressiveness of axle groups on T1 concrete road structure*

| Lorry type | axle | type | Ni | Ai=Nref/Ni | Npav/Ni |
|---|---|---|---|---|---|
| T1.3 | A | Single | 9,51E+09 | 0,12 | 0,21 |
| | B | Single | 1,02E+10 | 0,11 | 0,20 |
| | C | Tridem | 7,47E+09 | 0,16 | 0,27 |
| T2.1 | A | Single | 1,18E+10 | 0,10 | 0,17 |
| | B | Tandem | 2,01E+09 | 0,58 | 1,00 |
| | C | Tandem | 3,58E+09 | 0,32 | 0,56 |
| T3.1 | A | Single | 1,33E+10 | 0,09 | 0,15 |
| | B | Tandem | 3,85E+10 | 0,03 | 0,05 |
| | C | Tridem | 5,69E+09 | 0,20 | 0,35 |
| | D | Tridem | 2,59E+10 | 0,04 | 0,08 |
| T4.5 | A | Single | 7,65E+09 | 0,15 | 0,26 |
| | B | Tandem | 6,97E+09 | 0,17 | 0,29 |
| | C | Tandem | 3,04E+09 | 0,38 | 0,66 |
| | D | Tandem | 3,86E+09 | 0,30 | 0,52 |

| | | | | | |
|---|---|---|---|---|---|
| T5.1 | A | Single | 1,04E+10 | 0,11 | 0,19 |
| | B | Tandem | 2,91E+10 | 0,04 | 0,07 |
| | C | Tridem | 5,58E+09 | 0,21 | 0,36 |
| | D | Tandem | 1,14E+10 | 0,10 | 0,18 |
| | E | Tridem | 5,65E+09 | 0,21 | 0,36 |
| T6.1 | A | Single | 6,98E+09 | 0,17 | 0,29 |
| | B | Tandem | 8,91E+09 | 0,13 | 0,23 |
| | C | Tandem | 7,58E+09 | 0,15 | 0,27 |
| | D | Tandem | 1,21E+09 | 0,96 | 1,66 |
| | E | Tridem | 4,78E+09 | 0,24 | 0,42 |

*Table 44: Aggressiveness of axle groups on T1 semi-rigid road structure*

| Lorry type | axle | type | Ni | Ai=Nref/Ni | Npav/Ni |
|---|---|---|---|---|---|
| T1.3 | A | Single | 1,39E+09 | 0,03 | 0,08 |
| | B | Single | 1,41E+09 | 0,03 | 0,08 |
| | C | Tridem | 1,62E+09 | 0,03 | 0,07 |
| T2.1 | A | Single | 1,94E+09 | 0,02 | 0,06 |
| | B | Tandem | 1,07E+08 | 0,41 | 1,00 |
| | C | Tandem | 3,99E+08 | 0,11 | 0,27 |
| T3.1 | A | Single | 1,84E+09 | 0,02 | 0,06 |
| | B | Tandem | 8,35E+09 | 0,01 | 0,01 |
| | C | Tridem | 6,53E+08 | 0,07 | 0,16 |
| | D | Tridem | 8,59E+09 | 0,01 | 0,01 |
| T4.5 | A | Single | 3,48E+09 | 0,01 | 0,03 |
| | B | Tandem | 2,81E+09 | 0,02 | 0,04 |
| | C | Tandem | 1,28E+09 | 0,03 | 0,08 |
| | D | Tandem | 1,69E+09 | 0,03 | 0,06 |
| T5.1 | A | Single | 1,81E+09 | 0,02 | 0,06 |
| | B | Tandem | 6,72E+09 | 0,01 | 0,02 |
| | C | Tridem | 1,38E+09 | 0,03 | 0,08 |
| | D | Tandem | 3,23E+09 | 0,01 | 0,03 |
| | E | Tridem | 1,14E+09 | 0,04 | 0,09 |
| T6.1 | A | Single | 8,13E+08 | 0,05 | 0,13 |
| | B | Tandem | 1,17E+09 | 0,04 | 0,09 |
| | C | Tandem | 1,90E+09 | 0,02 | 0,06 |
| | D | Tandem | 7,15E+07 | 0,62 | 1,50 |
| | E | Tridem | 4,45E+08 | 0,10 | 0,24 |

*Table 45: Aggressiveness of axle groups on T1 thick bituminous road structure*

| Lorry type | axle | type | Ni | Ai=Nref/Ni | Npav/Ni |
|---|---|---|---|---|---|
| T1.3 | A | Single | 5,65E+09 | 0,27 | 0,31 |
| | B | Single | 8,27E+09 | 0,18 | 0,21 |
| | C | Tridem | 6,32E+09 | 0,24 | 0,27 |
| T2.1 | A | Single | 6,25E+09 | 0,24 | 0,28 |
| | B | Tandem | 1,73E+09 | 0,87 | 1,00 |

| | | | | | |
|---|---|---|---|---|---|
| | C | Tandem | 1,81E+09 | 0,83 | 0,96 |
| T3.1 | A | Single | 6,25E+09 | 0,24 | 0,28 |
| | B | Tandem | 2,43E+10 | 0,06 | 0,07 |
| | C | Tridem | 2,18E+09 | 0,69 | 0,79 |
| | D | Tridem | 1,15E+10 | 0,13 | 0,15 |
| T4.5 | A | Single | 4,50E+09 | 0,33 | 0,38 |
| | B | Tandem | 5,89E+09 | 0,25 | 0,29 |
| | C | Tandem | 1,63E+09 | 0,92 | 1,06 |
| | D | Tandem | 1,87E+09 | 0,80 | 0,93 |
| T5.1 | A | Single | 6,04E+09 | 0,25 | 0,29 |
| | B | Tandem | 2,03E+10 | 0,07 | 0,09 |
| | C | Tridem | 2,97E+09 | 0,50 | 0,58 |
| | D | Tandem | 5,66E+09 | 0,26 | 0,31 |
| | E | Tridem | 2,94E+09 | 0,51 | 0,59 |
| T6.1 | A | Single | 4,23E+09 | 0,35 | 0,41 |
| | B | Tandem | 6,64E+09 | 0,23 | 0,26 |
| | C | Tandem | 4,05E+09 | 0,37 | 0,43 |
| | D | Tandem | 9,79E+08 | 1,53 | 1,77 |
| | E | Tridem | 2,72E+09 | 0,55 | 0,64 |

*Table 46: Aggressiveness of axle groups on T5 flexible road structure*

| Lorry type | axle | type | Ni | Ai=Nref/Ni | Npav/Ni |
|---|---|---|---|---|---|
| T1.3 | A | Single | 8,99E+02 | 0,67 | 0,46 |
| | B | Single | 1,45E+03 | 0,41 | 0,29 |
| | C | Tridem | 4,35E+02 | 1,38 | 0,96 |
| T2.1 | A | Single | 9,12E+02 | 0,66 | 0,46 |
| | B | Tandem | 5,40E+02 | 1,11 | 0,77 |
| | C | Tandem | 4,18E+02 | 1,43 | 1,00 |
| T3.1 | A | Single | 9,31E+02 | 0,64 | 0,45 |
| | B | Tandem | 1,68E+03 | 0,36 | 0,25 |
| | C | Tridem | 3,73E+02 | 1,61 | 1,12 |
| | D | Tridem | 7,19E+02 | 0,83 | 0,58 |
| T4.5 | A | Single | 7,95E+02 | 0,75 | 0,53 |
| | B | Tandem | 8,53E+02 | 0,70 | 0,49 |
| | C | Tandem | 4,10E+02 | 1,46 | 1,02 |
| | D | Tandem | 4,20E+02 | 1,43 | 0,99 |
| T5.1 | A | Single | 9,13E+02 | 0,66 | 0,46 |
| | B | Tandem | 1,50E+03 | 0,40 | 0,28 |
| | C | Tridem | 4,16E+02 | 1,44 | 1,00 |
| | D | Tandem | 6,20E+02 | 0,97 | 0,67 |
| | E | Tridem | 4,05E+02 | 1,48 | 1,03 |
| T6.1 | A | Single | 8,17E+02 | 0,73 | 0,51 |
| | B | Tandem | 9,12E+02 | 0,66 | 0,46 |
| | C | Tandem | 5,08E+02 | 1,18 | 0,82 |
| | D | Tandem | 3,62E+02 | 1,65 | 1,15 |
| | E | Tridem | 3,68E+02 | 1,63 | 1,13 |

## 6.4. Discussion of results

We could conclude from Table 43, Table 44, Table 45 and Table 46 that some axle groups on LHVs 4.5 and 6.1 are more aggressive than axle groups on LHVs 3.1 and 5.1.
When we only look at the aggressiveness *A* of the different road structures (Table 27), where none of the trucks are loaded up to their respective maximal weights, then it shows that the individual LHV combinations are all almost always “more aggressive” than reference truck 1.3 but not so when compared to truck 2.1. Table 28 hints us that none of the non-fully loaded LHVs considered in Table 27 are more aggressive than a fully loaded truck of type 2.1.
For the flexible pavement for T5-traffic LHV 5.1, just like LHVs 4.5 and 6.1, is not in a favourable position, as we can see in Table 27 and Table 32.
When considering the axle groups of the trucks separately, one of the axle groups of LHV 6.1 is more aggressive than the axle groups of reference trucks 1.3 and 2.1. The axle groups of the other LHVs are comparable to the axle groups of reference trucks 1.3 and 2.1.

### 6.4.1. Implications for transport operators

From the point of view of the transporter, the comparison of the aggressiveness relative to the transported freight volume between new LHV combinations and trucks currently in use is of importance. Since in this study the density of the freight is constant, the same results hold for aggressiveness relative to the volume or to the weight of the freight. Somewhat different results are obtained when taking the GCM into account, as we did in Table 38 to Table 41.

### 6.4.2. Implications for national road agencies

The main advantage of LHVs is the reduction of the number of standard axle loads used for transporting the same freight. Indeed, in order to transport the same amount of freight carried by an LHV (expressed in volume or in weight) more than one “ordinary” truck has to be used. Such advantage is expressed by previously defined indicator “*AperVrel*1.3” or by “*AperVrel2.*1” (with analogue definition to “*AperVrel*1.3” but with respect to truck 2.1).
The LHVs 3.1, 4.5 and 5.1 do have values for indicators “*AperVrel*1.3” and “*AperVrel2.*1” that indicate less aggressiveness per transported volume.

### 6.4.3. Implications for vehicle manufacturers

The evaluation of aggressiveness w.r.t. GCM may seem less relevant since the aggressiveness *A* already includes the effect of the load on the road structure. However, two truck combinations with the same GCM may have different aggressiveness due to different load distribution (different number of axles, different distances between consecutive axles or axle groups, more dual configurations or more axles with dual tyres, different distribution of the weight). The aggressiveness w.r.t. GCM gives an indication of the efficiency of the load distribution over the truck combination. Hence, this may be of interest for vehicle manufacturers.
The manufacturers may also be interested in the aggressiveness of individual axle groups, to limit their aggressiveness by adaptations in the design of their vehicles.

### 6.4.4. Influence of total load on the results

The computations in this study were done for the loads that can reasonably be expected, taking into account the average loads that are currently carried by trucks on European roads. However, we expect that the results will not significantly differ from the ones obtained here, when the computations are repeated with the maximal loads of the truck combinations. Indeed, the value of aggressiveness *A* is expected to be higher for higher loads carried by the same truck on the same road structure, but we do not expect significant changes in the ranking between the truck combinations. A few additional computations with heavier loads for three truck combinations (2.1, 3.1 and 6.1) on one road structure (T1 thick bituminous) were presented and support this expectation.
Since the aggressiveness of the LHVs under consideration stay within the range of the aggressiveness obtained for the trucks that are already allowed on the road network, we do

not think that it will be necessary to introduce new criteria for the acceptance of new LHV combinations, when it comes to the possibly excessive wear of road structures.

#### 6.4.5. Alternative indicator formulas

The combination of parameters such as aggressiveness *A*, carried volume, cargo mass and GCM can be done in many different ways. Inspiration on how to do it in the best way can for instance be found in documentation related to Pavement Asset Management. We refer to the final report of COST action 354 [56] and to the PIARC report addressing KPIs [57] as possible sources of inspiration for the definition of “combined indicators”.
Note that the absolute value of aggressiveness depends on the computations of stresses and strains (here done with the Alizé-LCPC software) and therefore the absolute values for a same vehicle are not comparable between different road structures. Indeed, the computation of aggressiveness depends on stress or strain, depending on the type of road structures and their different materials. Combining the aggressiveness itself over several road structures is therefore not at all recommended.
A good way of taking different pavement structures into consideration is by looking at the “worst” case.

### 6.5. Conclusions and recommendations

#### 6.5.1. Restrictions

From the point of view of the wear of the road structure and its bearing capacity, the existing axle load limits should be respected also by LHVs, but no further restrictions seem to be necessary.

#### 6.5.2. Proposal for a European road wear impact assessment method

It was observed that truck 2.1, currently in use throughout Europe, is more aggressive to the pavements than truck 1.3, and also more than most of the LHVs, at least under the assumptions made in this document. We suggest the following procedure as to evaluate the potential of a particular (new) LHV combination without negative effect on the expected lifetime of existing or new pavements:

- Consider truck 2.1 with maximal load of 40 tonnes (the legal limit in EU),
- Consider in each individual country a few (e.g. 3) representative road structures among those present in the country (as the road structures differ significantly between countries),
- Consider the appropriate material properties and climate conditions for each individual country,
- Compute the aggressiveness of truck 2.1 for each of these representative road structures and consider these as maximum allowed aggressiveness,

When considering a new LHV combination with given axle configurations: compute for each of the representative pavements the maximal load that can be carried by the LHV without surpassing the maximum allowed aggressiveness per mass or per volume (computed with truck 2.1). In this way, that particular LHV can be allowed on all European roads under the condition that it does not surpass the maximal load obtained from these computations. Moreover, in this way all LHVs are certified to be used up to a certain limit of weight of freight. The approach takes national differences into account but can be used throughout Europe.
The computations can be done by the local NRA, who is probably also best placed for selecting the most representative road structures. The computations can also be done with the design tools and software that are currently in use on local (national or regional) level. In this approach, the definition of *aggressiveness* must be fixed. One could consider the highest aggressiveness $A_{max}$ amongst the axle groups, the sum *A* of the aggressiveness’s of all axle groups present in the truck combination, or the sum of the aggressiveness’s of all axle groups present in the truck combination scaled to the available freight volumes (*AperV*).

For the perspective of the road administrator and for road structure preservation, $A_{max}$ and *A* may be more appropriate, whereas *AperV* may be more significant from the point of view of a transporter and for the development of his future business case.
Throughout Europe the method for pavement design is not standardised, the materials used for road construction and the climate conditions are different. We recommend that for each of the road access levels and for each the truck configuration of a new LHV, computations are made on a set of pavement structures that are representative for the “worst case” amongst existing roads in Europe of that road access level. Then a threshold of aggressiveness per tonne can be applied to that LHV on the different road access levels. When an LHV passes the threshold for the “worst case” road of a road access level, that LHV will be allowed on all roads in Europe of that same road access level.
Although the set of pavement structures considered in this document is not sufficient and the computations of aggressiveness are too simple (for instance, they do not take climate conditions into account), the exercise presented in this document shows the feasibility of the recommended approach.

### 6.5.3. Particular interpretations

For very particular road structures, it may be useful to check the aggressiveness of the LHVs. Indeed, road structures are different in different countries in Europe and some may behave in a different way than those pavements considered here. Decision makers may want to make use of other indicators as those used here, such as *Rave* and *Pave,* or similar alternative indicators.

### 6.5.4. Limitations

The computations presented in this document were limited in scope and some assumptions were made that simplified them. We did not consider climate aspects and the viscoelastic behaviour of bituminous materials. The analysis is based on fatigue performance whereas for flexible road structures one could also consider rutting criteria. In the computations we only considered 1 criterion of failure: the stress or the strain at one particular depth in the road structure. A limited number of trucks was considered and of these it was truck 2.1 that came out to be the “most aggressive” truck currently in use but this conclusion is only valid within the scope of this document.
When similar computations would be performed with a larger variety of trucks, with other road structures, with other assumptions, other models (e.g. including climate effects or viscoelastic behaviour), then maybe another truck combination may turn out to be the “most aggressive” one currently in use. However, the recommendations stay valid, replacing truck 2.1 by the truck combination found to be the “most aggressive” one and by applying the other models for computation of aggressiveness.

# 7. Defining Road Access Levels

## 7.1. Introduction

Table 47 outlines the existing Australian road access classification system. It ranges from Level 1 vehicles which are permitted access to all of the Australian road network and for which the required performance criteria are set accordingly strictly. Levels 2–4 accommodate longer vehicle combinations that are restricted to increasingly smaller subsets of the road network, with accordingly less strict criteria on some standards. At the extreme end is Level 4, which caters for the longest vehicles operating in remote regions of the country. This is the category into which new Australian "road train"-type combinations are categorised.

*Table 47: Australian road access level classification*

| Road access level | Permitted vehicle length | Permitted routes | Performance criteria |
|---|---|---|---|
| Level 1 | ≤ 20 m | Unrestricted road access | Most stringent |
| Level 2 | ≤ 30 m | Significant freight routes | |
| Level 3 | ≤ 42 m | Major freight routes | |
| Level 4 | ≤ 60 m | Remote areas | Least stringent |

Using the Australian framework as a baseline, a possible general road access classification system for Europe is shown in Table 48. Consideration was given to the existing road network characteristics, existing regulations, and geography. The concept of "unrestricted road access" was deemed inappropriate for equivalent Level 1 European vehicles, and was replaced with "existing truck routes", to avoid the possibility of long articulated heavy vehicles travelling through medieval European city centres for example. The UK/EU roundabout test would be enforced for this level.

A new "Level 0" was added, to account for city-level freight activities such as garbage collection and home grocery delivery. Here, it is envisaged that additional stricter manoeuvrability tests (as yet undefined) representative of small city intersections be imposed. This also allows for the possibility of higher capacity vehicles serving these industries in the future, provided that they can be shown to meet the strict manoeuvrability criteria (using advanced steering control systems for example) as well as other city-level requirements for noise and air pollution (by using electric drive for example). Levels 2 and 3 were deemed approximately equivalent to the Australian system, with the observation that Level 2 would typically serve EMS-type vehicle combinations, and Level 3 would serve "EMS 2"-type combinations. Level 4 was deemed non-applicable to European conditions.

*Table 48: Proposed European road access level classification*

| Road access level | Permitted routes | Notes |
|---|---|---|
| Level 0 | Unrestricted road access | Stricter manoeuvrability criteria for city access for garbage trucks, home delivery *etc.* |
| Level 1 | General access (Existing truck routes) | Includes EU/UK roundabout manoeuvre |
| Level 2 | Significant freight routes | Approximately equivalent to EMS vehicles |
| Level 3 | Major freight routes | Approximately equivalent to EMS 2 vehicles |

In the remainder of this chapter, a method to pair the PBS performance levels of the vehicle combinations and the relevant segments of infrastructure (as described in the representative infrastructure catalogue [6]) is developed. This method can be used to guarantee that the scaling of performance criteria as a function of road access is balanced with respect to national topologies, road characteristics and climatic conditions. The provided numerical values for different road characteristics in this chapter are valid only for the considered region in the example study. Thus, they should be updated according to the operational condition and national topologies, when used for different countries and regions.

## 7.2. Approach

First, a set of critical infrastructure segments that may represent potential safety risk is identified. To assess the vehicle dynamical behaviour on the critical infrastructure segments, several representative vehicle states were selected. Then, a framework to characterise the envelopes of the road classes is defined for the representative fleet. A set of varying operational conditions is then defined covering both the characteristics of the infrastructure, and the real-life operational condition of a vehicle.  The framework is then verified through a set of Monte Carlo vehicle simulations to ensure that the vehicles can safely operate on these road segments under varying operational conditions.

Simulations were carried out by HAN, using multi-body vehicle dynamics models, and utilising the same vehicle fleet and vehicle parameters already presented. All simulations were done in MATLAB and SimMechanics. To ensure consistency with the TruckSIM models used by te CSIR, a validation exercise was carried out, the results of which will be discussed briefly in the following section.

## 7.3. Vehicle simulation cross-validation

This section describes the benchmarking exercise performed to ensure consistency between the vehicle dynamics simulations for Task 3.5 and Task 3.6 (carried out by CSIR and HAN respectively). The simulations for each task were performed by different organisations using different modelling software, and thus it was required to ensure consistency between the results. In Task 3.5, the CSIR made use of TruckSim models, whereas for Task 3.6, HAN University used MATLAB with the SimMechanics toolbox. The reference vehicle chosen for the validation was TK6x4-DY2-ST3 (based on combination 4.1). A two-step analysis was carried out:

- Static analysis – A comparison of the static axle loads were initially compared
- Dynamic analysis – Three dynamic manoeuvres were performed, as follows:
    - A high-speed single lane-change
    - A high-speed J-turn
    - A low-speed roundabout manoeuvre

Both models used the same input dataset including the tyre characteristics. All vehicles were modelled without torsional stiffness and friction in the coupling points.

### 7.3.1. Static validation

A comparison of static axle loads is given in Table 49. The comparison is good, with only minor differences in truck drive axle and the dolly axle loads (up to a maximum of approximately 3%). These small differences were caused by slightly different methods of chassis modelling, resulting in different centre of gravity locations. It is considered to have a minor impact and thus the static validation is concluded as sufficient.

*Table 49: Static loads per axle*

| Vehicle unit | Axle | CSIR model (kg) | HAN model (kg) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Truck | Steer axle | 6768 | 6664 |
| | Drive axle 1 | 7255 | 7472 |
| | Drive axle 2 | 7255 | 7472 |
| Dolly | Dolly axle 1 | 6327 | 6166 |
| | Dolly axle 2 | 6327 | 6166 |
| Semitrailer | Semitrailer axle 1 | 6430 | 6430 |
| | Semitrailer axle 2 | 6430 | 6430 |
| | Semitrailer axle 3 | 6430 | 6430 |
| **Gross Combination Mass (GCM)** | | **53221** | **53230** |

### 7.3.2. Dynamic validation

The single lane change manoeuvre was performed to benchmark the lateral vehicle dynamics. Lateral accelerations and lateral axle deviations were measured and compared. Two different steering inputs were used, reaching maximum hand-wheel steering angles of 39° and 69°, respectively. The smaller steer input represented "normal operation", and the higher steer input represented the case where the vehicle would approach instability. In both cases a steering ratio of 1:20 was used.

Corresponding results presenting the peak values of lateral acceleration and axle position are given in Table 50. Detailed time histories of the simulations can be found in Appendix I. Overall, the results are deemed to correlate sufficiently. Small differences in results were thought to originate from the simplified manner in which tyre data is modelled in TruckSIM versus MATLAB SimMechanics.

*Table 50: Single lane-change validation results*

| Steering angle = 39 (deg) | | |
|---|---|---|
| | CSIR | HAN |
| Max. Acceleration Semitrailer Last Axle (g) | 0.2 | 0.18 |
| Min. Acceleration Semitrailer Last Axle (g) | -0.31 | -0.27 |
| Max Lateral Position Semitrailer Last Axle (m) | 3.54 | 3.45 |
| Steering angle = 69 (deg) | | |
| | CSIR | HAN |
| Max. Acceleration Semitrailer Last Axle (g) | 0.34 | 0.36 |
| Min. Acceleration Semitrailer Last Axle (g) | -0.42 | -0.41 |
| Max Lateral Position Semitrailer Last Axle (m) | 6.12 | 6.01 |

The J-Turn manoeuvre was performed to benchmark rollover stability. The rollover thresholds of the HAN and CSIR models were compared and shown to be sufficiently consistent as illustrated in Table 51.

*Table 51: J-Turn validation results*

| | **CSIR** | **HAN** |
|---|---|---|
| Rollover Threshold (g) | 0.35 | 0.32 |

The chosen inputs for the low-speed roundabout manoeuvre were the longitudinal velocity and the steering angle profile to follow a certain path radius. The results are shown in Table 52, demonstrating acceptable correlation between models.

*Table 52: Low-speed roundabout manoeuvre validation results*

| | CSIR | HAN |
|---|---|---|
| Path radius (m) | 16.488 | 16.508 |
| Swept path width (m) | 7.576 | 7.477 |

### 7.3.3. Conclusion

Results obtained for both static and dynamic benchmarking demonstrated that the models of HAN and CSIR delivered reasonably consistent results.

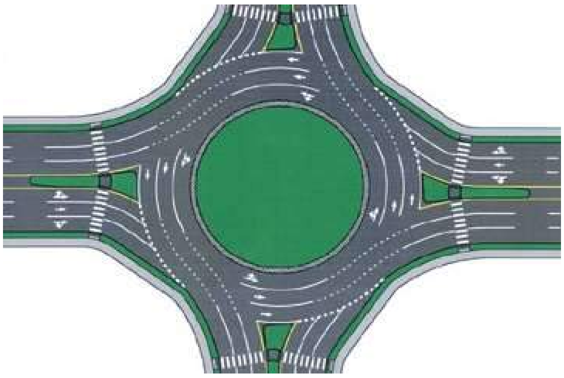
## 7.4. Critical infrastructure segments and safety-related vehicle dynamics states

To verify the safe operation of the representative fleet in all possible infrastructure scenarios would require a near infinite number of permutations, which is not viable. To simplify the problem, the most critical infrastructure segments have been identified in which the vehicle combination has a higher chance of safety failures. The selection is motivated by the results collected by Rijkswaterstaat in Netherlands [58]. Demonstrating that the vehicle is safe in these critical segments is considered enough to infer the safety of the vehicle in less critical situations. Three critical infrastructure segments where there is a high chance of failure have been identified. These are:

1. **Highway Exits:** Highway exits are considered as a critical infrastructure segment, where vehicles transition from a highway to a lower level road. This involves a curved exit from the highway which causes high lateral accelerations possibly leading to rollover. Furthermore, due to the swept width of HCVs, there exists a chance that the vehicle leaves its lane while negotiating a low radius exit. Highway exits may also result in jack-knifing. If the exit has a longitudinal slope there is an added possibility of a gradeability failure. An example of a highway exit is depicted in Figure 63(a).
2. **Single Lane Roundabouts** may be a potential safety risk, due to the larger swept path of HCVs. Since such a roundabout is usually negotiated at low speeds, there is no risk of rollover or high-speed jack-knife. However, the small radius of curvature may become problematic for longer vehicle combinations as some vehicle units may not stay within dedicated lane/space. An example of a possible failure on a single lane roundabout is depicted in Figure 63(b).
3. **Multi Lane Roundabout:** These roundabouts are typically of larger radius ($R > 30$ m) than the single lane roundabouts and occur on roads with a higher traffic throughput. The width of the lanes proportionally decreases with increasing radius (Lane width in curve = Lane width in straight segment + 50/R). Hence, there exists a risk that a vehicle combination will intrude to an adjacent lane due to off-tracking, which is considered to be a potential critical scenario. Moreover, these roundabouts are negotiated at higher speeds which may lead to higher levels of lateral acceleration and thus increased chance of rollover. An example of a multilane roundabout is given in Figure 63(c)

(a)

(b)



(c)

*Figure 63: Critical infrastructure segments: (a) highway exit, (b) single lane roundabout, the vehicle crosses the lane, (c) multilane roundabout*

## 7.5. Possible failure modes and representative vehicle states

Given the expected vehicle dynamics behaviour on the identified critical infrastructure segments, we can define possible failure modes which may compromise the safe vehicle operation. The following failure modes have been identified:

1. **Rollover**: Due to a generally higher centre of gravity (CoG) and varying loading conditions there exist a risk of rolling over for all vehicles considered in the representative fleet, especially during cornering if speeds are too high.
2. **Jack-knifing**: This is a failure mode encountered only by articulated vehicles. It refers to the situation when one or more of the vehicles in the combination experiences an excessive increase in articulation angle through yaw instability. Jack-knifing may be caused by equipment failure, improper braking, or adverse road conditions such as icy surfaces.
3. **Departure from driving lane**: Vehicle combinations with one or more articulation joints and long wheelbases tend to have a higher swept path width during turning. This may result in the vehicle colliding with other road users in the adjacent lane or other infrastructure furniture (barriers, lamp posts, etc.).
4. **Inability to maintain speed:** This effects vehicles on gradients. Speed should not fall below a required minimum specified for the given road class. This is desirable to minimize traffic congestion.

All these failure modes can be identified through representative vehicle states which are measurable. The representative vehicle states are defined as follows:

1. **Lateral Acceleration:** This can be used to identify the risk of rollover. As a safety limit a static rollover threshold can be used, which defines the level of lateral acceleration required to induce the rollover instability of the vehicle combination.

2. **Articulation Angle:** This is the difference in yaw (heading) angle between adjacent vehicle units such as a truck and trailer, or between trailers. It can be used to identify the jack-knife failure mode occurring at speeds above 40 km/h when reaching given articulation angle limit.
3. **Vehicle trajectories during turning:** These are employed to check if the vehicle combination is driving within dedicated space of the driving lane and not protruding into adjacent lanes. Hence the positions of the edges determining the outer vehicle contours with respect to lane boundaries are considered as representative vehicle state. The minimum distance of the extremities to the lane limits over time are analysed. If the minimum distance between the position of the extremities and the lane limit position reaches zero or goes negative, the vehicle may be claimed intrude the adjacent lane.
4. **Longitudinal Velocity:** This is used to analyse the ability of the vehicle to maintain its speed on an upgrade. If the difference between the nominal required velocity and the actual one is greater than defined threshold, the vehicle does not have enough traction force to maintain its speed, which is considered to be a safety failure mode.

As an alternative to lateral acceleration the load transfer ratio can also be utilized. This has been already defined as a part of the recommended PBS framework, and is appropriate for the simulation-based assessment. However, SRT is more easily assessed for the infrastructure segment analysis.

A summary of the selected numerical thresholds for representative vehicle states is listed in Table 53. The values should be interpreted as a proposal. A final selection of limits may vary for each jurisdiction based on national topologies and operational conditions.

*Table 53: Key performance indicators selected for monitoring safety*

| Key Performance Indicator (KPI) | Value | Units |
|---|---|---|
| Lateral Acceleration | < Static Rollover Threshold of vehicle (3.5-4) | ($m/s^2$) |
| Articulation angle | < 30 (for high speeds above 40 km/h) | (deg) |
| Distance of outermost points to lane boundary | >0 | (m) |
| Minimum Longitudinal Velocity | 30 | (km/h) |

## 7.6. Determination of road classes

In this sub-section, the properties of the infrastructure segments are quantified, including the critical ones, to ensure a proper match between the vehicle and the road class during nominal operating conditions. Thus, the impact of varying friction, loading conditions or cross slope are not considered at this stage.

### 7.6.1. Highway exits

To determine the range of exit radii, data from the representative infrastructure catalogue was used in combination with a desktop survey based mainly Google maps data for Netherlands, Germany and Sweden. The radii of these exits were found range between 40 m and 150 m. Due to the geometries of the trucks in the representative fleet, some of the larger vehicles may not be able negotiate an exit at certain radii. To get a baseline range of radii for the different road levels, the longest vehicle from each group, given in Table 54, was selected.

*Table 54: Longest vehicles per group of representative fleet*

| | |
|---|---|
| 1.2 | TR6x2-ST3 (2x7.8m) |
| 2.1 | TK6x2-CT2 (2x7.8m) |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) |

| | |
|---|---|
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) |

These vehicles were simulated for all radii of curvature, to analyse whether departure from the lane occurred at a given road level. The road class was primarily defined by the width of the driving lane which ranges between 2.75 m, 3.25 m, 3.5 m, for road access Levels 1, 2, 3, respectively. Road access Level 0 was not considered here. The results are given in Table 55.

*Table 55: Road classification based on road exits*

| Road Level | Road Description | Lane Width (straight Road) | Lane Width (in Exit) | Radius of Exit | Vehicle Group Permitted |
|---|---|---|---|---|---|
| 3 | Motorways | 3.5 m | (3.5+50/R) m | 70m – 150 m | 1,2,3,4,5,6 |
| 2 | Inter Urban Arterial Main/Express Roads | 3.25 m | (3.25+50/R) m | 40m – 150 m | 1,2,3,4 |
| 1 | General Access | 2.75 m | (2.75+50/R) m | 40m – 150 m | 1,2 |

### 7.6.2. Single lane roundabouts (outer radius<30m):

The boundary limits of roundabout dimensions including the inner and outer radius are necessary to determine for each road class to guarantee the vehicle combinations are capable of safe operation. To obtain representative data, vehicles with the maximum swept path width (LSSP) identified in the PBS simulations, were selected. This is summarised in Table 56.

*Table 56: Vehicle Selected for Roundabout Simulation (highest LSSP)*

| | |
|---|---|
| 1.2 | TR6x2-ST3 (2x7.8m) |
| 2.1 | TK6x2-CT2 (2x7.8m) |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) |

Roundabout dimensions were defined according to the representative infrastructure catalogue [59]. This document provided values for outer radii up to 18 m. The remaining values were extrapolated using a polynomial fit until an outer radius approached 30 m.

Vehicles were simulated for 20 different dimensions of roundabouts, listed in Appendix J, and the maximum width of the vehicle swept path in the roundabout was determined. This was then compared to the available space in the roundabout to check if the vehicle could safely negotiate the roundabout. The width of the lane is depicted in Figure 64(a) by the red line, and the remaining coloured lines describe the maximum width of swept path at different values of outer radius. The black lines, solid and dashed, represent the limits for the vehicles 5.3 and 6.1 to stay within the available space of the roundabout, where the lower one is also used as the entry to Table 57.

Moreover, it can be seen from the figure that vehicles from groups 1-4 have sufficient space to negotiate the roundabout at all values of outer radius of a single lane roundabout, as the maximum width of the swept path is always less than the width of the circular carriageway. Therefore, vehicles from groups 1-4 can operate on all single lane roundabouts which comply with the dimensions stated Appendix J. The smallest roundabout dimensions were used to populate Table 57. An example of failure for vehicle 6.1 is depicted in Figure 64 (b). A summary is given in Table 57.

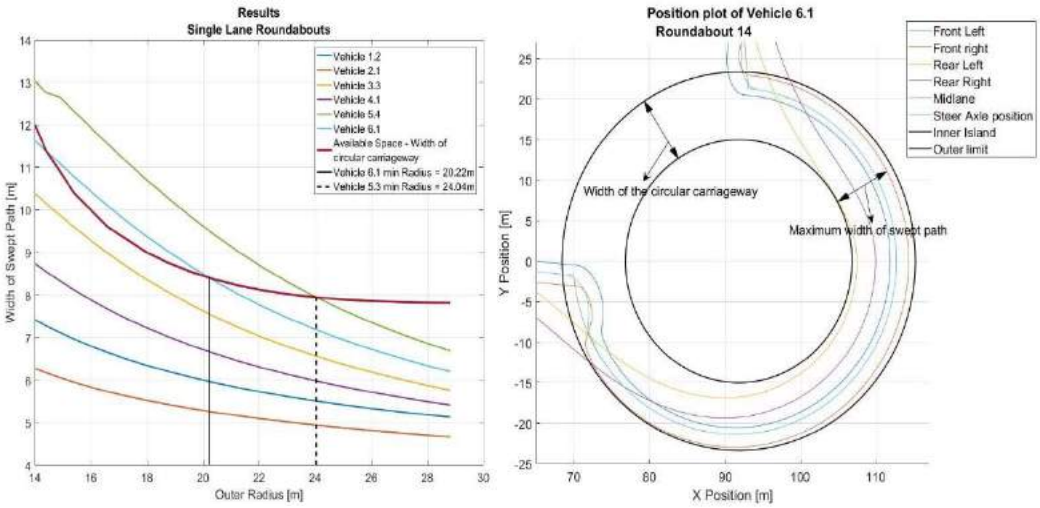



*Figure 64: (a) results single lane roundabout, (b) example of failing vehicle 6.1*

*Table 57: Summary of road classification based on exits and single lane roundabout*

| Road Level | Road Description | Minimum Radius of Single Lane Roundabout | | Vehicle Group Permitted |
|---|---|---|---|---|
| | | Outer | Inner | |
| 3 | Motorways | 24.9 m | 17 m | 1,2,3,4,5,6 |
| 2 | Inter Urban Arterial Main/Express Roads | 14 m | 2 m | 1,2,3,4 |
| 1 | General access | 12.5 m | 5.3 m | 1,2 |

### 7.6.3. Multi lane roundabouts (outer radius 50>R≥30m)

Multi lane roundabouts were assessed in a similar manner to the single lane roundabouts. The only difference is in the dimensions of the inner circle which determine the available turning space, and which are governed by the relation $R_{in}=R_{out}-(w+50/R_{out})$. Here w designates the width of the land, and $R_{out}$ is the radius of the outer roundabout boundary. The selected vehicles from the representative fleet are unchanged. Details on the dimensions of multi lane roundabouts are given in Appendix J.

Vehicles were simulated for all sizes of roundabouts ($R_{out}$ <30, 50>) and the maximum width of the vehicle swept path in the roundabout was calculated. The maximum speed was 30 km/h. The results of the simulations are given in Figure 65. Vehicle combinations from groups 1-4 have sufficient space to negotiate all roundabouts of outer radiuses ($R_{out}$ <30, 50>), and the maximum swept path width is always less than the width available circular carriageway. Hence, while considering multi lane roundabouts of $R_{out}$ >30 m, the access criteria for vehicles of group 1-4, is given by the smallest roundabout width.

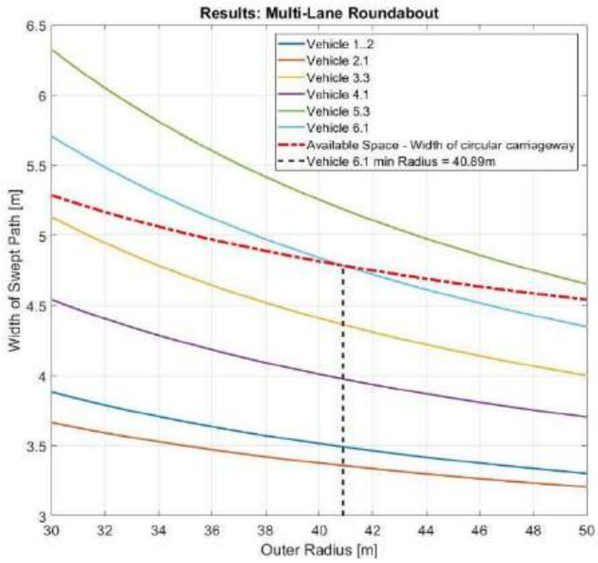



*Figure 65: Multi lane roundabouts results*

The group 5 vehicle could not negotiate the roundabouts at any values of outer radius, as the maximum width of the swept path is greater than the amount of space available. Likewise, the group 6 vehicle could not negotiate the roundabouts at lower values of outer radius, but for radii above 41 m the vehicle meets the requirements.

Considering the poor performance of vehicles from groups 5 and 6, it is seen as undesirable to allow such vehicles on any multilane roundabouts. The proposed road levels are shown in Table 58.

*Table 58: Summary of road classification based on exits and multilane lane roundabout*

| Road Level | Road Description | Minimum Radius of Multi Lane Roundabout | | Vehicle Group Permitted |
|---|---|---|---|---|
| | | Outer | Inner | |
| 3 | Motorways | Multi Lane roundabouts not permitted | | - |
| 2 | Inter Urban Arterial Main/Express Roads | 30 m | 24.7 m | 1,2,3,4 |
| 1 | General Access | 30 m | 24.7 m | 1,2 |

## 7.6.4. Longitudinal road slope

To set limits on the uphill gradient for each road level, the group of representative vehicles from the previous section were simulated while driving on a road with road grade varying from 1% - 25%, and the maximum velocity after 700 m was recorded. A minimum limit of 30 km/h was established as the threshold. The results are shown in Figure 66.

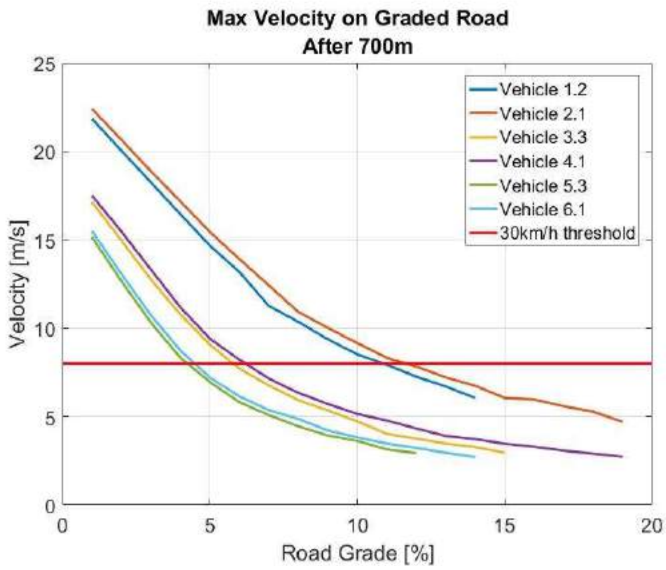



*Figure 66: Maximum achieved velocity at varying longitudinal slope*

Based on the simulation results, the maximum road grade was identified at which each vehicle can reach 30km/h. The results are summarised in Table 59, along with the results from the previous sections.

*Table 59: Final road classification proposal*

| Road Level | Road Description | Lane Width (straight Road) | Lane Width (in Exit) | Radius of Exit | Longitudinal slope | Minimum Radius of Single Lane Roundabout | | Minimum Radius of Multi Lane Roundabout | | Proposed Vehicle Group Permitted |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Outer | Inner | Outer | Inner | |
| 3 | Motorways | 3.5m | (3.5+50/R) m | 70m – 150m | ±4% | 25m | 17m | Multi Lane roundabouts not permitted | | 1,2,3,4,5,6 |
| 2 | Inter Urban Arterial Main/Express Roads | 3.25m | (3.25+50/R) m | 40m – 150m | ±6% | 14m | 2m | 30m | 24.7m | 1,2,3,4 |
| 1 | General Access | 2.75m | (2.75+50/R) m | 40m – 150m | ±10% | 12.5m | 5.3m | 30m | 24.7m | 1,2 |

## 7.7. Definition of inputs for safety validation framework

Considering the pairing between the vehicle groups and the road levels defined for the nominal conditions in the previous subsections, we now propose a framework to validate vehicle operational safety during the conditions which are *not nominal*. Here emphasis is placed on the highway exits, where the variation of input parameters can be high in practice.

Two classes of relevant input parameters for the safety assessment were identified relating the infrastructure design characteristics to the operational conditions of the vehicle combinations. The infrastructure related parameters were:

- Cross slope
- Radius of curvature
- Longitudinal slope

Parameters related to the operating conditions were:

- Loading factor
- Road Friction

Hereafter, the ranges for all parameters are elaborated more in depth.

### 7.7.1. Drive lane cross slope (road banking)

Table 60 shows the drive lane cross slope in different countries within the EU as obtained from the representative infrastructure catalogue. For the straight segments, most countries have a minimum prescribed value for cross slope of 2.5%. Hence, this value was also selected as the cross slope on the straight portion of the highway exits scenario.

- For curved segments, the cross slope increases with decreasing radius of the turn.
- For values of radius below 120m the max cross slope was used.
- For radius values between 120m and 450m the cross slope varies linearly from 7% at 120m to 2.5% at 450m.
- For radius values greater than 450, the cross slope is 2.5%

*Table 60: Representative cross-slope value*

| | |
|---|---|
| Sweden | 2.5% - 5% |
| Norway | Min. 2% |
| Netherlands | 2.5% - 7% |
| Germany | Motorways: 2% - 6%<br>Country roads: 2% - 7% |
| France | 2.5% - 7% |
| UK | 2.5% - 7% |
| Belgium | Min. 2.5% |

### 7.7.2. Longitudinal slope

Table 61 shows the grades of the road in different countries within the EU. A maximum value of 8% for road grade was selected to cover all expected values for road grade. Therefore, for the safety assessment simulation input:

$$-8\% \leq Longitudinal\ slope \leq 8\%$$

The road grade will be selected using a normal distribution with mean 0 and standard deviation (σ=4) corresponding to the distribution in Figure 67. To limit the infinite possibilities of road grade between -8% and 8%, each random value of road grade selected between these limits was rounded off to the nearest integer.

*Table 61: Representative longitudinal slope values*

| | |
|---|---|
| Sweden | Main Roads: 6 - 8%<br>Minor Roads: 10% |
| Norway | 6% |
| Netherlands | Motorways: 3 - 4%<br>Main roads: 4 - 5%<br>Minor roads: 6-7% |
| Germany | Motorways: 4 - 6%<br>Country roads: 4.5 - 8% |
| France | Motorways: 5 - 6%<br>Main roads: 7%<br>Hilly main roads: 10/8% (with/out snow) |
| UK | Motorways: 3%<br>Carriageways 4-6%<br>Hilly carriageways: 8% |

| | |
|---|---|
| Belgium | 4-8% |

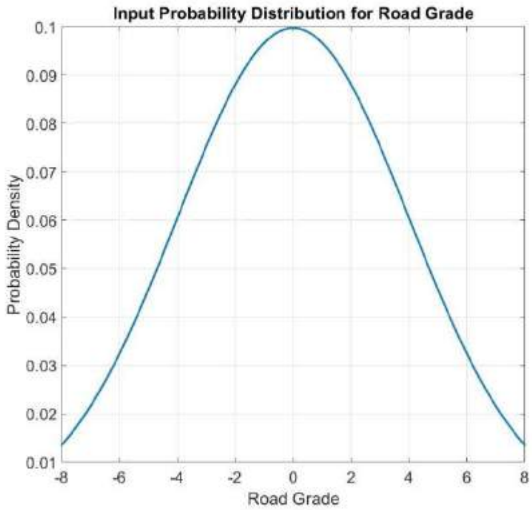



*Figure 67: Input probability distribution for road gradient*

### 7.7.3. Road radius

To set the distribution of the highway exit radiuses, the motorways in Germany and Netherlands were considered. The radii of these exits were found to lie in the range 40 m to 150 m. Radii of curvature greater than 120 m were considered a luxury exit with the highest allowed speed. Radii of curvature of around 100m are standard exits, as confirmed by infrastructure experts, and are more prevalent compared to luxury exits. Radii of curvature of above 60 m were considered to be standard exit loops with a high prevalence, especially on double-lane highways, with a prevalence similar to that of standard exits around 100 m of radius. Radii of curvature between 40 m and 50 m correspond to a minimum allowed loop. These exits are typically built when there are space constraints on the road design. Table 62 shows the probabilities of selecting values of radius of curvature together with the target speed at which the turn is negotiated.

*Table 62: Input probabilities for exit radius*

| Range of Radius (m) | Probability of Occurrence (%) | Target Speed(km/h) |
|---|---|---|
| 40 – 53 | 20 | 40 |
| 54 – 99 | 30 | 50 |
| 100 – 120 | 30 | 60 |
| 120 – 150 | 20 | 65 |

More detailed information relating to the highway exits radiuses on representative highways in Netherlands and Germany are provided in Appendix K.

### 7.7.4. Road friction

As documented in [60], the minimum allowed nominal road friction in the Netherlands is 0.42, and comparable results can be found in Germany, Norway, or Sweden. Below this value, the road authorities are obliged to either close the road or perform some friction-increasing operations such as snow ploughs or slating the road. Therefore, a minimum value of 0.8 for road friction was selected to cover all expected values for road grade. Therefore, the input for the simulation is defined as:

$$0.42 \leq Road\ Friction \leq 1$$

To quantify the distribution of the friction levels, annual precipitation in the areas were considered. Table 63 shows the average number of days with precipitation in the Netherlands over each month in the year. From this table, on average, precipitation occurs on 117 days of the year. Out of these 117 days, 33 of these days with precipitation occur during the winter months where icy conditions can occur, and 84 days of precipitation occur in the non-freezing months. Since icy conditions can prevail overnight in the winter months, the number of icy days was increased by a factor of 1.2 to account for the fact that icy conditions can continue even after the day that precipitation has occurred. Table 64 shows the probabilities for selecting the road friction. To limit the infinite possibilities of road grade between 0.42 and 1, each random value selected was be rounded off to the nearest hundredth.

*Table 63: Average number of days with precipitation in a year*

| | Jan | Feb | Mar | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Average number of days with precipitation** | 8 | 11 | 9 | 12 | 12 | 9 | 12 | 11 | 10 | 9 | 7 | 7 |

*Table 64: Input probabilities for road friction*

| Road Condition | Number of day/year | Peak Friction Level | Probability of Occurrence |
|---|---|---|---|
| Dry | 241 | 0.8 – 1 | 66% |
| Wet | 84 | 0.6 – 0.8 | 23% |
| Icy | 40 | 0.42 – 0.6 | 11% |

### 7.7.5. Load factor

As documented in [30] the average nominal load density of commercial vehicles operating in long-haul transport equates to approximately 156 kg/m$^3$. For the safety purposes the factor of 1.2 was included resulting in an average load density of 187 kg/m$^3$. The load density corresponding to the “critical” loading condition was 312.6 kg/m$^3$ (approximately double the average nominal load). Selecting 187.56 kg/m$^3$ as the mean, and 312.6 kg/m$^3$ as the upper limit delivers a lower limit of 62.52 kg/m$^3$ in a Gaussian distribution yields a standard deviation of $\sigma = 62.52$ kg/m$^3$. Figure 68 shows the probability distribution of the input Load Density.

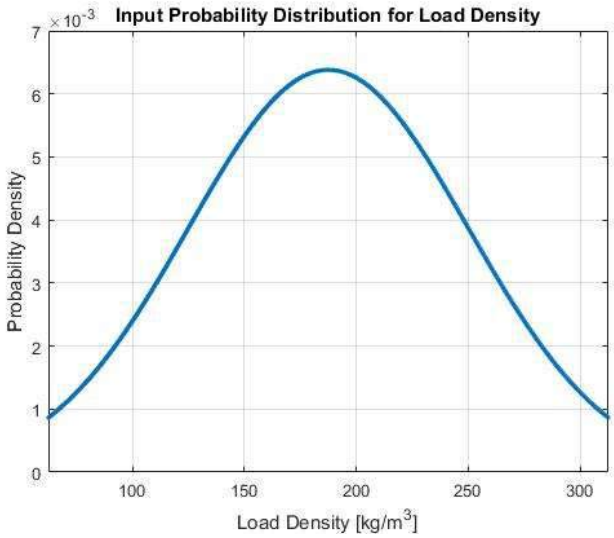



*Figure 68: Input probability distribution for load density*

## 7.8. Simulation results using Monte Carlo for highway exits

To verify the impact of the varying input parameters described in Section 7.6 on the representative vehicle states (Section 7.4), a set of Monte Carlo simulations was performed. In total, more than 1500 permutations per vehicle combination of varying input conditions were simulated according to the probability distributions. It should be emphasised that the range of inputs is bounded implicitly by the geometric limits listed in Table 59, combined with the allowable speeds for these manoeuvres. To illustrate the approach of the simulation analysis, the results for combination 5.3 are described next.

### 7.8.1. Lateral acceleration

Figure 69 shows a histogram of the accelerations achieved by vehicle combination 5.3 during varying operational conditions. At the top of the histogram, designated by the black line, is the probability distribution. Instead of a Gaussian distribution, in this case we employ a non-parametric uniform rectangular kernel function, which results in a better fit with the histogram. The use of non-parametric models may result in an “over-fitted” model that is biased by the data. In our case however, it is useful as the input data distribution does not comply reasonably with any parametric probability model distribution.

In the figure the red line designates the safety limit for roll stability in terms of lateral acceleration (m/s$^2$). Using the probability distribution, we can quantify the possibility of the vehicle combination exceeding the rollover threshold. In this case, the probability reaches 0.3%, representing 3 failures per 1000 cases.

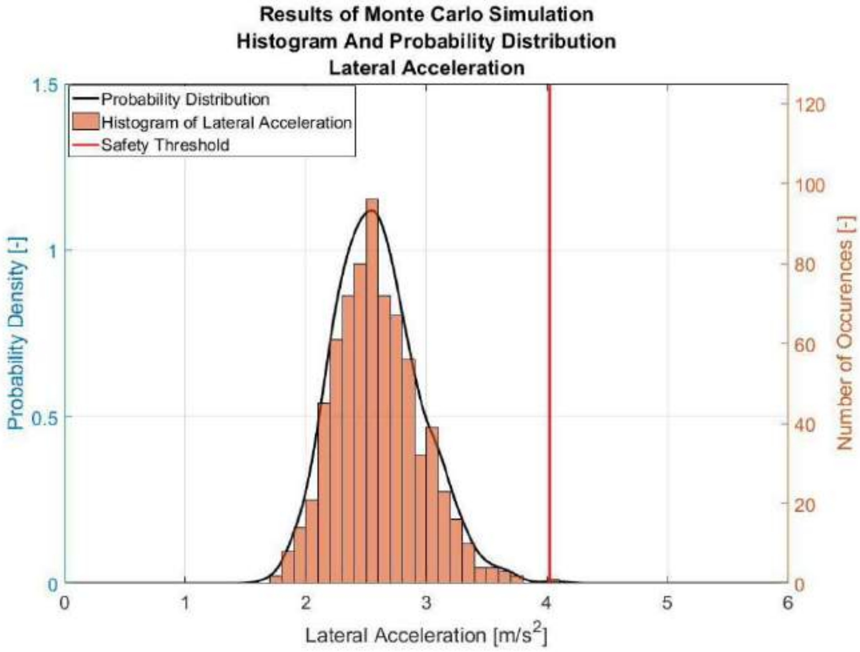



*Figure 69: Histogram lateral accelerations*

The permutations of the inputs which lead to violations of the safety limit are summarized in Table 65. It should be clarified that none of the permutations actually ended up in rollover, as the cross-slope contributes to a natural increase in the roll stability threshold. Nevertheless, all the events occurred on the radius range between 126-128 m, where the target velocity was 70km/h. To minimize the eventual risk of rollover it is recommended to reduce the allowed speed to 60km/h if the radius of curvature is smaller than 130m.

*Table 65: Input permutations leading to lateral acceleration safety limit violations*

| Serial No. | Radius (m) | Cross slope (%) | Longitudinal Slope (%) | Road Friction (-) | Load Density (kg/m³) | Lateral Acceleration (m/s²) |
|---|---|---|---|---|---|---|
| 1 | 135 | 6.79 | -4 | 0.86 | 173.84 | 4.06 |

### 7.8.2. Articulation angle

Articulation angle was used to identify instances of high-speed jack-knifing. Figure 70 shows the histogram and probability distribution of maximum articulation angles reached during the exit manoeuvre. All results were safely within the limit. Considering the probability distribution, the chance the vehicle combination exceeds this limit and jack-knifes is infinitely small in the given operational conditions. Therefore, the risk of jack-knifing for this vehicle combination does not exist and therefore there is no need to modify any of the road classes.

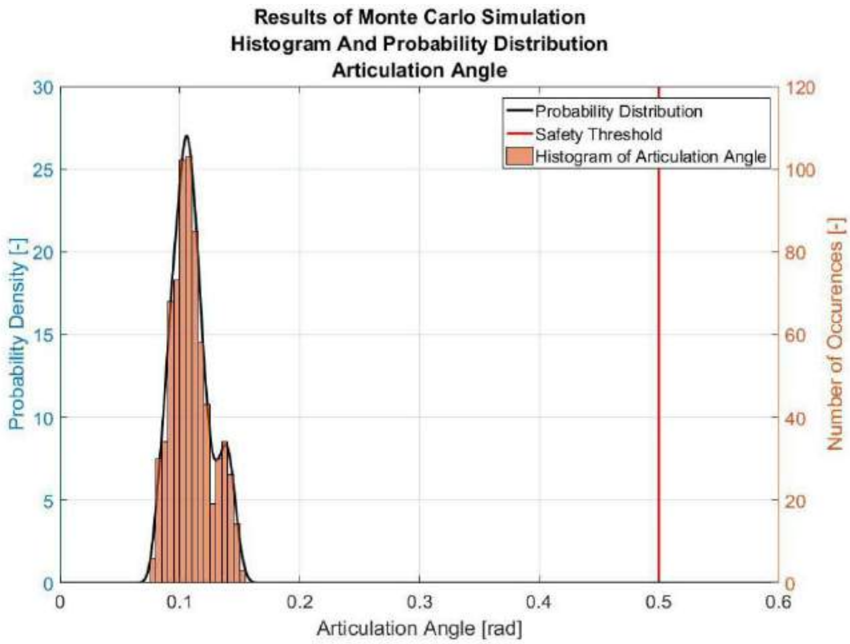



*Figure 70: Histogram of articulation angle*

### 7.8.3. Distance of outermost points to lane boundary

Figure 71 shows the probability distribution of the vehicle swept path exceeding the lane width during the highway exit manoeuvre. The results indicate no cases in which the vehicle combination would reach the limits. The probability distribution given by the black line gives a failure probability of 0.2 %, which is acceptable for Level 2 and 3 roads.

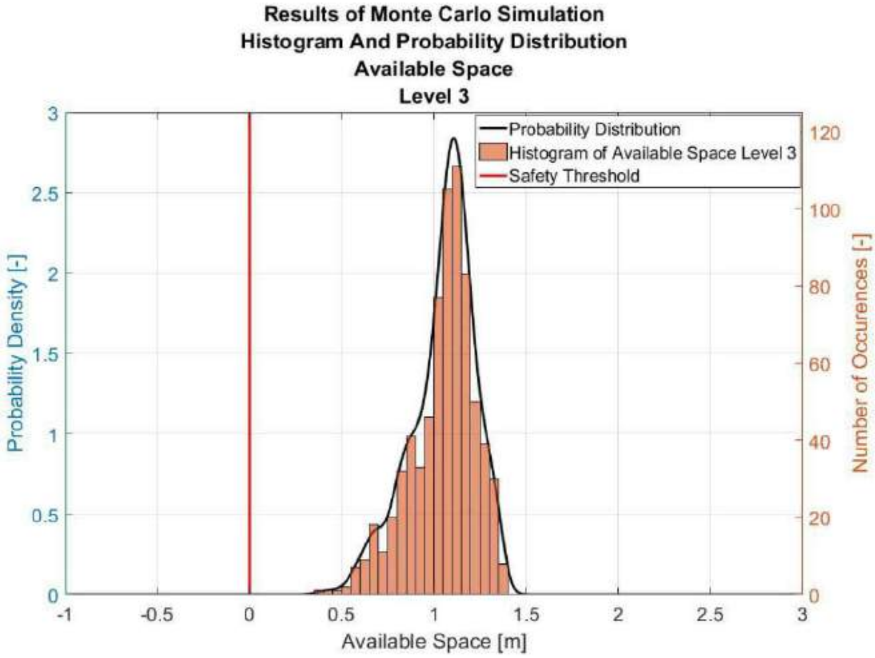



*Figure 71: Histogram of available space in the lane (not the width of the lane is dependent on the curve radius)*

### 7.8.4. Difference in longitudinal velocity

In Figure 72, the histogram of maximum velocity during the highway exit manoeuvre is shown. The failure rate calculated from the probability density function reaches 0.6%. In all identified cases listed in Table 66, the maximal achieved velocity does not significantly breach the limit of 30 km/h. Nevertheless, the correlation to the loading state can be drawn. The reduction of the maximal allowed slope would eliminate this failure.

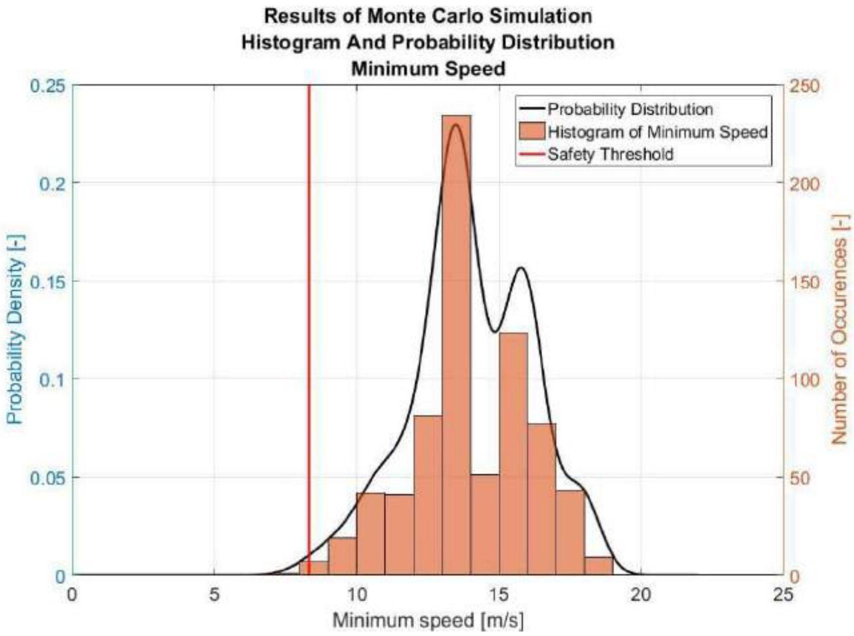



*Figure 72: Histogram of maximal achieved longitudinal velocity*

*Table 66: Permutations of input parameters leading to insufficient longitudinal velocity*

| Serial No. | Radius (m) | Cross slope (%) | Longitudinal | Road Friction (-) | Load Density (kg/m3) | Minimum Speed (km/h) |
|---|---|---|---|---|---|---|

| | | | Slope (%) | | | |
|---|---|---|---|---|---|---|
| 1 | 117 | 7 | 4 | 0.89 | 279.99 | 29.1 |
| 2 | 84 | 7 | 4 | 0.95 | 289.86 | 28.4 |

## 7.9. Summary and final road classification proposal

We have outlined a framework to match the safety of a given vehicle combination with a specific road level and have applied this process to all the vehicles from the representative fleet. The assessment resulted in the categorisation of the representative fleet combinations into three clusters consistent with the road classes defined in Table 59.

The final road classification proposal, and the categorisation of vehicles into each, is given in Table 67. It can be seen that vehicles from group 2 do not meet the very strict requirements for road access level 1 and are therefore all clustered into road access level 2. This is mainly due to the limits on off-tracking which were exceeded. Similarly, combinations 4.5 and 4.6 are restricted to road access level 3. Vehicle combinations 4.1, 4.2, and 3.3 do not meet the requirements for road access level 2, limited by longitudinal slope, where the limit is currently set to ±6%. However, it should be noted that by reducing the road longitudinal slope to ±5% the limits would be satisfied. Detailed results of the simulations may be found in Appendix K.

*Table 67: Final road classifications proposal*

| Road Level | Road Description | Lane Width (straight Road) | Lane Width (in Exit) | Radius of Exit | Long. slope | Minimum Radius of Single Lane Roundabout | | Minimum Radius of Multi Lane Roundabout | | Vehicles Permitted |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Outer | Inner | Outer | Inner | |
| 3 | Motorways | 3.5m | (3.5+50/R) m | 70m – 150m | ±4% | 25m | 17m | Multi Lane roundabouts not permitted | | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 5.1, 5.2, 5.3, 5.4, 6.1, 6.2, 6.3, 6.4, 6.5 |
| 2 | Inter Urban Arterial Main Express Roads | 3.25m | (3.25+50/R) m | 40m – 150m | ±6% | 14m | 2m | 30m | 24.7m | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.4, 4.3, 4.4, 4.7 |
| 1 | General Access | 2.75m | (2.75+50/R) m | 50m – 150m | ±10% | 12.5m | 5.3m | 30m | 24.7m | 1.1, 1.2, 1.3, 1.4 |

## 7.10. Conclusions and recommendations

In this section, we outlined a generic approach to establish a match between the road characteristics and the vehicle combination through the safety assessment considering three aspects: representative vehicle states, critical infrastructure segments and varying operational conditions. All three aspects in general, can be further expanded, if NRA's will consider the necessity or the operational conditions are going beyond the scope of FALCON.

With this approach a probability of failure can be identified and if reaching the excessive values, the operational conditions per vehicle can be adjusted accordingly to meet the required safety targets. From the simulation results the most frequent failure mode is the off-tracking of the rear most vehicle, which may collide with lane boundaries during some of the scenarios described above. The same reason also leads to excluding multilane roundabouts from the roads of level 3, dedicated for long vehicle combinations in groups 5 and 6. On the contrary, both lateral and roll instability limits were not exceeded, proving that these safety criteria are not compromised even though the length of the vehicle combinations from groups 3-6 considerably exceeds limits imposed by currently valid European directive 96/53.

An illustrative example of the road satisfying the criteria of the level 2 and having good multi-modal potential is given in Appendix L.

# 8. Final PBS/SIAP Framework Proposal

## 8.1. Summary of proposed PBS framework

The final proposed outline of the PBS framework is presented in Table 68. The table contains the list of performance standards which were evaluated in the course of this study, the final recommendations for their inclusion/exclusion, and recommendations for how their pass/fail criteria should be reviewed for application to Europe. Specific details of the proposed methods for assessing bridge and road wear impact are given in Sections 8.2 and 8.3.

It is proposed that a road access level categorisation be used, based loosely on the Australian system but with road access levels 0-3. Level 0 only exists as a proposal at this stage for vehicles accessing city centres for applications such as garbage collection or home delivery and will require further investigation. This will likely consist of rigid vehicles, and possibly highly optimised steered tractor semi-trailer combinations. The road classification system is summarised in Table 69. The proposed categorisation of the vehicle combinations in the representative fleet has been included in the table. Note that this is a specific road classification proposal based on the infrastructure segments considered in this report, but the classification may differ according to the jurisdiction under consideration. The methodology employed in Section 7 should be employed for different jurisdictions.

*Table 68: Final recommendations for a proposed PBS framework for Europe*

| Performance Standard | Include? | Recommendations |
|---|---|---|
| Driveability | | |
| Startability | Y | Consider reducing L1 to 12%. Allow jurisdictions to review criteria based on local road grades. |
| Gradeability A (Maintain motion) | Y | Consider reducing criteria in accordance with adjustments on startability. Allow jurisdictions to define limits on local conditions. |
| Gradeability B (Maintain speed) | Y | Appropriate as is (aligned to speed limits). |
| Acceleration Capability | Y | Review criteria. Allow jurisdictions to review the criteria based on local intersection and crossing geometries. |
| Manoeuvrability | | |
| Low-Speed Swept Path | Y | Criteria too lenient – review against existing European road geometries and roundabout standards. |
| Frontal Swing | Y | Criterion can possibly be reduced to 0.5 m for all levels, based on the fleet assessed. However there is no documented need to reduce the limit below the current 0.7 m. |
| Difference of Maxima | (review) | Potentially too complicated, and not aligned with direct safety risk. Could be removed or replaced with a single standard. Requires further investigation. |
| Maximum of Difference | (review) | |
| Tail Swing | Y | Criteria can possibly be reduced to 0.3 m for all levels (subject to further investigation). Car-carriers should be included in further investigations. |
| Steer-Tyre Friction Demand | Y | The ≤ 80% requirement is possibly too high and should be reviewed. |
| EU turning circle | Y (L1) | Applicable as an additional test for Level 1-type vehicles. |
| Netherlands turning circle | N | Found to offer no additional information vs. LSSP, while requiring multiple different manoeuvres to assess longer vehicle combinations. |
| High-speed stability | | |
| Static Rollover Threshold | Y | Applicable as is. |
| Rearward Amplification (last trailer) | Y | Criterion of 2 requires further review, as appropriate to the rear trailer method, and once the vehicle designs have been optimised further. |
| Rearward Amplification (RRCU) | N | Last trailer method preferable, as the standard has been decoupled from assessing direct rollover risk. |

| | | |
|---|---|---|
| Dynamic Load Transfer Ratio | Y | A better indication of rear trailer rollover risk in transient manoeuvres. The criterion of 0.6 may require review in parallel with RA=2. |
| High-Speed Transient Off-tracking | Y | Vehicle and lane widths are similar to Australia and so the criteria may be transferable, but Level 1 vehicles may use minor roads of width 2.5 or 2. 75 m. This requires further investigation. |
| Yaw Damping Coefficient | Y | Applicable as is. |
| Tracking Ability on a Straight Path | N | Found to be highly correlated with HSTO, and prone to simulation error due to complexity. |
| High-Speed Steady-State Off-tracking | N | Found to be highly correlated with vehicle length, but also influenced by vehicle mass. Can be used to inform vehicle length limits per road access level, however for very heavy vehicles (i.e. higher than the loading conditions considered in this study), the influence of mass may become a limiting factor. |
| Winter conditions | | |
| Low friction braking | Y | The faultless function of ABS system is necessary for braking stability of HCVs in winter. |
| Steer-Tyre Friction Demand | N | Shown to be correlated with high friction performance for the fleet considered. High friction criteria could be set accordingly to ensure low friction performance.[2] |
| Drive-Tyre Friction Demand | N | Correlated with high friction performance, and found to be less meaningful than steer tyre friction demand, due to the dissimilar direction of the forces in a two-axle drive bogie.. High friction criteria could be set accordingly to ensure low friction performance. |
| Low friction startability | N | Temporary drive axle load proportioning should be permitted to increase drive axle loads as required for starting. |
| Low friction high-speed standards | N | A speed reduction to 60 km/h was found to ensure comparable performance to high friction conditions. |
| Infrastructure | | |
| Bridge-loading | Y | See methodology below (Section 8.2) |
| Road wear impact | Y | See methodology below (Section 8.3) |

*Table 69: Final road classifications proposal*

| Road access level | Description | Vehicles permitted |
|---|---|---|
| 0 | City access | TBC (not considered in this study) |
| 1 | Minor Roads | 1.1, 1.2, 1.3, 1.4 |
| 2 | Inter Urban Arterial Main Express Roads | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.4, 4.3, 4.4, 4.7 |
| 3 | Motorways | 1.1, 1.2, 1.3, 1.4, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 5.1, 5.2, 5.3, 5.4, 6.1, 6.2, 6.3, 6.4, 6.5 |

## 8.2. Bridge loading effects

In order to better regulate traffic load effects on bridges (for bridges in good condition), two approaches exist and should be combined:

1. to develop a bridge formula, and

[2] For the most accurate results, friction demand should be simulated in winter conditions. However, if it is practical to perform all simulations in summer conditions without the need for winter-specific models, then correlation between summer and winter performance can be investigated (as done here) for the specific fleet under concern, and used to set a safe performance level to ensure both summer and winter performance.

2. to determine thresholds on Effect values induced by design load models which must not be exceeded by heavy vehicles and their combinations within the traffic.

### 8.2.1. Development of a bridge formula

The proposed method for the assessment of bridge loading effects focusses on the development of a deterministic “bridge formula” (a probabilistic bridge formula would need to consider the uncertainties of structure/materials and of actions/loads through for example reliability calculations). In this case, the permitted vehicle, axle and axle group loads should have the shape $W = f(L, N)$, where $L$ is the length between the first and last axles in the group being considered, and $N$ is the number of axles. The proposed method for determining a suitable bridge formula is then as follows:

1. Create a representative set of vehicles (as done), structures and structural effects that represent that which currently exists in Europe.
2. Calculate the effects of all vehicles on all structures against all structural effects. From this, define a suitable limit for each effect, taking into account, for example, the fractions of the effects of the load model, a fractile of the effects of the vehicles or depending on the acceptability (or not) of given vehicles.
3. For each structural effect, the outcome would be a limit that should not be exceeded. A bridge formula can be fitted as follows:

A first solution may be a linear fit for equation $W = f(L, N)$ as follows: $W = a_0 L \times N + a_1 L + a_2 N + a_3$, where $a_0, a_1, a_2, a_3$ are constant numerical values. This equation must fit the envelope of effects for each vehicle, axle and group of axles. Another option would be to fit higher order equations to the envelope of the most aggressive effect. To do that, the degree of the fitted curve can be fixed *a priori* as the highest degree of the influence lines, given that the effect is linked to the influence line which is a polynomial function of given order. For example, for a single span structure, the polynomial is linear with respect to shear force, and of degree two for bending moments.

### 8.2.2. Threshold of Effect values

As has been done in countries such as South Africa, a threshold on Effects induced by traffic may be stated as part of the regulatory framework. This threshold is then applicable to all types of traffic, meaning “usual” vehicles and their combinations within traffic and special permit vehicles. In order to achieve that, the following successive steps have to be taken:

1. Define a representative bridge catalogue (as done in FALCON task 3.2 [6]),
2. For each of the structures within the catalogue, define the weakest design criteria in Europe. This work was started in FALCON task 3.4 [27].
3. Calculate the Effects induced by these weakest design criteria.
4. Compare these Effects with the same Effect induced by all vehicles and their combinations and decide on a safety margin between these values.

## 8.3. Road wear impact

The following procedure is proposed for assessing a given vehicle combination for inclusion in a European PBS framework:

1. Use combination 2.1 loaded to 40 tonnes (the legal limit in EU) as the reference case.
2. For each individual country, select representative road structures (~three) from those present in the country (as the road structures differ significantly between countries).
3. Compute the aggressiveness of combination 2.1 on each of these road structures and consider this to be the upper limit of permitted aggressiveness for new vehicles.
4. For each road access level throughout Europe, these computations allow the determination of a threshold on aggressiveness by considering the “worst case” amongst the roads with that access level.

5. Assess the aggressiveness of the proposed vehicle against the thresholds for the different road access levels.

The computations can be done by the local road regulator, which will be best placed for selecting the most representative road structures. The computations can also be done with the design tools and software that are currently in use on a local (national or regional) level. The definition of *aggressiveness* must be fixed, *i.e.* whether it is based on a vehicle or axle group level, or whether the aggressiveness is scaled by payload volume etc. A measure scaled by volume will be the most representative of the net impact of the overall freight task. This will require coordination between the road authorities in Europe.

### 8.4. Supporting framework

It is proposed that a European PBS framework should adopt a set of supporting frameworks such as those that have been put in place in Australia and South Africa. These include systems that ensure adequate driver training, speed monitoring, vehicle maintenance, loading control, and vehicle tracking (to ensure compliance with approved routes). Such systems are crucial for the long-term sustainability and impact of a PBS framework. Reference should be made to the Australian Intelligent Access Programme (IAP) and National Heavy Vehicle Accreditation Scheme (NHVAS) [7], and the South African Road Transport Management System (RTMS) [8]. Any existing equivalent systems in Europe should be used where possible.

### 8.5. Guidelines for implementation

As a guideline for the implementation of PBS in Europe, the implementation of PBS in other countries including Canada, Australia, Sweden and South Africa, as covered in Section 1.2, should be reviewed. South Africa has followed most closely the implementation recommended in this report, in that the Australian PBS framework has been used as a starting point, and local conditions have been used to refine and adapt is as applicable to the South African context. Local variations in existing legislation, geography, and truck designs have, over time, moulded the system for the country.

However, Europe presents distinct differences in climate, geography, road infrastructure and existing vehicle designs to both Australia and South Africa. In this case, the PBS experience in Canada and Sweden will give additional insights with specific applicability to Europe. European-specific considerations also include a large emphasis on intermodality, existing conventional vehicles with notably smaller weights and dimensions than conventional vehicles in South Africa and Australia (due to respectively different legislation), and low friction conditions. All of these existing PBS experiences present useful blueprints for the European initiative to build on. Furthermore, the process through which PBS has been implemented in these cases provides guidelines for implementation in Europe, including conducting pre-emptive research projects to assess regional relevance (such as in project FALCON), isolated pilot programmes, and data collection and monitoring programmes to garner political support.

In Europe, heavy goods vehicles, buses and coaches must comply with the weights and dimensions requirements of Directive (EU) 2015/719, which amends Directive 96/53/EC. This gives the maximum weights and dimensions for international traffic and ensures that EU Member States cannot restrict the circulation of vehicles which comply with these limits from performing international transport operations within their territories. Moreover, national regulations cannot be more restrictive than the Directive 96/53/EC. In fact, they are often more permissive, as evidenced by the European Modular Systems in Sweden and Netherlands, the longer trucks (25.25 meters) in Germany, and the 13-ton axle weight limit in France. The Directive also aims to avoid instances of national operators benefitting from advantages over their competitors from other Member States when performing national transport.

The recently ratified Directive (EU) 2015/719 gives indications of forward-thinking relaxations of length and weight limits where vehicles demonstrate elements of sustainability, including:

- Derogations on weights are allowed for vehicles powered by alternative fuels: for example, an extra tonne is allowed on the gross vehicle weight (GVW) of a rigid truck for alternative fuel technology, engines, batteries or any other related components.
- Derogations on the maximal lengths to make heavy goods vehicles greener by improving their aerodynamic performance.
- Higher lengths allowances to enable the addition of new safety features in extra space in the driver cabin.

The existing European Modular System, in which vehicles may be up to 25.25 m for cross-border transport, is in itself evidence of a move towards high capacity vehicles, and it is within such a cross-border framework which PBS may be best implemented. These indicate that European PBS may be best implemented through a cross-border exemption system similar to EMS, or possibly could even be adopted as an upcoming revision and extension of the EMS scheme. Alternatively, or in addition, it may be incorporated as future amendments to Directive 96/53/EC, along the lines of Directive 2015/719.

# 9. Final Conclusions and Recommendations

1. The FALCON project has set out to contribute to the reduction of carbon emissions in European road freight transport. A Performance-Based Standards framework has been proposed and investigated for this purpose.
2. A representative fleet of European vehicle combinations was defined and simulated against a wide range of potential performance standards. Findings from these results were used to guide the choice of applicable European performance standards.
3. The proposed framework is based largely around the Australian PBS scheme, with modifications and additions addressing performance of the representative fleet, existing European regulations, regional icy conditions, and European-specific approaches to infrastructure protection.
4. A list of recommended performance measures has been proposed for inclusion in a European PBS programme, and recommendations have been given for how the pass/fail criteria for each should be reviewed for European conditions. It is recommended that criteria for certain standards such as Startability, Gradeability A, and Low-speed sept path be reviewed on an individual jurisdiction level.
5. Methodologies for assessing the impact of HCVs on roads and bridges have been proposed. Individual jurisdictions will need to review these methodologies, and tailor them as required for local conditions.
6. A four-level road access level classification system has been proposed, including Level 0 (city transport), Level 1 (existing truck routes, minor roads), Level 2 (inter urban arterial main express roads) and Level 3 (motorways). This can serve as a basis for individual jurisdictions to set their own performance criteria based on vehicle category, as appropriate for local conditions. A methodology which jurisdictions can follow to set appropriate limits and criteria for each road access level has been discussed.
7. In the next and last stage of the FALCON project, the proposed PBS framework will be validated against its impact on modal split, road damage, and congestion.
8. Guidelines for implementation have been provided, by giving examples of the implementation of PBS in other jurisdictions and highlighting the scope within EU Directive 2015/719 which lays the groundwork for incorporating high capacity vehicle developments in future.

## 10. Final event feedback and evaluation

The FALCON research project has been concluded with a final event which took a place on 12-13.12.2018 at Arnhem. The event was visited by more than 30 delegates representing national road authorities, research organizations, OEM's, and academia. The format of the event was a balanced mixture of practical case studies, lessons learned, conclusions and recommendations and discussion panels. The aim of the event was to disseminate the results achieved in the research program and define the next steps how the results can be exploited and implemented by CEDR members. This section summarizes these findings and conclusions as follows:

- Established concept of Smart Infrastructure Access Policy should be implemented to the H2020|AEROFLEX project and used as a reference model for the future legislative framework
- The results should be disseminated also on EU level. Hence, a workshop together with ACEA for DG Move/Grow/Clima should be organized.
- There has been common agreement that pilot projects adopting SIAP on national level are desirable. Example should be based on 'best practices' such as done in Sweden.
- Emphasis should be given to communicate clearly with road authorities what is meant with the road categorization as this principle is in EU quite unknown.
- Develop and certify open-access tools enabling SIAP implementation on multi-national basis (vehicle and infrastructure assessment)
- Development of enforcement programs for SIAP is crucial (enabling geofencing, driver training, road classification, vehicle and loading state tracking…)
- Many of vehicle units need to be optimized w.r.t dimensions as they were not primarily developed to be used for in HCV combination
- Given the big variation of the pavement design rules in EU, the interaction of HCV with the pavement should be investigated in more jurisdictions w.r.t. 96/53/EC vehicle combinations
- Develop a bridge formula that will be valid for EU
- Proposed SIAP may be in the future expanded towards hybrid and distributed powertrains which are expected to be widely introduced in the future.

## 11. References

[1] National Transport Commission, “Performance based standards scheme – The standards and vehicle assessment rules,” Melbourne, 2008.

[2] European Council, *Directive 97/27/EC of 22 July 1997 on the masses and dimensions of certain categories of motor vehicles and their trailers*. European Parliament, Council of the European Union, 1997, pp. 1–31.

[3] Netherlands Vehicle Authority (RDW), “Beleidsregel ontheffing gerelateerde voertuigdocumenten (JBZ 2013/ 9832).” 2013.

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# Appendix A *Vehicle Modelling Parameters*

*Table 70: Vehicle parameters, vehicle configuration and payloads*

| Vehicle | Vehicle description | Drivetrain option | Vehicle configuration | | | | Payload | | | | Payload location (rearwards from hitch/steer axle to front of container) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 1 | Unit 2 | Unit 3 | Unit 4 |
| Group 1 | | | | | | | | | | | | | | |
| 1.1 | TR6x2-ST3 (45ft) | 400 hp 4x2/6x2 | TR6x2 | ST3 45ft | - | - | - | 45' ISO | | | - | -1.999 | | |
| 1.2 | TR6x2-ST3 (2x7.8m) | 400 hp 4x2/6x2 | TR6x2 | ST3/s3 2x7.8 | - | - | - | 2 x C782 | | | - | -1.668 | | |
| 1.3 | TR4x2-ST3 (13.6m) | 400 hp 4x2/6x2 | TR4x2 | ST3 13.6 | - | - | - | 13.6 m | | | - | -1.668 | | |
| 1.4 | TR4x2-ST3 (14.9m) | 400 hp 4x2/6x2 | TR4x2 | ST3 14.92 | - | - | - | 14.92 m | | | - | -1.668 | | |
| Group 2 | | | | | | | | | | | | | | |
| 2.1 | TK6x2-CT2 (2x7.8m) | 400 hp 4x2/6x2 | TK6x2 | CT2 | - | - | C782 | C782 | | | 0.925 | 2.25 | | |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 400 hp 4x2/6x2 | TK6x2 | FT1+1 | - | - | C782 | C782 | | | 0.925 | -1.06 | | |
| 2.3 | TK6x2-CT3(2x20ft) | 400 hp 4x2/6x2 | TK6x2 | CT3 | - | - | 20' ISO | 20' ISO | | | 2.681 | 2.07 | | |
| Group 3 | | | | | | | | | | | | | | |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 440 hp 6x4 | TR6x4 | ST3 45ft | CT3 | - | - | 45' ISO | 20' ISO | | - | -1.999 | 2.07 | |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 440 hp 6x4 | TR6x4 | ST3/s3 2x7.8 | CT2 | - | - | 2 x C782 | C782 | | - | -1.668 | 2.25 | |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 440 hp 6x4 | TR6x4 | LT2 | ST3/s3 2x7.8 | - | - | C782 | 2 x C782 | | - | -1.57 | -1.668 | |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 440 hp 6x4 | TR6x4 | LT3 | ST3 45ft | - | - | 20' ISO | 45' ISO | | - | -1.31 | -1.999 | |
| Group 4 | | | | | | | | | | | | | | |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 440 hp 6x4 | TK6x4 | DY2 | ST3/s3 2x7.8 | - | C782 | - | 2 x C782 | | 0.975 | - | -1.668 | |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 440 hp 6x4 | TK6x4 | FT2+3/s3 2x7.8 | - | - | C782 | 2 x C782 | | | 0.975 | -1.668 | | |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 440 hp 6x4 | TK6x4 | DY2 | ST3 45ft | - | 20' ISO | - | 45' ISO | | 2.731 | - | -1.999 | |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 440 hp 6x4 | TK6x4 | FT2+3 | - | - | 20' ISO | 45' ISO | | | 2.731 | -1.49 | | |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 440 hp 6x4 | TK6x4 | CT2 | CT2 | - | C782 | C782 | C782 | | 0.975 | 2.69 | 2.69 | |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 440 hp 6x4 | TK8x4 SWB | CT3 | CT3 | - | 20' ISO | 20' ISO | 20' ISO | | 1.671 | 2.07 | 2.07 | |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 440 hp 6x4 | TK8x4 SWB | FT2+3 | - | - | 20' ISO | 45' ISO | | | 1.671 | -1.49 | | |
| Group 5 | | | | | | | | | | | | | | |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 480 hp 6x4 | TR6x4 | ST3 45ft | DY2 | ST3 45ft | - | 45' ISO | - | 45' ISO | - | -1.999 | - | -1.999 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 480 hp 6x4 | TR6x4 | ST3 45ft | FT2+3 45ft | - | - | 45' ISO | 45' ISO | | - | -1.999 | -1.49 | |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 480 hp 6x4 | TR6x4 | LT2 | LT2 | ST3/s3 2x7.8 | - | C782 | C782 | 2 x C782 | - | -1.57 | -1.57 | -1.668 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 480 hp 6x4 | TR6x4 | LT3 | LT3 | ST3 45ft | - | 20' ISO | 20' ISO | 45' ISO | - | -1.31 | -1.31 | -1.999 |
| Group 6 | | | | | | | | | | | | | | |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 480 hp 6x4 | TK6x4 | DY2/s1 | LT2 | ST3/s3 2x7.8 | C782 | - | C782 | 2 x C782 | 0.975 | - | -1.57 | -1.668 |
| 6.2 | TK6x4-DY2-LT2-ST3 (2x7.8m+45ft) | 480 hp 6x4 | TK6x4 | DY2/s1 | LT3 | ST3 45ft | 20' ISO | - | 20' ISO | 45' ISO | 2.731 | - | -1.31 | -1.999 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 480 hp 6x4 | TK6x4 | CT2 | CT2 | CT2 | C782 | C782 | C782 | C782 | 0.975 | 2.69 | 2.69 | 2.69 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 480 hp 6x4 | TK8x4 LWB | DY2 | LT2 | ST3/s3 2x7.8 | C782 | - | C782 | 2 x C782 | 1 | - | -1.57 | -1.668 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 480 hp 6x4 | TK8x4 SWB | DY2 | LT3 | ST3 45ft | 20' ISO | - | 20' ISO | 45' ISO | 1.671 | - | -1.31 | -1.999 |

*Table 71: Vehicle parameters, prime movers (inset: front corner geometry)*

| | units | TR4x2 | TR6x2 | TK6x2 | TR6x4 | TK6x4 | TK8x4 SWB | TK8x4 LWB |
|---|---|---|---|---|---|---|---|---|
| Representative truck | | | | | | | | |
| Truck model | | MAN TGX 4x2 Tractor | MAN TGX 6x2 Midlift Tractor | MAN TGX 6x2 Drawbar | MAN TGX 6x4 Tractor | MAN TGX 6x4 Rigid | Volvo FM 11 8x4 | Volvo FM 11 8x4 |
| Geometry | | | | | | | | |
| Wheelbase (to first rear axle) | m | 3.6 | 2.6 | 4.8 | 3.3 | 4.8 | 3.7 | 4.6 |
| Axle spacing (between rear axles 1,2) | m | 0 | 1.35 | 1.35 | 1.35 | 1.35 | 1.37 | 1.37 |
| Axle spacing (between rear axles 2,3) | | - | - | - | - | - | 1.38 | 1.38 |
| Number of rear axles | | 1 | 2 | 2 | 2 | 2 | 3 | 3 |
| Geometric wheelbase | | 3.6 | 3.275 | 5.475 | 3.975 | 5.475 | 5.075 | 5.975 |
| Front overhang | m | 1.475 | 1.475 | 1.475 | 1.475 | 1.475 | 1.475 | 1.475 |
| Rear overhang | m | see payloads | see payloads | see payloads | see payloads | see payloads | see payloads | see payloads |
| Rear width (for tail swing) | m | - | - | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 |
| Front width (for frontal swing) (use ref. points) | | see below | see below | see below | see below | see below | see below | see below |
| Frontal area (for aerodynamics) | m^2 | 5.246 | 5.246 | 5.246 | 5.246 | 5.246 | 5.246 | 5.246 |
| Height of loading deck | m | - | - | 0.97 | - | 0.96 | 0.96 | 0.96 |
| Hitch | | | | | | | | |
| Hitch type | | B | B | A | B | A | A | A |
| Hitch location (behind steer axle) | m | 3.015 | 3.015 | 7.296 | 3.525 | 7.35 | 7.33 | 8.45 |
| Hitch height (above ground, unladen) | m | 1.15 | 1.15 | 0.8 | 1.15 | 0.8 | 0.8 | 0.8 |
| Inertia | | | | | | | | |
| Tare mass front | kg | 5160 | 5320 | 5060 | 5270 | 5295 | 4510 | 4600 |
| Tare mass rear | kg | 1980 | 3055 | 3525 | 4035 | 4225 | 4740 | 4775 |
| Tare mass | kg | 7140 | 8375 | 8585 | 9305 | 9520 | 9250 | 9375 |
| Rear position reference for rear tare | m | 3.600 | 3.275 | 5.475 | 3.975 | 5.475 | 5.070 | 5.970 |
| Unsprung mass front (steer axle) | kg | 750 | 750 | 750 | 750 | 750 | 750 | 750 |
| Unsprung mass rear (drive, tag axles) | kg | 1300 | 2050 | 2050 | 2600 | 2600 | 3350 | 3350 |
| Sprung mass front load | kg | 4410 | 4570 | 4310 | 4520 | 4545 | 3760 | 3850 |
| Sprung mass rear load | kg | 680 | 1005 | 1475 | 1435 | 1625 | 1390 | 1425 |
| **Sprung mass** | kg | 5090 | 5575 | 5785 | 5955 | 6170 | 5150 | 5275 |
| **Sprung mass CoG location (behind ste** | m | 0.481 | 0.590 | 1.396 | 0.958 | 1.442 | 1.370 | 1.614 |
| **Sprung mass CoG height (UNLADEN)** | m | 1.300 | 1.300 | 1.300 | 1.300 | 1.300 | 1.300 | 1.300 |
| **Radius of gyration (for calculation)** | m | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 | 0.736 |
| **W_f (for calculation)** | kg | 4410 | 4309 | 4103 | 4226 | 4316 | 3243 | 3424 |
| **W_r (for calculation)** | kg | 680 | 1266 | 1682 | 1729 | 1854 | 1907 | 1851 |
| Roll moment of inertia (about CoG) | kg·m^2 | 2757 | 3020 | 3134 | 3226 | 3342 | 2790 | 2857 |
| Yaw moment of interia (about CoG) | kg·m^2 | 5052 | 4746 | 21003 | 10201 | 23057 | 13728 | 20751 |
| Pitch moment of inertia (about CoG) | kg·m^2 | 5052 | 4746 | 21003 | 10201 | 23057 | 13728 | 20751 |
| Axles | | | | | | | | |
| Axle 1 | | steer LD | steer LD | steer LD | steer HD | steer HD | steer HD | steer HD |
| Axle 2 | | drive | tag | drive | drive | drive | drive | drive |
| Axle 3 | | - | drive | tag | drive | drive | drive | drive |
| Axle 4 | | - | - | - | - | - | tag | tag |
| Rear axle load proportioning | | | | | | | | |
| Axle 2 | % | 100 | 40 | 35 | 50 | 50 | 35 | 35 |
| Axle 3 | | - | 60 | 65 | 50 | 50 | 35 | 35 |
| Axle 4 | | - | - | - | - | - | 30 | 30 |
| Driver | | | | | | | | |
| Mass | kg | 75 | 75 | 75 | 75 | 75 | 75 | 75 |
| COGx (ahead of steer axle) | m | 0.218 | 0.218 | 0.218 | 0.218 | 0.218 | 0.218 | 0.218 |
| COGy (to right of centre line) | m | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| COGz above ground (unladen) | m | 1.815 | 1.815 | 1.815 | 1.815 | 1.815 | 1.815 | 1.815 |
| MOIx | kg·m^2 | 7.35 | 7.35 | 7.35 | 7.35 | 7.35 | 7.35 | 7.35 |
| MOIy | kg·m^2 | 7.94 | 7.94 | 7.94 | 7.94 | 7.94 | 7.94 | 7.94 |
| MOIz | kg·m^2 | 4.11 | 4.11 | 4.11 | 4.11 | 4.11 | 4.11 | 4.11 |

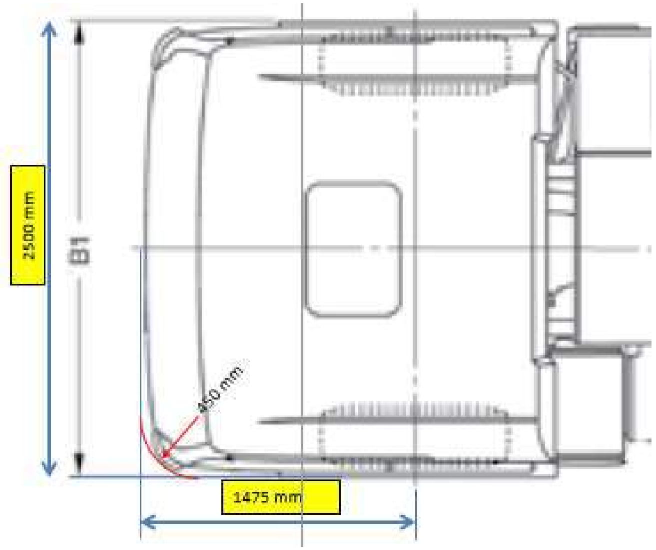


*Table 72: Vehicle parameters, trailers*

| | units | ST3 45ft | ST3/s3 2x7.8 | ST3 13.6 | ST3 14.9 | LT2 | LT3 | CT2 | CT3 | FT1+1 dolly (left), semi (right) | | FT2+3 45ft dolly (left), semi (right) | | FT2+3/s5 2x7.8 dolly (left), semi (right) | | DY2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Geometry | | | | | | | | | | | | | | | | |
| Total length | m | 13.72 | 15.64 | 13.62 | 14.92 | 12.85 | 10.15 | 7.825 | 6.1 | - | 7.825 | 3.2 | 13.72 | 3.2 | 15.64 | 3.2 |
| Front overhang (in front of kingpin) | | 1.999 | 1.668 | 1.668 | 1.668 | 1.57 | 1.31 | - | - | - | 1.06 | - | 1.49 | - | 1.668 | - |
| Wheelbase (hitch to first axle) | m | 6.07 | 8.32 | 6.32 | 7.63 | 7.005 | 4.19 | 5.68 | 3.895 | 2.95 | 5.17 | 3.25 | 6.38 | 3.25 | 8.32 | 3.2 |
| Axle spacing (between axles 1,2) | m | 1.41 | 1.31 | 1.31 | 1.31 | 1.81 | 2.06 | 1.81 | 1.3 | - | - | 1.3 | 1.3 | 1.3 | 1.31 | 1.4 |
| Axle spacing (between axles 2,3) | m | 1.31 | 1.31 | 1.31 | 1.31 | - | 1.81 | - | 1.3 | - | - | - | 1.3 | - | 1.31 | - |
| Width | m | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | - | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 |
| Height of loading deck (unladen) | | 1.3 | 1.3 | 1.3 | 1.3 | 1.37 | 1.37 | 1.255 | 1.255 | - | 1.3 | - | 1.3 | - | 1.3 | - |
| Hitch | | | | | | | | | | | | | | | | |
| Drawbar length | | - | - | - | - | - | - | 2.69 | 2.07 | 2.95 | - | 2.3 | - | 2.3 | - | 2.3 |
| Front hitch height | m | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 0.8 | 0.8 | 0.8 | 1.15 | 0.8 | 1.15 | 0.8 | 1.15 | 0.8 |
| Rear hitch type | | A | A | - | - | B (5th wheel) | B (5th wheel) | A | A | B (t. table) | - | B (t. table) | - | B (t. table) | - | B (5th wheel) |
| Hitch roll stiffness | Nm/deg | 0 | 0 | - | - | 100000 | 100000 | 0 | 0 | 100000 | - | 100000 | - | 100000 | - | 100000 |
| Lash in roll (plus minus) | deg | 0 | 0 | - | - | 1 | 1 | 0 | 0 | 0 | - | 0 | - | 0 | - | 1 |
| Rear hitch location (behind hitch) (M) | m | 10.5 | 12.42 | - | - | 8.75 | 7.22 | 8.59 | 7.33 | 2.95 | - | 3.9 | - | 3.9 | 12.42 | 3.9 |
| Rear hitch height (above ground, unladen) | m | 0.8 | 0.8 | - | - | 1.15 | 1.15 | 0.8 | 0.8 | 1.15 | - | 1.15 | - | 1.15 | 0.8 | 1.15 |
| Inertia | | | | | | | | | | | | | | | | |
| Tare mass | kg | 5000 | 5500 | 6160 | 6660 | 6060 | 5700 | 3340 | 4500 | 950 | 2390 | 3000 | 6000 | 3000 | 5500 | 3000 |
| Sprung mass | kg | 2750 | 3250 | 3910 | 4410 | 4560 | 3450 | 1840 | 2250 | 200 | 1640 | 1500 | 3750 | 1500 | 3250 | 1500 |
| Sprung mass CoG height | m | 1 | 1 | 1.506 | 1.449 | 1.07 | 1.07 | 0.955 | 0.955 | 0.65 | 1 | 0.65 | 1 | 0.65 | 1 | 0.65 |
| Sprung mass CoG location (behind hitch) | m | 4.861 | 6.152 | 5.142 | 5.792 | 4.855 | 3.765 | 6.6025 | 5.12 | 1.475 | 2.8525 | 3.9 | 5.37 | 3.9 | 6.152 | 3.9 |
| Roll moment of interia (about CoG) | kg·m^2 | 1580 | 1867 | 6650 | 7501 | 2461 | 1862 | 1057 | 1293 | 110 | 942 | 735 | 1580 | 735 | 1867 | 735 |
| Pitch moment of inertia (about CoG) | kg·m^2 | 51745 | 79466 | 79168 | 107151 | 70303 | 33186 | 20336 | 8369 | 175 | 10038 | 1300 | 51745 | 1300 | 79466 | 1300 |
| Yaw moment of inertia (about CoG) | kg·m^2 | 52936 | 81295 | 76731 | 103853 | 71589 | 33793 | 20804 | 8562 | 280 | 10269 | 2090 | 52936 | 2090 | 81295 | 2090 |
| Axles | | | | | | | | | | | | | | | | |
| Axle 1 | | trailer | trailer | trailer | trailer | dolly | dolly | trailer | trailer | dolly | trailer | dolly | trailer | dolly | trailer | dolly |
| Axle 2 | | trailer | trailer | trailer | trailer | dolly | dolly | trailer | trailer | - | | dolly | trailer | dolly | trailer | dolly |
| Axle 3 | | trailer | trailer (steered) | trailer | trailer | - | dolly | - | trailer | - | - | - | trailer | - | trailer (steered) | - |

*Table 73: Vehicle parameters, axles*

| | units | steer LD | steer HD | drive | tag | trailer | trailer/s | dolly | dolly/s | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| Steering | | | | | | | | | | |
| Steering type | | steered | steered | none | none | none | self-steered | none | self-steered | |
| Suspension type | | | | | | | | | | |
| | m | steel with roll-bar | steel with roll-bar | air | air | air overslung | air overslung | air underslung | air underslung | |
| Geometry | | | | | | | | | | |
| Tyre track width | m | 2.05 | 2.05 | 1.84 | 2 | 2.14 | 2.14 | 2.14 | 2.14 | Check Karel data |
| Roll center height above wheel centre | m | 0.1 | 0.1 | 0.35 | 0.35 | 0.15 | 0.15 | 0 | 0 | |
| Lateral distance btw dampers | m | 1 | 1 | 1 | 1 | 0.94 | 0.94 | 0.94 | 0.94 | |
| Lateral distance btw springs | m | 0.85 | 0.85 | 0.75 | 0.75 | 1.2 | 1.2 | 1.2 | 1.2 | |
| Inertia | | | | | | | | | | |
| Unsprung mass (INCL. wheels and tyres) | kg | 750 | 750 | 1300 | 750 | 750 | 750 | 750 | 750 | INCLUDING wheels and tyres |
| Unsprung mass CoG (excl. wheels and tyres) | m | wheel centre | wheel centre | wheel centre | wheel centre | wheel centre | wheel centre | wheel centre | wheel centre | |
| Mass of wheel and tyre assembly (one side) | kg | 150 | 150 | 280 | 150 | 200 | 200 | 200 | 200 | Estimates from Winkler data |
| Wheel and tyre rotational moment of inertia (one side) | kg·m^2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | Estimates from Winkler data |
| Axle roll moment of inertia (incl. wheels, tyres) | kg·m^2 | 420 | 420 | 500 | 420 | 420 | 420 | 420 | 420 | Estimates from Winkler data |
| Dynamic | | | | | | | | | | |
| Damper constant (extension) | N·s/m | 16900 | 16900 | 16900 | 16900 | 20000 | 20000 | 20000 | 20000 | |
| Damper constant (compression) | N·s/m | 5300 | 5300 | 5300 | 5300 | 8000 | 8000 | 8000 | 8000 | |
| Spring stiffness (per spring) | N/m | 2.50E+05 | 2.90E+05 | (see below) | (see below) | (see below) | (see below) | (see below) | (see below) | Assume steel for trucks and air for trailers |
| Auxilliary roll stiffness | Nm/rad | 220000 | 250000 | 800000 | 800000 | 1400000 | 1400000 | 1400000 | 1400000 | This excludes roll stiffness from springs, and is only the additional contribution from stabilisers or trailing arms, axle twist etc |
| Auxilliary roll stiffness | Nm/deg | 3840 | 4363 | 13963 | 13963 | 24435 | 24435 | 24435 | 24435 | |
| Tyres | | | | | | | | | | |
| Tyre | | 315/70 R22.5 | 315/70 R22.5 | 315/70 R22.5 | 315/70 R22.5 | 385/65 | 385/65 | 385/65 | 385/65 | |
| Tyre width | m | 0.315 | 0.315 | 0.315 | 0.315 | 0.385 | 0.385 | 0.385 | 0.385 | |
| Single/dual | | single | single | dual | single | single | single | single | single | Decide - we using S-S tyres for all trailers? |
| Dual tyre spacing (if applicable) | m | - | - | 0.35 | - | - | - | - | - | |
| Typical airbag for semitrailer axles (adjusted for trailing arm lever ratio) - HAN | | | | | | | | | | |
| Pressure | bar | 1 | 3 | 6 | | | | | | |
| Static wheel load: | N | 5000 | 16100 | 34000 | | | | | | |
| Stiffness at axle N/mm | N/m | 124000 | 273900 | 401300 | | | | | | |

*Table 74: Vehicle parameters, powertrains*

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| Engine option | units | **400 hp 4x2/6x2** | **400 hp 6x4** | **440 hp 4x2/6x2** | **440 hp 6x4** | **480 hp 4x2/6x2** | **480 hp 6x4** | **540 hp 8x4** |
| Engine output | hp | 400 | 400 | 440 | 440 | 480 | 480 | 540 |
| Engine spec | | 12.5 litre, 6 cyl | 12.5 litre, 6 cyl | 12.5 litre, 6 cyl | 12.5 litre, 6 cyl | 12.5 litre, 6 cyl | 12.5 litre, 6 cyl | 12.8 litre, 6 cyl |
| Axle/diff. ratio | | 2.71 | 3.08 | 2.53 | 3.08 | 2.53 | 3.08 | 2.83 |
| Diff efficiency | | 97% | 97% | 97% | 97% | 97% | 97% | 97% |
| Gear efficiency | | 97% | 97% | 97% | 97% | 97% | 97% | 97% |
| Engine inertia | kg·m^2 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Gear ratios | gear | gear ratio | gear ratio | gear ratio | gear ratio | gear ratio | gear ratio | gear ratio |
| | 1 | 15.86 | 16.41 | 15.86 | 16.41 | 15.86 | 16.41 | 14.94 |
| | 2 | 12.33 | 13.8 | 12.33 | 13.8 | 12.33 | 13.8 | 11.73 |
| | 3 | 9.57 | 11.28 | 9.57 | 11.28 | 9.57 | 11.28 | 9.04 |
| | 4 | 7.44 | 9.49 | 7.44 | 9.49 | 7.44 | 9.49 | 7.09 |
| | 5 | 5.87 | 7.76 | 5.87 | 7.76 | 5.87 | 7.76 | 5.54 |
| | 6 | 4.57 | 6.53 | 4.57 | 6.53 | 4.57 | 6.53 | 4.35 |
| | 7 | 3.47 | 5.43 | 3.47 | 5.43 | 3.47 | 5.43 | 3.44 |
| | 8 | 2.7 | 4.57 | 2.7 | 4.57 | 2.7 | 4.57 | 2.7 |
| | 9 | 2.1 | 3.59 | 2.1 | 3.59 | 2.1 | 3.59 | 2.08 |
| | 10 | 1.63 | 3.02 | 1.63 | 3.02 | 1.63 | 3.02 | 1.63 |
| | 11 | 1.29 | 2.47 | 1.29 | 2.47 | 1.29 | 2.47 | 1.27 |
| | 12 | 1 | 2.08 | 1 | 2.08 | 1 | 2.08 | 1 |
| | 13 | - | 1.7 | - | 1.7 | - | 1.7 | - |
| | 14 | - | 1.43 | - | 1.43 | - | 1.43 | - |
| | 15 | - | 1.19 | - | 1.19 | - | 1.19 | - |
| | 16 | - | 1 | - | 1 | - | 1 | - |
| Engine | | MAN D2676LF47 | MAN D2676LF47 | MAN D2676LF46 | MAN D2676LF46 | MAN D2676LF45 | MAN D2676LF45 | Volvo D13K540, gearbox AT2612F, axle RTS2370A |
| Engine torque | rpm | Nm | Nm | Nm | Nm | Nm | Nm | Nm |
| | 800 | - | - | - | - | - | - | 1700 |
| | 870 | 2030 | 2030 | 1940 | 1940 | 1860 | 1860 | 1970 |
| | 900 | 2200 | 2200 | 2030 | 2030 | 1880 | 1880 | 2080 |
| | 930 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2300 |
| | 1000 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2600 |
| | 1100 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2600 |
| | 1200 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2600 |
| | 1300 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2600 |
| | 1400 | 2300 | 2300 | 2100 | 2100 | 1900 | 1900 | 2600 |
| | 1450 | 2260 | 2260 | 2060 | 2060 | 1880 | 1880 | 2600 |
| | 1500 | 2200 | 2200 | 2000 | 2000 | 1850 | 1850 | 2550 |
| | 1600 | 2060 | 2060 | 1900 | 1900 | 1750 | 1750 | 2360 |
| | 1700 | 1950 | 1950 | 1800 | 1800 | 1650 | 1650 | 2220 |
| | 1800 | 1850 | 1850 | 1690 | 1690 | 1570 | 1570 | 2100 |
| | 1900 | 1700 | 1700 | 1570 | 1570 | 1440 | 1440 | 1950 |
| | 2000 | 1580 | 1580 | 1410 | 1410 | 1310 | 1310 | 1580 |
| | 2100 | 900 | 900 | 950 | 950 | 950 | 950 | 1270 |
| | 2110 | 700 | 700 | 900 | 900 | 900 | 900 | - |

*Table 75: Vehicle parameters, payload inertial data, representative loading*

| | units | 20' ISO | 40' ISO | 45' ISO | C782 | 2xC782 | 13.6 m | 14.92 m |
|---|---|---|---|---|---|---|---|---|
| Inertial | | | | | | | | |
| Mass (total, container and payload) | kg | 8302 | 16217 | 20106 | 11712 | 23424 | 16313 | 20613 |
| CoG height (above loading deck) | m | 1186 | 1184 | 1256 | 1236 | 1236 | 1056 | 1248 |
| CoG location (behind front edge of payload) | m | 3035 | 6096 | 6858 | 3913 | 7825 | 6810 | 7460 |
| Roll moment of interia (about CoG) | kg.m^2 | 9713 | 19131 | 26034 | 15265 | 30531 | 14422 | 25292 |
| Pitch moment of inertia (about CoG) | kg.m^2 | 31937 | 215501 | 335040 | 69918 | 498402 | 258246 | 397520 |
| Yaw moment of inertia (about CoG) | kg.m^2 | 31502 | 214598 | 333290 | 69499 | 497564 | 260546 | 396452 |
| Geometry | | | | | | | | |
| External length | m | 6069 | 12192 | 13716 | 7825 | 15650 | 13620 | 14920 |
| External width | m | 2362 | 2438 | 2500 | 2550 | 2550 | 2550 | 2550 |
| External height | m | 2590 | 2591 | 2775 | 2725 | 2725 | 2700 | 2700 |

*Table 76: Vehicle parameters, payload inertial data, critical loading*

| | units | 20' ISO | 40' ISO | 45' ISO | C782 | 2xC782 | 13.6 m | 14.92 m |
|---|---|---|---|---|---|---|---|---|
| Inertial | | | | | | | | |
| Mass (total, container and payload) | kg | 11368 | 22288 | 27896 | 16144 | 32287 | 24354 | 29432 |
| CoG height (above loading deck) | m | 1176 | 1175 | 1247 | 1226 | 1226 | 1056 | 1244 |
| CoG location (behind front edge of payload) | m | 3035 | 6096 | 6858 | 3913 | 7825 | 6810 | 7460 |
| Roll moment of interia (about CoG) | kg.m^2 | 12569 | 24672 | 34126 | 19881 | 39762 | 21530 | 34789 |
| Pitch moment of inertia (about CoG) | kg.m^2 | 42425 | 291407 | 458552 | 94027 | 682299 | 385524 | 562997 |
| Yaw moment of inertia (about CoG) | kg.m^2 | 41926 | 290266 | 456351 | 93572 | 681389 | 388958 | 561546 |
| Geometry | | | | | | | | |
| External length | m | 6069 | 12192 | 13716 | 7825 | 15650 | 13620 | 14920 |
| External width | m | 2362 | 2438 | 2500 | 2550 | 2550 | 2550 | 2550 |
| External height | m | 2590 | 2591 | 2775 | 2725 | 2725 | 2700 | 2700 |

*Table 77: Vehicle parameters, tyres*

| | units | tyre 1 | tyre 2 |
|---|---|---|---|
| Size | | 315/70 R22.5 | 385/65 R22.5 |
| Vertical Stiffness | N/mm | from HAN | from HAN |
| Unladen Radius | m | from HAN | from HAN |
| Loaded radius | m | from HAN | from HAN |
| Effective rolling radius | | from HAN | from HAN |
| Fy curve | | from HAN | from HAN |
| Fx curve | | from HAN | from HAN |
| Rolling resistance co-efficient 1 | kg/kg | 0.0041 | 0.0041 |
| Rolling resistance co-efficient 2 | h/km | 2.55E-05 | 2.55E-05 |
| Axles used on | | steer, drive, tag | dolly, trailer |

## Appendix B *Description of Performance Standards*

**Startability** (ST) is the maximum upgrade on which the vehicle can start from rest.
**Gradeability A** (GraA) is the maximum upgrade on which the vehicle can maintain forward motion.
**Gradeability B** (GraB) is the maximum speed that the vehicle can maintain on a 1% upgrade.
**Acceleration Capability** (Acc Cap) is the time taken for the vehicle to cover 100 m, starting from rest on a 0% grade.
**Tracking Ability on a Straight Path** (TASP) is the total vertical projection of road width used by the vehicle when travelling at high speed along a straight road with an uneven and cross-sloping surface as the trailing units deviate from the path of the hauling unit, illustrated in Figure 73.

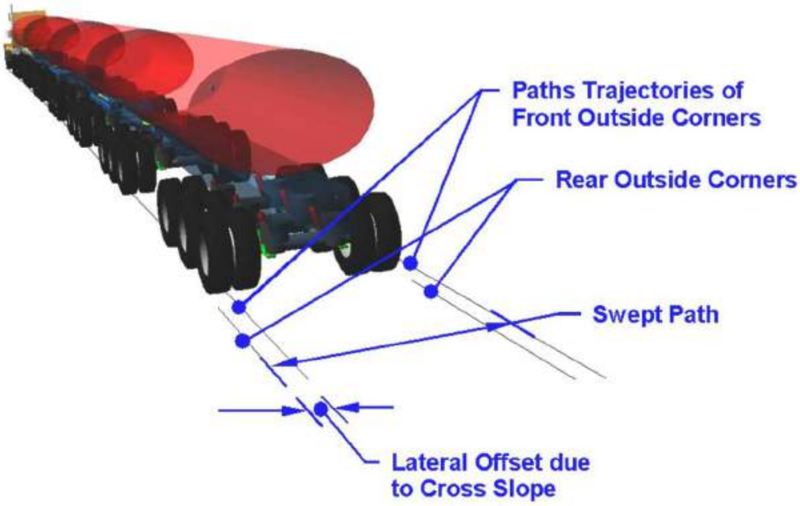



*Figure 73: Rear view of a vehicle combination illustrating Tracking Ability on a Straight Path* [1]

**Low-Speed Swept Path** (LSSP) is the amount of road width required by the vehicle when executing a prescribed low-speed 90° turn as the trailing units track inside of the path followed by the hauling unit.

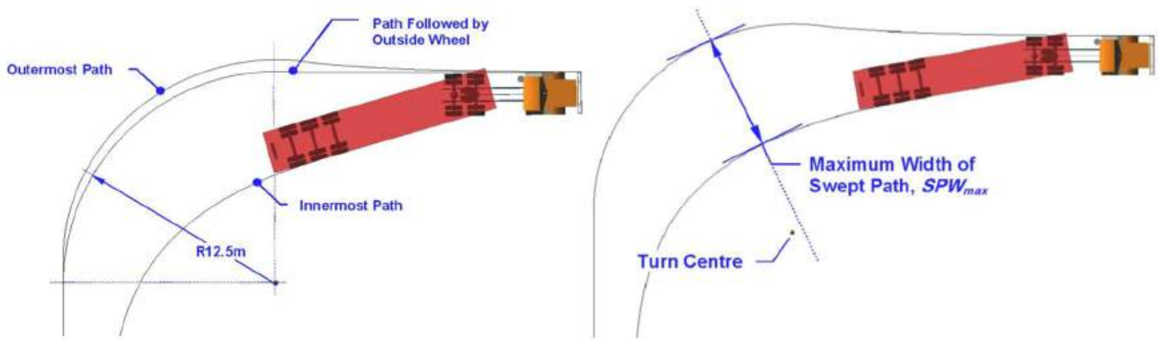



*Figure 74: Illustration of Low-Speed Swept Path* [1]

**Tail Swing** (TS) is the amount which the rear outside corner of a vehicle unit swings out at the commencement of the prescribed low-speed 90° turn. This may cause collisions with objects in adjacent lanes or on the roadside. This is of particular concern for vehicle units with a large rear overhang.

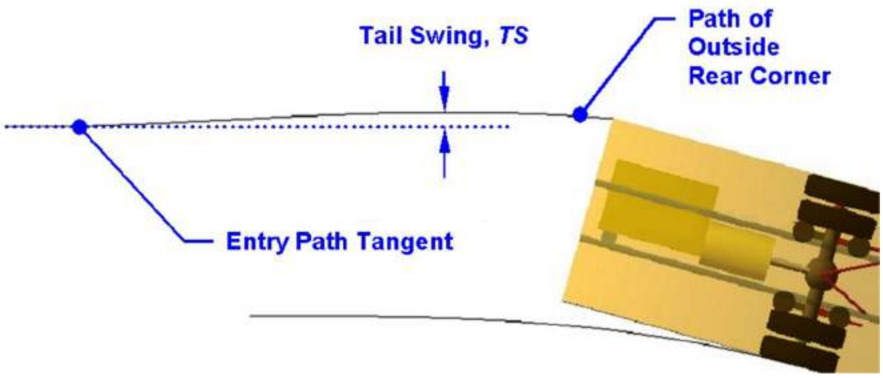



*Figure 75: Illustration of Tail Swing* [1]

**Frontal Swing** (FS) is the amount that the front outside corner of the hauling unit swings outside of the path followed by the widest section of the vehicle in the exit region of the low-speed 90° turn. For semitrailers, **Maximum of Difference** (MoD) and **Difference of Maxima** (DoM) pertain to the amount by which the front outside corner of a semitrailer swings out beyond that of the hauling unit or preceding semitrailer.

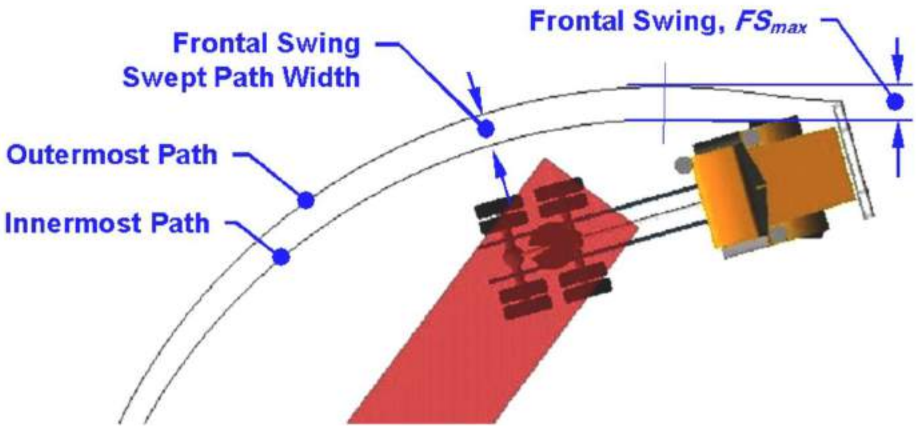



*Figure 76: Illustration of Frontal Swing* [1]

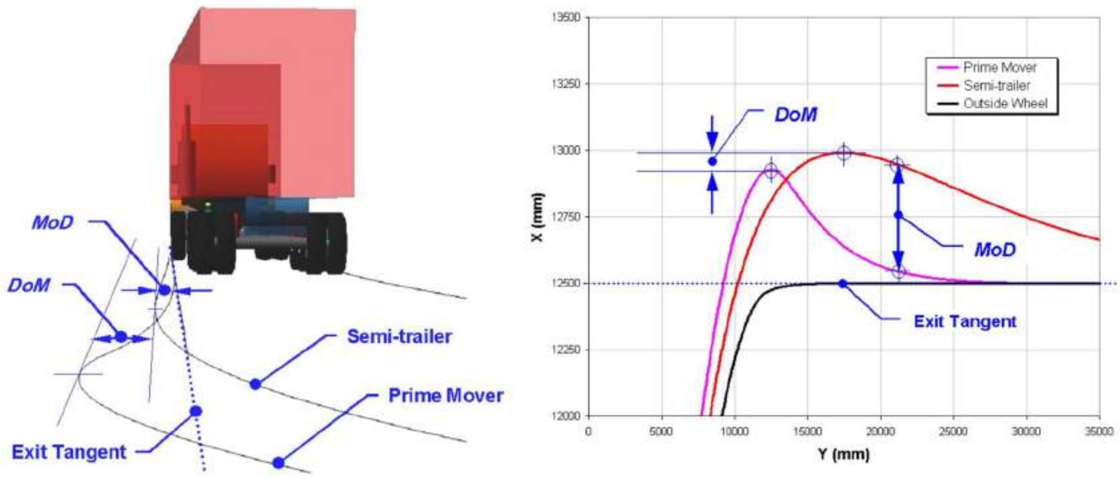



*Figure 77: Illustration of Maximum of Difference and Difference of Maxima* [1]

**Steer-Tyre Friction Demand** (STFD) is the proportion of the available friction that is used by the vehicle's steer tyres when performing the low-speed 90° turn. This is of particular concern for vehicles with a tri-drive prime mover.

**Static Rollover Threshold** (SRT) is the maximum steady-state lateral acceleration that can be sustained in constant-radius high-speed turn and directly measures the vehicle's rollover stability. SRT is alternatively measured using a tilt-table test.

**Rearward Amplification** (RA) is a measure of the degree to which the lateral acceleration of the towing unit is amplified in the trailing units in a high-speed single lane-change manoeuvre. This is important for predicting the likelihood of rollover of the rearmost unit during a rapid avoidance manoeuvre.
For the SRT and RA standards, the concept of rearmost roll-coupled unit (rrcu) is introduced and defined as all the rear units that are connected by mechanical components or devices able to transmit overturning moments. For this purpose, fifth wheels and turn tables are considered to transmit overturning moments, but pintle hitches are not.

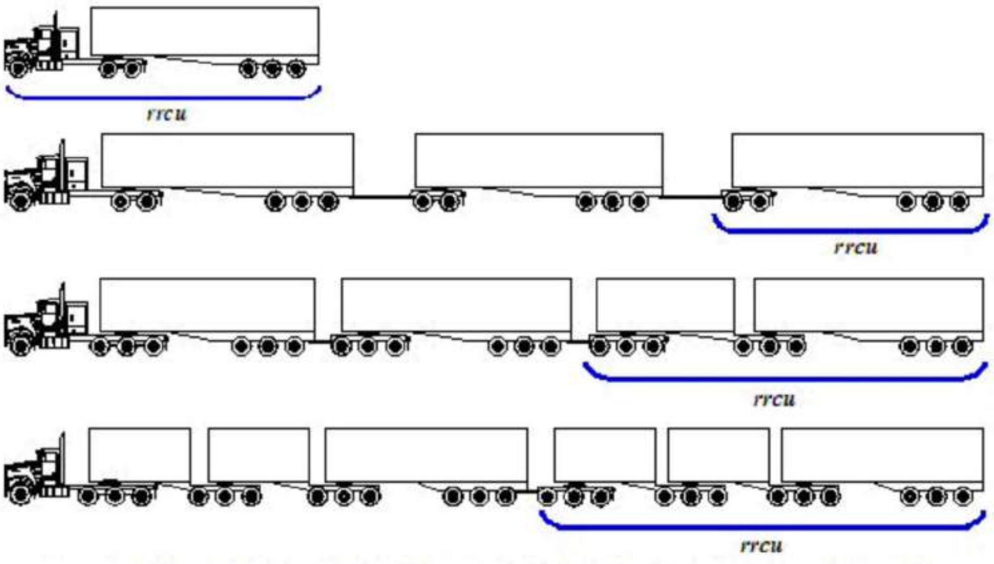



*Figure 78: Illustration of Rearmost Roll-Coupled Unit* [1]

**High-Speed Transient Offtracking** (HSTO) is the excess lateral displacement, or overshoot, of the rearmost axle of the vehicle when performing a high-speed single lane-change manoeuvre. This indicates the amount which the vehicle will deviate out of its own lane.

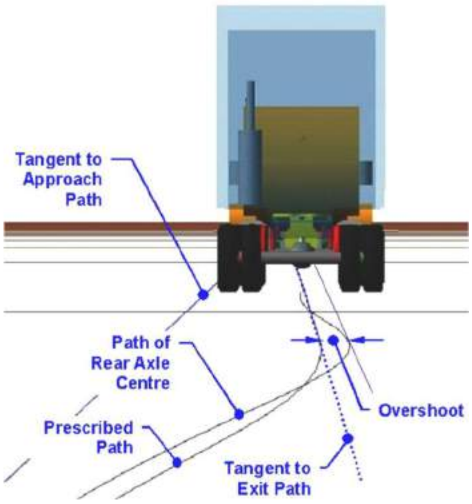



*Figure 79: Illustration of High-Speed Transient Offtracking*

**Load Transfer Ratio** (LTR) is the proportion of vertical tyre loads on one side of a vehicle unit that is transferred to the other side during a high-speed single lane-change manoeuvre [28].

**Yaw Damping Coefficient** (YDC) is the rate at which yaw oscillations or “snaking” decay after a severe steering input at high speed.

# Appendix C *Vehicle Dynamics Simulation Results*

*Table 78: Simulation results, representative loading, driveability standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Startability (%) | Gradeability A (Maintain motion) (%) | Gradeability B (Maintain speed) (km/h) | Acceleration Capability (s) |
|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 33 545 | 9.70 | 9.55 | 124.65 | 18.91 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 37 361 | 10.70 | 10.55 | 120.01 | 19.11 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 29 678 | 17.70 | 17.34 | 129.48 | 16.56 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 31 757 | 17.40 | 18.78 | 126.92 | 16.24 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 35 412 | 15.50 | 21.01 | 122.36 | 15.98 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 35 426 | 15.50 | 17.62 | 122.34 | 16.51 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 29 754 | 18.70 | 23.22 | 129.39 | 15.56 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 47 280 | 16.80 | 19.54 | 142.10 | 17.56 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 53 348 | 15.60 | 21.22 | 142.36 | 18.30 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 56 067 | 14.80 | 19.65 | 142.47 | 18.55 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 48 479 | 15.50 | 17.99 | 142.16 | 17.79 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 53 221 | 15.60 | 23.29 | 142.36 | 18.15 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 53 221 | 15.60 | 23.83 | 142.36 | 18.11 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 45 995 | 18.20 | 24.07 | 142.05 | 17.82 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 46 995 | 17.80 | 23.94 | 142.09 | 17.87 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 51 405 | 16.20 | 25.03 | 142.28 | 17.97 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 43 222 | 17.50 | 18.43 | 141.92 | 17.55 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 46 723 | 15.20 | 15.75 | 142.08 | 18.09 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 62 581 | 13.20 | 14.94 | 84.89 | 19.65 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 63 580 | 13.00 | 14.68 | 84.05 | 19.73 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 73 837 | 11.10 | 14.35 | 76.63 | 20.15 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 62 479 | 12.10 | 13.63 | 84.97 | 19.18 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 70 993 | 11.60 | 17.04 | 78.99 | 19.70 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 59 997 | 13.80 | 18.07 | 87.12 | 19.13 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 66 456 | 12.40 | 19.30 | 81.93 | 19.30 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 70 846 | 11.10 | 11.36 | 97.38 | 17.78 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 59 725 | 11.50 | 11.77 | 107.25 | 17.44 |

| |
|---|
| Pass |
| Level 1 |
| Level 2 |
| Level 3 |
| Level 4 |
| Fail |

*Table 79: Simulation results, representative loading, low-speed manoeuvrability standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Low Speed Swept Path (m) | Frontal Swing (m) | Difference of Maxima (m) | Maximum of Difference (m) | Tail Swing (m) | Steer-Tyre Friction Demand (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 33 545 | 5.51 | 0.26 | 0.35 | 0.63 | 0.25 | 23.25 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 37 361 | 6.62 | 0.29 | 0.25 | 0.60 | 0.24 | 23.90 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 29 678 | 5.61 | 0.30 | 0.18 | 0.50 | 0.27 | 7.25 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 31 757 | 6.26 | 0.30 | 0.24 | 0.58 | 0.25 | 7.23 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 35 412 | 5.50 | 0.43 | -0.44 | 0.01 | 0.27 | 29.34 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 35 426 | 5.34 | 0.46 | -0.49 | 0.13 | 0.23 | 29.19 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 29 754 | 4.95 | 0.43 | -0.43 | 0.07 | 0.29 | 30.06 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 47 280 | 6.38 | 0.35 | -0.17 | 0.27 | 0.12 | 23.89 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 53 348 | 7.89 | 0.36 | 0.14 | 0.55 | 0.22 | 25.13 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 56 067 | 8.52 | 0.36 | 0.01 | 0.42 | 0.13 | 25.00 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 48 479 | 6.96 | 0.33 | -0.04 | 0.30 | 0.15 | 24.98 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 53 221 | 7.60 | 0.46 | -0.18 | 0.39 | 0.19 | 29.55 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 53 221 | 7.64 | 0.46 | -0.18 | 0.39 | 0.20 | 29.73 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 45 995 | 6.64 | 0.46 | -0.20 | 0.34 | 0.20 | 30.10 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 46 995 | 6.75 | 0.46 | -0.32 | 0.26 | 0.23 | 30.11 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 51 405 | 7.04 | 0.47 | 0.00 | -0.02 | 0.22 | 29.62 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 43 222 | 5.81 | 0.42 | 0.00 | 0.08 | 0.14 | 29.09 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 46 723 | 6.53 | 0.43 | -0.26 | 0.30 | 0.26 | 29.18 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 62 581 | 7.67 | 0.35 | 0.19 | 0.53 | 0.24 | 24.36 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 63 580 | 7.75 | 0.35 | 0.20 | 0.55 | 0.25 | 24.64 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 73 837 | 10.03 | 0.36 | 0.01 | 0.41 | 0.12 | 24.95 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 62 479 | 8.06 | 0.34 | 0.05 | 0.27 | 0.10 | 24.07 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 70 993 | 9.23 | 0.46 | -0.11 | 0.26 | 0.20 | 29.59 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 59 997 | 7.81 | 0.46 | 0.04 | 0.18 | 0.20 | 29.66 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 66 456 | 8.17 | 0.47 | 0.00 | -0.02 | 0.22 | 29.58 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 70 846 | 9.30 | 0.50 | -0.09 | 0.24 | 0.13 | 30.02 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 59 725 | 7.61 | 0.43 | 0.02 | 0.22 | 0.14 | 29.19 |

| |
|---|
| Pass |
| Level 1 |
| Level 2 |
| Level 3 |
| Level 4 |
| Fail |

*Table 80: Simulation results, representative loading, turning circle standards ("0" = could not complete manoeuvre)*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | TC 1 Inner Radius (m) | TC 1 Tail Swing (m) | TC 2 Inner Radius (m) | TC 2 Tail Swing (m) | TC 3 Inner Radius (m) | TC 3 Tail Swing (m) | TC 4 Inner Radius (m) | TC 4 Tail Swing (m) | TC 5 Inner Radius (m) | TC 5 Tail Swing (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 33 545 | 5.910 | 0.225 | 6.634 | 0.225 | | | | | | |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 37 361 | 4.201 | 0.348 | 5.705 | 0.367 | | | | | | |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 29 678 | 5.711 | 0.227 | 6.494 | 0.239 | | | | | | |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 31 757 | 4.232 | 0.203 | 5.672 | 0.222 | | | | | | |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 35 412 | 5.917 | 0.241 | 6.621 | 0.245 | | | | | | |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 35 426 | 6.226 | 0.209 | 6.791 | 0.209 | | | | | | |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 29 754 | 6.977 | 0.235 | 7.293 | 0.239 | | | | | | |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 47 280 | 3.969 | 0.108 | 5.557 | 0.108 | | | | | | |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 53 348 | 0.798 | 0.148 | 3.581 | 0.148 | 6.301 | 0.123 | 8.913 | 0.105 | | |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 56 067 | 0.000 | 0.119 | 2.741 | 0.119 | 5.511 | 0.098 | 8.172 | 0.083 | | |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 48 479 | 2.399 | 0.138 | 4.808 | 0.138 | 7.445 | 0.115 | | | | |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 53 221 | 0.356 | 0.182 | 3.961 | 0.162 | 6.635 | 0.156 | | | | |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 53 221 | 0.209 | 0.182 | 3.913 | 0.182 | 6.593 | 0.156 | | | | |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 45 995 | 3.357 | 0.182 | 5.238 | 0.182 | 7.826 | 0.156 | | | | |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 46 995 | 3.060 | 0.215 | 5.096 | 0.215 | 7.695 | 0.179 | | | | |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 51 405 | 1.822 | 0.182 | 4.720 | 0.182 | 7.362 | 0.156 | | | | |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 43 222 | 5.315 | 0.104 | 6.270 | 0.104 | | | | | | |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 46 723 | 3.560 | 0.244 | 5.340 | 0.244 | | | | | | |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 62 581 | 0.000 | 0.169 | 3.871 | 0.169 | 6.583 | 0.139 | | | | |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 63 580 | 0.000 | 0.205 | 3.760 | 0.205 | 6.477 | 0.168 | 9.086 | 0.143 | | |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 73 837 | 0.000 | 0.071 | 0.643 | 0.071 | 3.545 | 0.057 | 6.335 | 0.049 | 10.210 | 0.040 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 62 479 | 0.000 | 0.088 | 3.323 | 0.088 | 6.087 | 0.072 | 8.738 | 0.062 | | |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 70 993 | 0.000 | 0.181 | 1.751 | 0.181 | 4.583 | 0.156 | 7.306 | 0.136 | 11.088 | 0.116 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 59 997 | 0.000 | 0.181 | 3.680 | 0.181 | 6.406 | 0.155 | 9.024 | 0.136 | | |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 66 456 | 0.000 | 0.182 | 3.205 | 0.182 | 5.967 | 0.156 | 8.615 | 0.137 | | |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 70 846 | 0.000 | 0.119 | 1.625 | 0.119 | 4.462 | 0.103 | 7.190 | 0.090 | 10.981 | 0.077 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 59 725 | 0.000 | 0.131 | 3.922 | 0.131 | 6.632 | 0.108 | | | | |

Pass
Fail

*Table 81: Simulation results, representative loading, high-speed dynamic standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Tracking Ability on a Straight Path (m) | Static Rollover Threshold (g) | Rearward Amplification RRCU | Rearward Amplification Last Unit | High-Speed Transient Offtracking (m) | High-Speed Steady-State Offtracking (m) | Load Transfer Ratio | Yaw Damping Coefficient @ 80 km/h |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 33 545 | 2.77 | 0.38 | 1.27 | 1.25 | 0.37 | 0.30 | 0.44 | 0.25 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 37 361 | 2.78 | 0.36 | 1.03 | 1.03 | 0.29 | 0.40 | 0.37 | 0.35 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 29 678 | 2.77 | 0.42 | 1.32 | 1.36 | 0.34 | 0.29 | 0.38 | 0.28 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 31 757 | 2.78 | 0.38 | 1.15 | 0.98 | 0.33 | 0.36 | 0.38 | 0.30 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 35 412 | 2.81 | 0.43 | 2.23 | 2.33 | 0.61 | 0.45 | 0.83 | 0.19 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 35 426 | 2.86 | 0.42 | 1.99 | 3.01 | 0.76 | 0.48 | 0.94 | 0.18 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 29 754 | 2.76 | 0.50 | 2.05 | 2.06 | 0.55 | 0.39 | 0.72 | 0.26 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 47 280 | 2.86 | 0.47 | 2.49 | 2.36 | 0.88 | 0.85 | 0.88 | 0.18 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 53 348 | 2.86 | 0.42 | 2.10 | 2.16 | 0.71 | 1.11 | 0.83 | 0.20 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 56 067 | 2.87 | 0.42 | 0.76 | 1.11 | 0.49 | 1.09 | 0.25 | 0.29 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 48 479 | 2.86 | 0.45 | 1.05 | 1.37 | 0.64 | 0.77 | 0.35 | 0.21 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 53 221 | 2.86 | 0.44 | 2.04 | 1.33 | 0.66 | 1.00 | 0.63 | 0.21 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 53 221 | 2.86 | 0.45 | 1.95 | 1.98 | 0.64 | 1.00 | 0.60 | 0.23 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 45 995 | 2.86 | 0.48 | 2.29 | 2.46 | 0.79 | 0.81 | 0.75 | 0.19 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 46 995 | 2.86 | 0.50 | 2.18 | 2.29 | 0.75 | 0.83 | 0.69 | 0.19 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 51 405 | 2.99 | 0.45 | 3.71 | 4.02 | 1.14 | 1.11 | 1.00 | 0.06 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 43 222 | 2.96 | 0.52 | 4.37 | 4.96 | 1.27 | 0.91 | 1.00 | 0.07 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 46 723 | 2.88 | 0.49 | 2.05 | 2.16 | 0.77 | 0.83 | 0.72 | 0.20 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 62 581 | 3.00 | 0.44 | 2.74 | 2.72 | 1.21 | 1.44 | 0.93 | 0.16 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 63 580 | 3.00 | 0.44 | 2.68 | 2.61 | 1.19 | 1.46 | 0.89 | 0.15 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 73 837 | 2.94 | 0.41 | 0.72 | 1.49 | 0.73 | 2.05 | 0.25 | 0.28 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 62 479 | 2.95 | 0.46 | 1.03 | 2.20 | 0.99 | 1.44 | 0.35 | 0.18 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 70 993 | 2.94 | 0.44 | 1.30 | 2.43 | 0.93 | 1.93 | 0.41 | 0.24 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 59 997 | 2.97 | 0.48 | 1.78 | 2.99 | 1.18 | 1.50 | 0.61 | 0.17 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 66 456 | 3.68 | 0.45 | 4.05 | 4.51 | 1.81 | 2.06 | 1.00 | 0.01 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 70 846 | 2.95 | 0.43 | 1.24 | 2.43 | 0.92 | 2.06 | 0.42 | 0.24 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 59 725 | 2.97 | 0.48 | 1.74 | 2.77 | 1.24 | 1.50 | 0.63 | 0.18 |

| |
|---|
| Pass |
| Level 1 |
| Level 2 |
| Level 3 |
| Level 4 |
| Fail |

*Table 82: Simulation results, critical loading, driveability standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Startability (%) | Gradeability A (Maintain motion) (%) | Gradeability B (Maintain speed) (km/h) | Acceleration Capability (s) |
|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 41 332 | 9.70 | 9.54 | 115.44 | 19.71 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 46 221 | 10.70 | 10.56 | 110.45 | 18.97 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 37 716 | 14.50 | 17.83 | 119.59 | 16.52 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 43 292 | 12.60 | 19.83 | 113.40 | 16.42 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 44 273 | 12.30 | 21.07 | 112.41 | 16.32 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 44 287 | 12.30 | 17.91 | 112.40 | 16.72 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 35 884 | 15.30 | 23.31 | 121.79 | 15.74 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 58 132 | 14.30 | 19.15 | 142.55 | 18.67 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 66 638 | 12.40 | 20.29 | 142.87 | 18.93 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 69 357 | 11.90 | 18.63 | 142.96 | 19.18 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 59 332 | 14.00 | 16.81 | 142.60 | 18.99 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 66 511 | 12.40 | 22.78 | 142.86 | 18.77 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 66 511 | 12.40 | 22.75 | 142.86 | 18.77 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 56 848 | 14.60 | 23.92 | 142.50 | 18.26 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 57 847 | 14.30 | 23.92 | 142.54 | 18.31 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 64 697 | 12.70 | 23.47 | 142.80 | 18.65 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 52 417 | 15.90 | 18.18 | 142.32 | 18.59 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 57 575 | 14.40 | 15.55 | 142.53 | 19.13 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 78 155 | 10.50 | 14.28 | 73.59 | 20.32 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 79 155 | 10.30 | 14.07 | 72.94 | 20.39 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 91 558 | 8.90 | 13.63 | 66.01 | 20.91 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 76 396 | 10.70 | 12.89 | 74.76 | 20.51 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 88 714 | 9.20 | 16.74 | 67.63 | 20.46 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 73 914 | 11.10 | 18.08 | 76.57 | 19.73 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 84 178 | 9.70 | 17.90 | 69.71 | 20.18 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 88 567 | 10.90 | 11.31 | 85.20 | 19.04 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 73 642 | 11.30 | 11.63 | 95.16 | 18.58 |

Pass
Level 1
Level 2
Level 3
Level 4
Fail

*Table 83: Simulation results, critical loading, low-speed manoeuvrability standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Low Speed Swept Path (m) | Frontal Swing (m) | Difference of Maxima (m) | Maximum of Difference (m) | Tail Swing (m) | Steer-Tyre Friction Demand (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 41 332 | 5.51 | 0.28 | 0.35 | 0.63 | 0.25 | 23.25 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 46 221 | 6.62 | 0.29 | 0.25 | 0.60 | 0.24 | 23.90 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 37 716 | 5.61 | 0.30 | 0.18 | 0.50 | 0.27 | 7.25 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 43 292 | 6.26 | 0.30 | 0.24 | 0.58 | 0.25 | 7.19 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 44 273 | 5.50 | 0.43 | -0.44 | 0.01 | 0.27 | 29.34 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 44 287 | 5.34 | 0.46 | -0.49 | 0.13 | 0.23 | 29.19 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 35 884 | 4.95 | 0.43 | -0.43 | 0.07 | 0.29 | 30.06 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 58 132 | 6.38 | 0.35 | -0.17 | 0.27 | 0.12 | 25.06 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 66 638 | 7.89 | 0.36 | 0.14 | 0.55 | 0.22 | 25.13 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 69 357 | 8.52 | 0.36 | 0.01 | 0.42 | 0.13 | 25.00 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 59 332 | 6.95 | 0.33 | -0.05 | 0.29 | 0.15 | 24.36 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 66 511 | 7.60 | 0.46 | -0.18 | 0.39 | 0.19 | 29.55 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 66 511 | 7.64 | 0.46 | -0.18 | 0.39 | 0.20 | 29.73 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 56 848 | 6.63 | 0.46 | -0.20 | 0.34 | 0.20 | 29.65 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 57 847 | 6.75 | 0.46 | -0.32 | 0.26 | 0.23 | 30.11 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 64 697 | 7.04 | 0.47 | 0.00 | -0.02 | 0.22 | 29.62 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 52 417 | 5.81 | 0.42 | 0.00 | 0.08 | 0.14 | 29.09 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 57 575 | 6.53 | 0.43 | -0.26 | 0.30 | 0.26 | 29.18 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 78 155 | 7.66 | 0.35 | 0.19 | 0.53 | 0.24 | 25.34 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 79 155 | 7.75 | 0.35 | 0.20 | 0.55 | 0.25 | 24.64 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 91 558 | 10.03 | 0.36 | 0.01 | 0.41 | 0.12 | 24.95 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 76 396 | 8.05 | 0.34 | 0.05 | 0.27 | 0.10 | 24.07 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 88 714 | 9.23 | 0.46 | -0.11 | 0.26 | 0.20 | 29.59 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 73 914 | 7.81 | 0.46 | 0.04 | 0.18 | 0.20 | 30.03 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 84 178 | 8.17 | 0.47 | 0.00 | -0.02 | 0.22 | 29.58 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 88 567 | 9.30 | 0.50 | -0.09 | 0.24 | 0.13 | 30.02 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 73 642 | 7.61 | 0.43 | 0.02 | 0.22 | 0.14 | 29.19 |

| |
|---|
| Pass |
| Level 1 |
| Level 2 |
| Level 3 |
| Level 4 |
| Fail |

*Table 84: Simulation results, critical loading, turning circle standards ("0" = could not complete manoeuvre)*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | TC 1 Inner Radius (m) | TC 1 Tail Swing (m) | TC 2 Inner Radius (m) | TC 2 Tail Swing (m) | TC 3 Inner Radius (m) | TC 3 Tail Swing (m) | TC 4 Inner Radius (m) | TC 4 Tail Swing (m) | TC 5 Inner Radius (m) | TC 5 Tail Swing (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 41 332 | 5.910 | 0.225 | 6.634 | 0.225 | | | | | | |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 46 221 | 4.201 | 0.348 | 5.705 | 0.367 | | | | | | |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 37 716 | 5.711 | 0.227 | 6.494 | 0.239 | | | | | | |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 43 292 | 4.232 | 0.203 | 5.672 | 0.222 | | | | | | |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 44 273 | 5.917 | 0.241 | 6.621 | 0.245 | | | | | | |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 44 287 | 6.226 | 0.209 | 6.791 | 0.209 | | | | | | |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 35 884 | 6.977 | 0.235 | 7.293 | 0.239 | | | | | | |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 58 132 | 3.969 | 0.108 | 5.557 | 0.108 | | | | | | |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 66 638 | 0.798 | 0.148 | 3.581 | 0.148 | 6.301 | 0.123 | 8.913 | 0.105 | | |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 69 357 | 0.000 | 0.119 | 2.741 | 0.119 | 5.511 | 0.098 | 8.172 | 0.083 | | |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 59 332 | 2.399 | 0.138 | 4.808 | 0.138 | 7.445 | 0.115 | | | | |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 66 511 | 0.356 | 0.182 | 3.961 | 0.162 | 6.635 | 0.156 | | | | |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 66 511 | 0.209 | 0.182 | 3.913 | 0.182 | 6.593 | 0.156 | | | | |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 56 848 | 3.357 | 0.182 | 5.238 | 0.182 | 7.826 | 0.156 | | | | |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 57 847 | 3.060 | 0.215 | 5.096 | 0.215 | 7.695 | 0.179 | | | | |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 64 697 | 1.822 | 0.182 | 4.720 | 0.182 | 7.362 | 0.156 | | | | |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 52 417 | 5.315 | 0.104 | 6.270 | 0.104 | | | | | | |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 57 575 | 3.560 | 0.244 | 5.340 | 0.244 | | | | | | |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 78 155 | 0.000 | 0.169 | 3.871 | 0.169 | 6.583 | 0.139 | | | | |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 79 155 | 0.000 | 0.205 | 3.760 | 0.205 | 6.477 | 0.168 | 9.086 | 0.143 | | |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 91 558 | 0.000 | 0.071 | 0.643 | 0.071 | 3.545 | 0.057 | 6.335 | 0.049 | 10.210 | 0.040 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 76 396 | 0.000 | 0.088 | 3.323 | 0.088 | 6.087 | 0.072 | 8.738 | 0.062 | | |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 88 714 | 0.000 | 0.181 | 1.751 | 0.181 | 4.583 | 0.156 | 7.306 | 0.136 | 11.088 | 0.116 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 73 914 | 0.000 | 0.181 | 3.680 | 0.181 | 6.406 | 0.155 | 9.024 | 0.136 | | |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 84 178 | 0.000 | 0.182 | 3.205 | 0.182 | 5.967 | 0.156 | 8.615 | 0.137 | | |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 88 567 | 0.000 | 0.119 | 1.625 | 0.119 | 4.462 | 0.103 | 7.190 | 0.090 | 10.981 | 0.077 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 73 642 | 0.000 | 0.131 | 3.922 | 0.131 | 6.632 | 0.108 | | | | |

| |
|---|
| Pass |
| Fail |

*Table 85: Simulation results, critical loading, high-speed dynamic standards*

| Vehicle | Combination | Combination Length (m) | GCM (kg) | Tracking Ability on a Straight Path (m) | Static Rollover Threshold (g) | Rearward Amplification RRCU | Rearward Amplification Last Unit | High-Speed Transient Offtracking (m) | High-Speed Steady-State Offtracking (m) | Load Transfer Ratio | Yaw Damping Coefficient @ 80 km/h |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | TR6x2-ST3 (45ft) | 16.211 | 41 332 | 2.78 | 0.35 | 1.25 | 1.25 | 0.42 | 0.33 | 0.52 | 0.23 |
| 1.2 | TR6x2-ST3 (2x7.8m) | 18.462 | 46 221 | 2.80 | 0.33 | 1.03 | 1.03 | 0.33 | 0.40 | 0.45 | 0.33 |
| 1.3 | TR4x2-ST3 (13.6m) | 16.442 | 37 716 | 2.78 | 0.39 | 1.36 | 1.36 | 0.39 | 0.29 | 0.46 | 0.26 |
| 1.4 | TR4x2-ST3 (14.9m) | 17.742 | 43 292 | 2.79 | 0.34 | 0.98 | 0.98 | 0.39 | 0.36 | 0.49 | 0.25 |
| 2.1 | TK6x2-CT2 (2x7.8m) | 19.286 | 44 273 | 2.84 | 0.40 | 2.33 | 2.33 | 0.67 | 0.47 | 0.93 | 0.16 |
| 2.2 | TK6x2-FT1+1 (2x7.8m) | 18.486 | 44 287 | 2.90 | 0.40 | 2.99 | 3.01 | 0.81 | 0.48 | 1.00 | 0.11 |
| 2.3 | TK6x2-CT3(2x20ft) | 16.941 | 35 884 | 2.77 | 0.46 | 2.06 | 2.06 | 0.60 | 0.41 | 0.77 | 0.28 |
| 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 23.670 | 58 132 | 2.87 | 0.43 | 2.37 | 2.36 | 0.96 | 0.85 | 0.95 | 0.19 |
| 3.2 | TR6x4-ST3-CT2(3x7.8m) | 27.935 | 66 638 | 2.88 | 0.40 | 2.16 | 2.16 | 0.78 | 1.11 | 0.96 | 0.16 |
| 3.3 | TR6x4-LT2-ST3(3x7.8m) | 27.722 | 69 357 | 2.88 | 0.39 | 0.65 | 1.11 | 0.53 | 1.09 | 0.31 | 0.29 |
| 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 23.941 | 59 332 | 2.87 | 0.42 | 0.95 | 1.37 | 0.69 | 0.77 | 0.43 | 0.21 |
| 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 26.697 | 66 511 | 2.89 | 0.42 | 0.90 | 1.33 | 0.73 | 1.00 | 0.55 | 0.24 |
| 4.2 | TK6x4-FT2+3 (3x7.8m) | 26.697 | 66 511 | 2.89 | 0.43 | 1.97 | 1.98 | 0.71 | 1.00 | 0.67 | 0.26 |
| 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 24.446 | 56 848 | 2.89 | 0.45 | 2.44 | 2.46 | 0.85 | 0.81 | 0.84 | 0.16 |
| 4.4 | TK6x4-FT2+3 (20ft+45ft) | 24.955 | 57 847 | 2.90 | 0.46 | 2.28 | 2.29 | 0.81 | 0.83 | 0.77 | 0.16 |
| 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 27.930 | 64 697 | 3.06 | 0.43 | 4.02 | 4.02 | 1.19 | 1.11 | 1.00 | 0.03 |
| 4.6 | TK8x4-CT3-CT3(3x20ft) | 24.305 | 52 417 | 3.01 | 0.50 | 4.96 | 4.96 | 1.32 | 0.91 | 1.00 | 0.05 |
| 4.7 | TK8x4-FT2+3(20ft+45ft) | 24.935 | 57 575 | 2.89 | 0.46 | 2.14 | 2.16 | 0.82 | 0.83 | 0.80 | 0.19 |
| 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 31.121 | 78 155 | 3.05 | 0.41 | 2.70 | 2.72 | 1.30 | 1.44 | 1.00 | 0.19 |
| 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 31.630 | 79 155 | 3.01 | 0.41 | 2.60 | 2.61 | 1.27 | 1.46 | 0.97 | 0.17 |
| 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 36.472 | 91 558 | 2.96 | 0.38 | 0.68 | 1.49 | 0.79 | 2.05 | 0.30 | 0.26 |
| 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 31.161 | 76 396 | 2.97 | 0.43 | 1.08 | 2.20 | 1.05 | 1.44 | 0.41 | 0.18 |
| 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 35.447 | 88 714 | 2.97 | 0.41 | 1.44 | 2.43 | 1.01 | 1.93 | 0.49 | 0.22 |
| 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 31.666 | 73 914 | 2.97 | 0.45 | 1.99 | 2.99 | 1.25 | 1.50 | 0.69 | 0.18 |
| 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 36.520 | 84 178 | 4.75 | 0.43 | 4.51 | 4.51 | 1.80 | 2.06 | 1.00 | 0.01 |
| 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 36.547 | 88 567 | 2.97 | 0.41 | 1.40 | 2.43 | 1.01 | 2.06 | 0.49 | 0.18 |
| 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 31.646 | 73 642 | 2.99 | 0.45 | 1.80 | 2.77 | 1.32 | 1.50 | 0.70 | 0.18 |

Pass
Level 1
Level 2
Level 3
Level 4
Fail

## Appendix D *Vehicle Dynamics Correlation Investigations*

In this section, correlations of fleet performance in the various standards are presented. The low-speed manoeuvrability and high-speed dynamic performance standards were studied. Where results for both representative and critical loading are given, recall that both representative and critical loading cases assumed uniform payload loaded up to 82% of the loading space height (and hence with a CoG of 41% of the loading space height).

Each standard has been plotted against each other standard. Existing unaltered pass/fail envelopes (*i.e.* from the Australian standards) have been superimposed on the plots in shaded boxes for road access levels 1-4 where applicable, or simple pass/fail. Note that the shaded boxes indicate the pass/fail envelopes for BOTH standards plotted. I.e. some points outside the boxes could pass one but fail the other, or fail both. Note where TASP vs SRT has already been plotted (for example), SRT vs TASP is not plotted. To illustrate, consider the plot of LTR vs TASP in Figure 80. The vehicles circled in blue meet the Level 1 TASP requirement and meet the LTR pass requirement (there are no road access level criteria for LTR, just pass/fail). The vehicles circled in red fail the LTR requirement, but are within the Level 2 requirement of TASP.

NOTE: In some cases some data points which are far removed from the others are not shown in order to maintain reasonable axis limits. In these cases the coordinate of the point is specified explicitly on the plot as “(x,y)”.

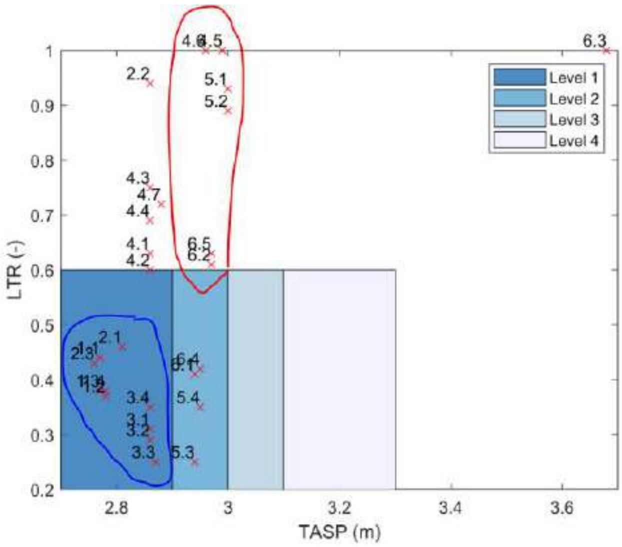



*Figure 80: Illustration of how to interpret the correlation plots*

The primary low-speed correlation results of interest is between LSSP and the EU, UK and Netherlands turning circles. The correlation between LSSP and TC1 (the EU roundabout, and also the first level of the NL roundabout) and TC2, TC3, TC4 (the 2nd, 3rd, and 4th levels of the NL roundabout) is shown in Figure 81 (a) and (b) respectively. It is clear that the LSSP standard is highly correlated with all turning circle manoeuvres. Although it is clear that the EU turning circle must be retained as a standard (at least for general access vehicles), we can conclude that the NL turning circle does not add any more value or insights. The Australian LSSP standard captures the same performance of the NL standard, but with only one defined manoeuvre, of fixed and manageable dimensions for all vehicle lengths, and which also includes defined measurements for frontal swing and tail swing. We can also notice from the plots that the existing Australian Level 1 performance criterion for LSSP seems to lie at a point between the criteria for TC 2 and TC 3, and the Level 2 criterion just above the criterion for TC 4.

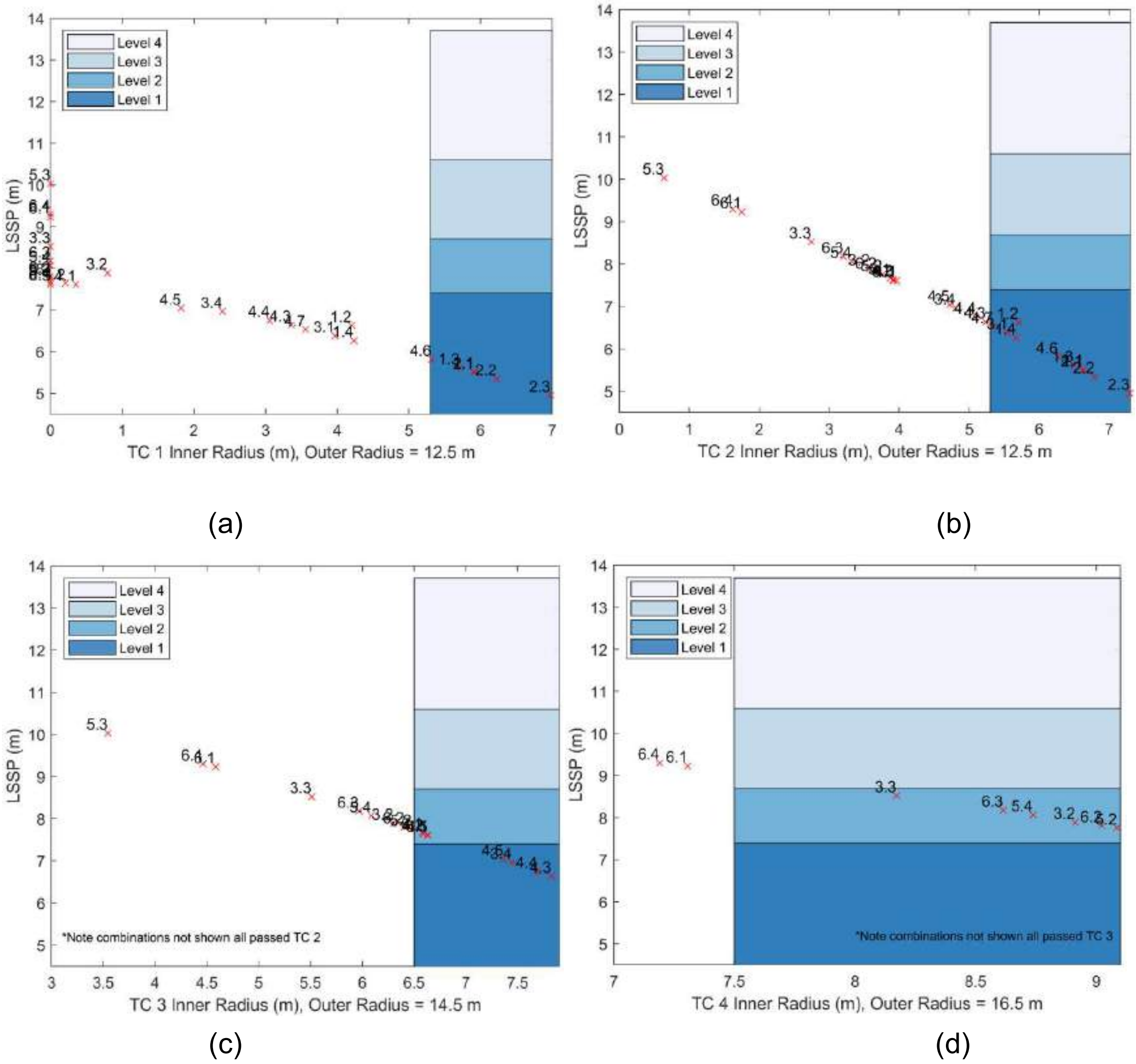
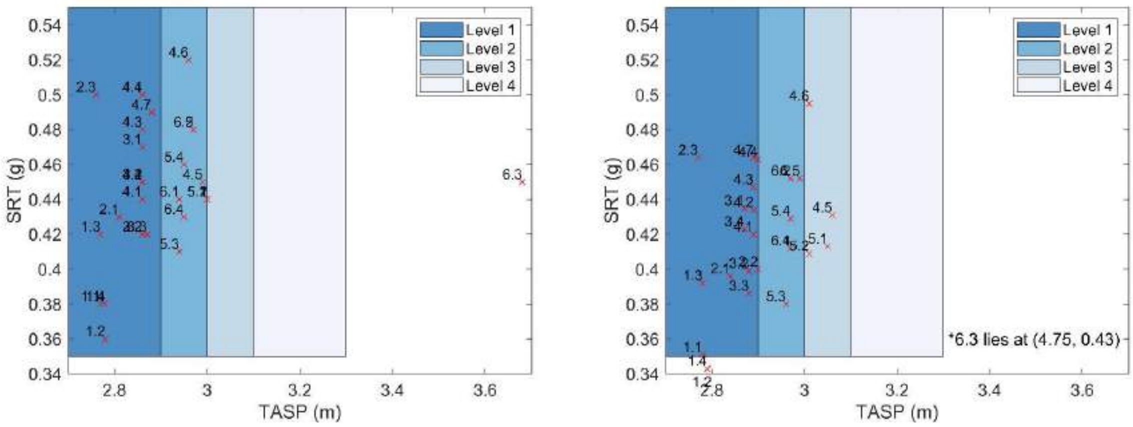



*Figure 81: Correlation between LSSP and: (a) TC 1, (b) TC 2, (c) TC 3, and (d) TC 4*

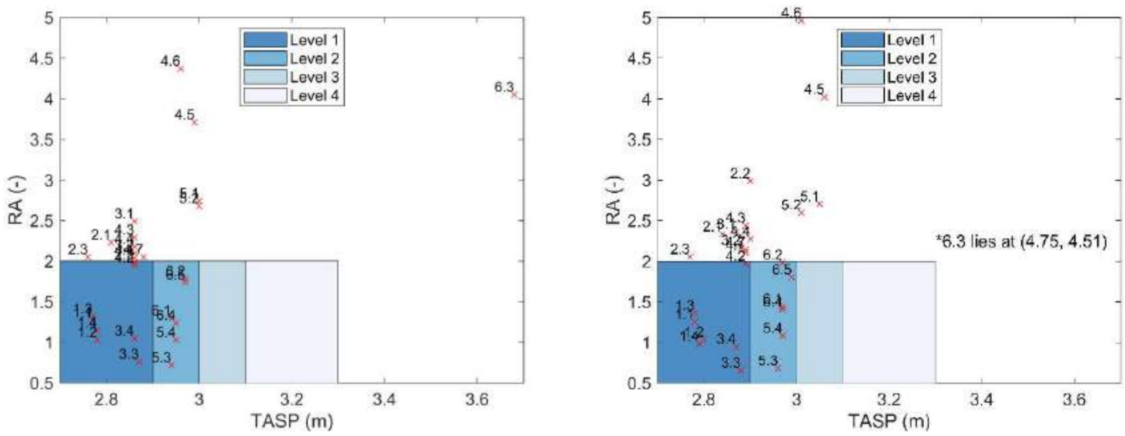
Figure 82 show the plot of SRT vs. TASP. All vehicles meet the SRT requirement, except for 1.2 & 1.4 in the heavy loading case. All vehicles except 6.3 meet at least Level 2 TASP with representative loading and Level 3 with heavy loading. Vehicle 6.3 (TK6x4-CT2-CT2-CT2) fails by a significant margin, while still meeting the SRT requirement. This triple-centre-axle-trailer combination was expected to perform poorly in the dynamic standards. There is no observable correlation between SRT and TASP.




(a) (b)

*Figure 82: Correlation between SRT and TASP: (a) representative loading, (b) critical loading*

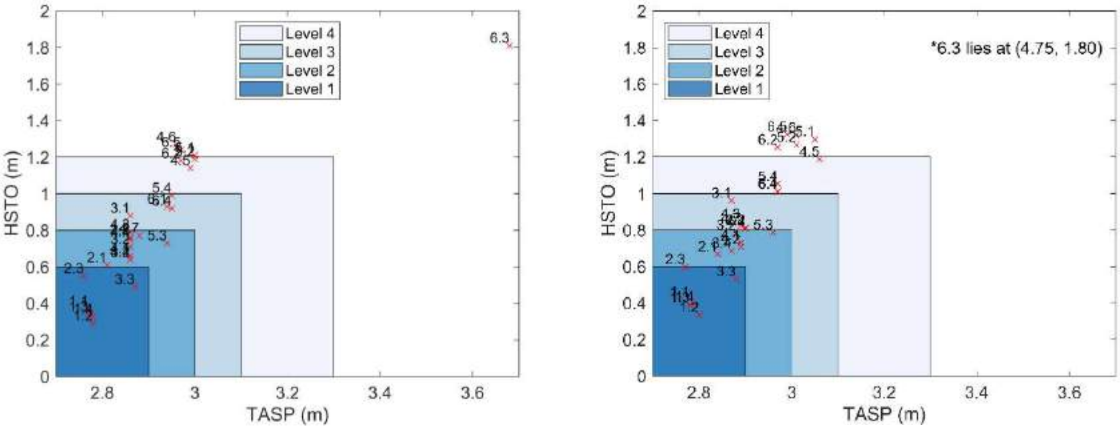
Figure 83 shows the plot of RA vs. TASP. At the RA limit of 2, over half the vehicles fail in both load cases. The worst performing combinations in RA are 4.5, 4.6 & 6.3 (all dual centre-axle trailer combinations). There is little correlation between RA and TASP.




(a) (b)

*Figure 83: Correlation between RA and TASP: (a) representative loading, (b) critical loading*

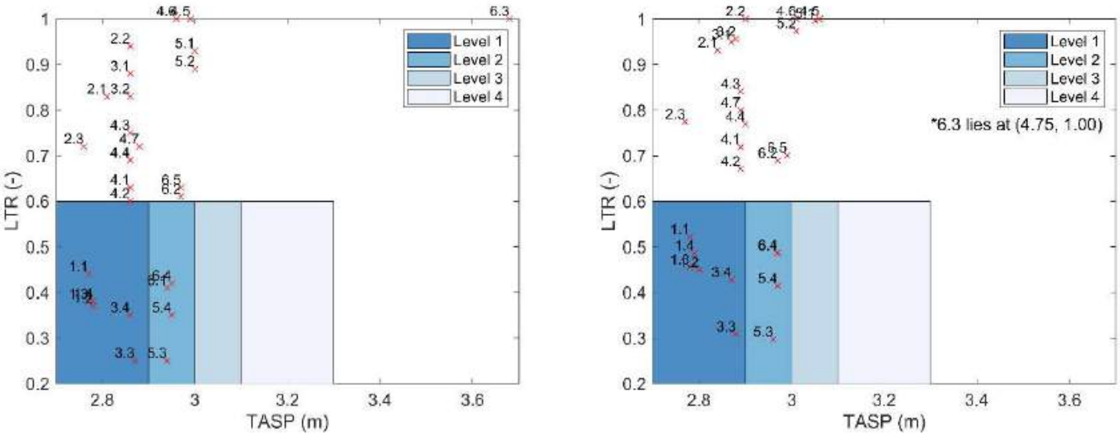
Figure 84 shows the plot of HSTO vs. TASP. There seems to be a convincing correlation between HSTO and TASP, though the pass/fail criteria for HSTO seem to be the limiting requirement in most cases (i.e. vehicles reach the Level limit for HSTO before reaching the same level limit for TASP). The worst performing vehicle in both cases, 6.3, seems to lie off the trend of the other data, assuming the trend to remain approximately linear. It should be noted that the rear trailer in 6.3 rolled during the lane change manoeuvre. However, without data points in-between, it is hard to draw a reliable conclusion here. Both these standards have a reasonable correlation with overall vehicle length, as seen by the partial grouping of vehicle combination in the same category groups (i.e. groups 1 to 6).




(a) (b)

*Figure 84: Correlation between HSTO and TASP: (a) representative loading, (b) critical loading*

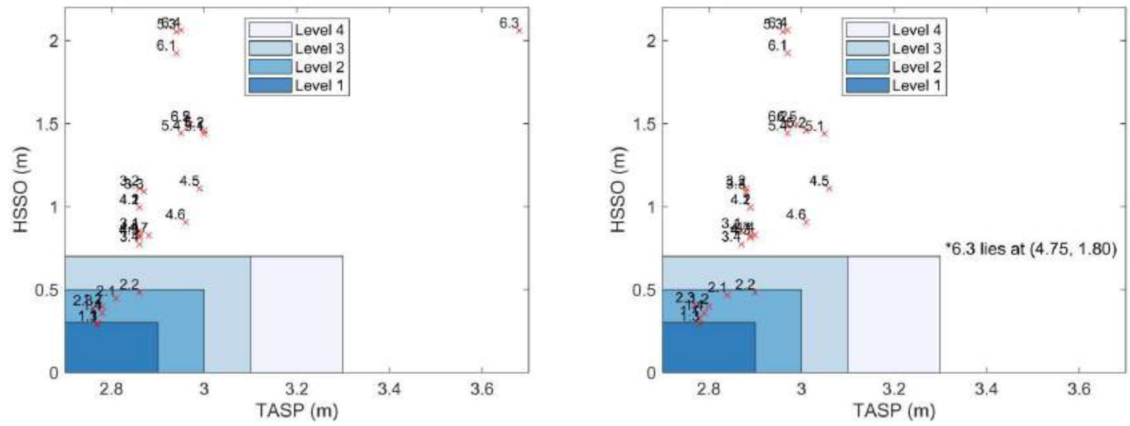
Figure 85 shows the plot of LTR vs TASP. No correlation evident. More than half the combinations fail LTR, even at representative loading. Vehicle 6.3 fails both standards by a large margin, experiencing wheel lift-off during the LTR lane change manoeuvre. Vehicles 4.5 & 4.6 also have wheel-lift and fail LTR, but meet Level 2 TASP in the representative loading case.




(a) (b)

*Figure 85: Correlation between LTR and TASP: (a) representative loading, (b) critical loading*

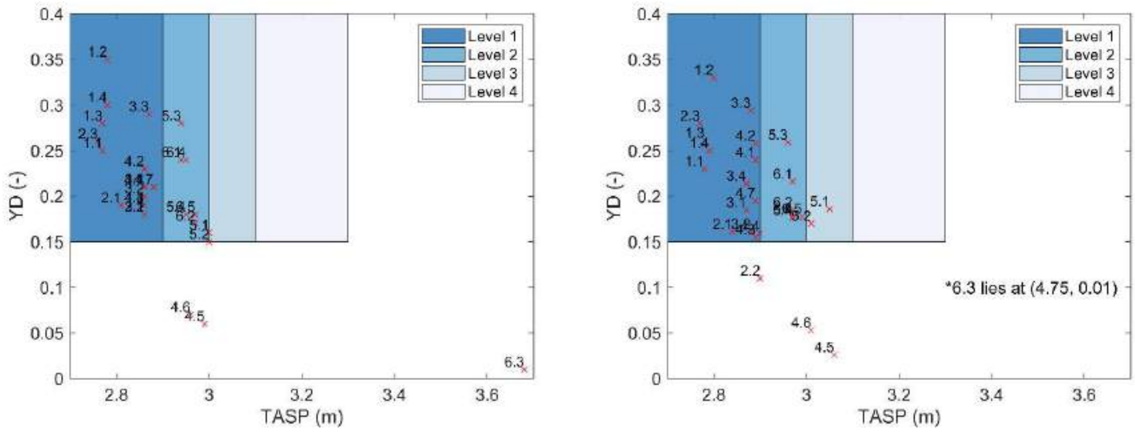
Figure 86 shows the plot of HSSO vs TASP. Similar to HSTO, there seems to be a convincing correlation between HSSO and TASP, and again the pass/fail criteria for HSSO seem to be the limiting requirement in most cases (i.e. vehicles reach the Level limit for HSSO before reaching the same level limit for TASP).




(a) (b)

*Figure 86: Correlation between HSSO and TASP: (a) representative loading, (b) critical loading*

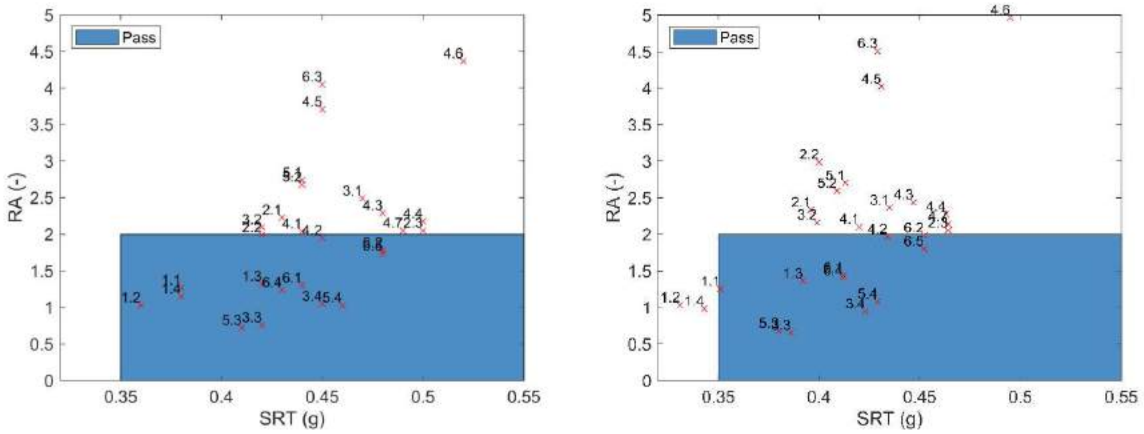
Figure 87 shows the plot of YD vs. TASP. Some small correlation is present between YD and TASP, especially within the “safe” zones of Levels 1 and 2. Vehicle 6.3 is again a distant outlier. The other two centre axle trailer combinations, 4.5 and 4.6, fail YD in both loading cases, while vehicle 2.2 fails in the heavy loading case.




(a) (b)

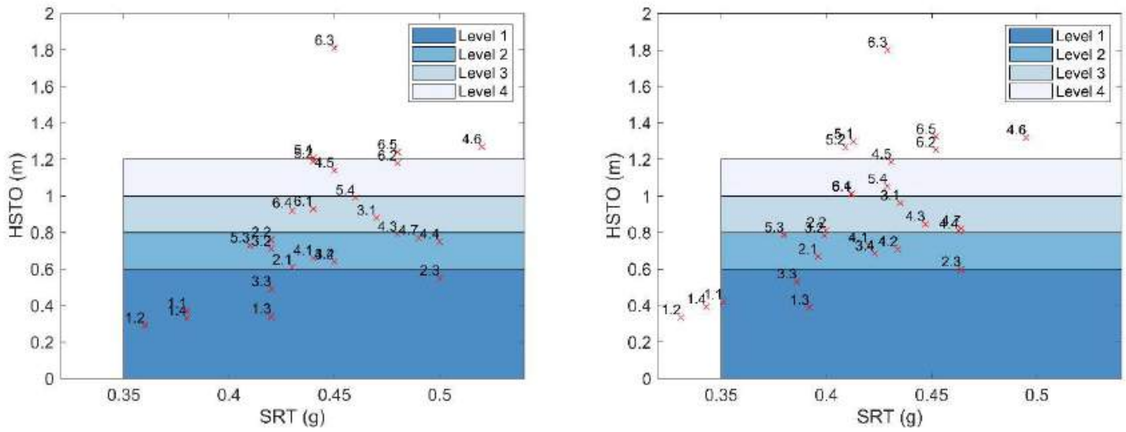
*Figure 87: Correlation between YD and TASP: (a) representative loading, (b) critical loading*

Figure 88 shows the plot of RA vs. SRT. No correlation is present. All vehicles meet SRT for the representative loading case, whilst combinations 1.2 & 1.4 fail SRT in the heavy loading case. Figure 89 shows the plot of HSTO vs. SRT. A small correlation component is present, but with large variances away from the trend. Figure 90 shows the plot of HSSO vs. SRT, demonstrating little correlation. Figure 91 shows the plot of HSSO vs. SRT, demonstrating little correlation. Figure 92 shows the plot of YD vs. SRT. There is some correlation here, but not enough to disregard one standard over the other. YD captures some yaw dynamics effects which SRT does not. Most vehicles pass the YD standard, with the exceptions being the centre axle combinations of 4.5, 4.6, and 6.3. Combination 2.2 fails YD in the heavy loading case.



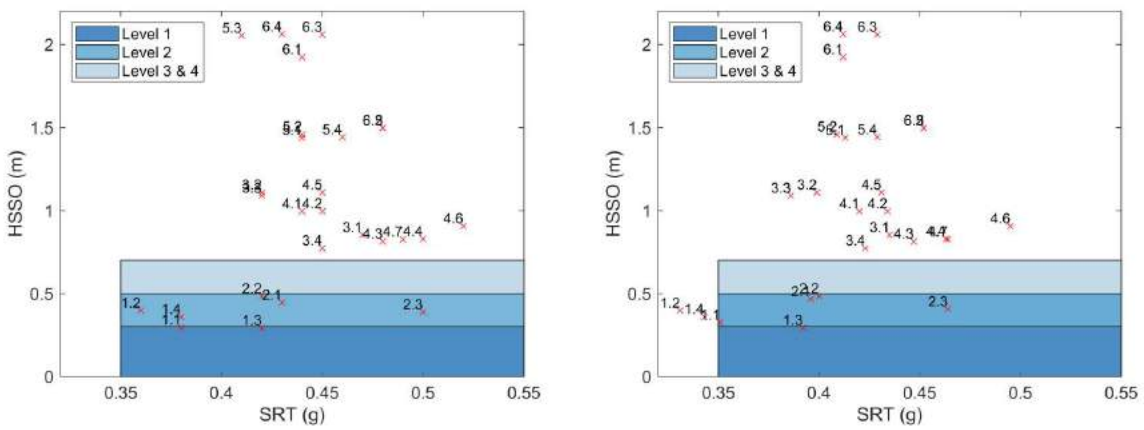

(a) (b)

*Figure 88: Correlation between RA and SRT: (a) representative loading, (b) critical loading*



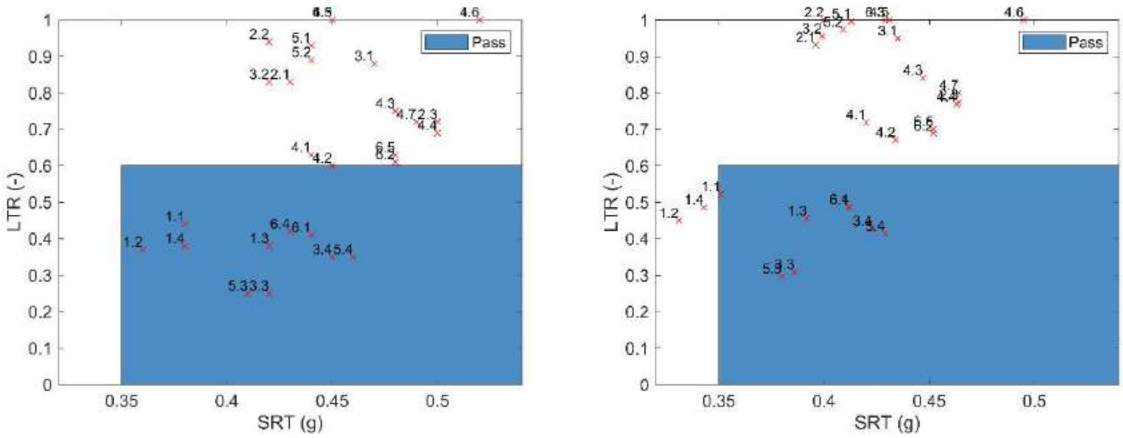

(a) (b)

*Figure 89: Correlation between HSTO and SRT: (a) representative loading, (b) critical loading*



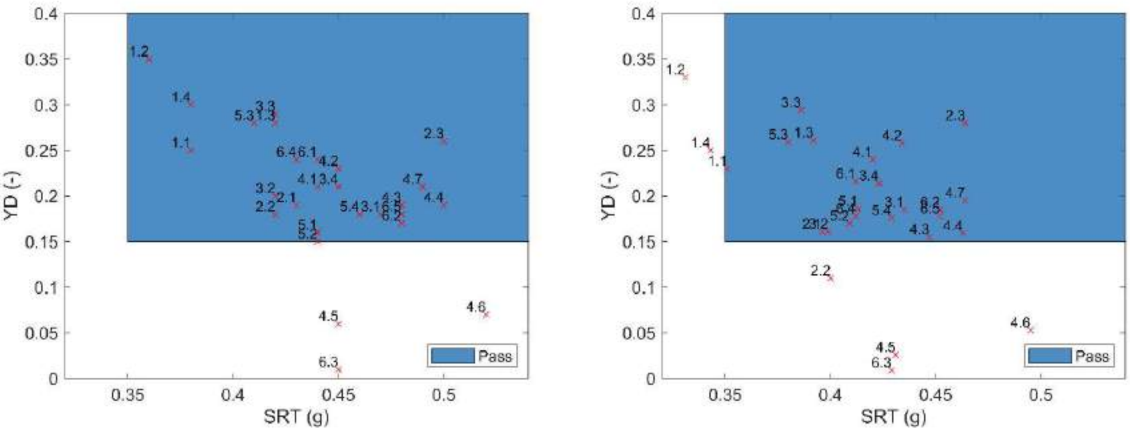

(a) (b)

*Figure 90: Correlation between HSSO and SRT: (a) representative loading, (b) critical loading*




(a) (b)

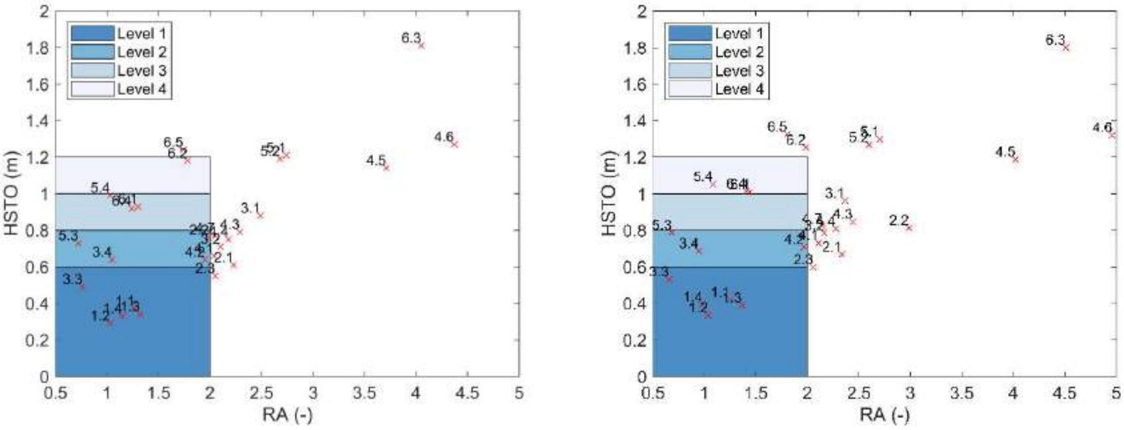
*Figure 91: Correlation between LTR and SRT: (a) representative loading, (b) critical loading*




(a) (b)

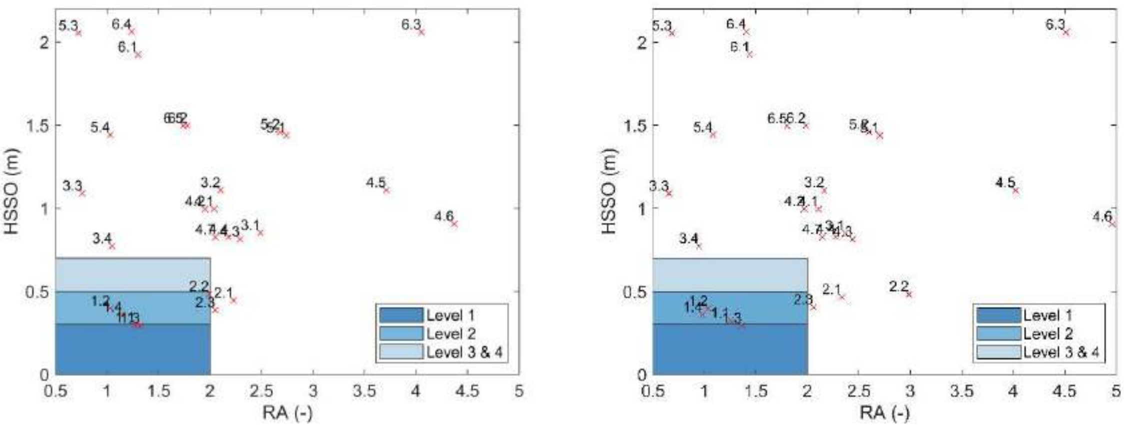
*Figure 92: Correlation between YD and SRT: (a) representative loading, (b) critical loading*

Figure 93 shows the plot of HSTO vs. RA. Some correlation is present. Generally speaking, where a vehicle fails RA, it also exceeds Level 2 HSTO. Figure 94 shows the plot of HSSO vs. RA, demonstrating no correlation. There is however a high correlation between HSSO and combination length as shown in Figure 95. Figure 96 shows the plot of LTR vs. RA. There is a very strong correlation, and the pass/fail limits seem to align quite well too at [2, 0.6], although the LTR limit of 0.6 seems to be the more critical by a small margin. Figure 97 shows the plot of YD vs. RA, showing a reasonable correlation.



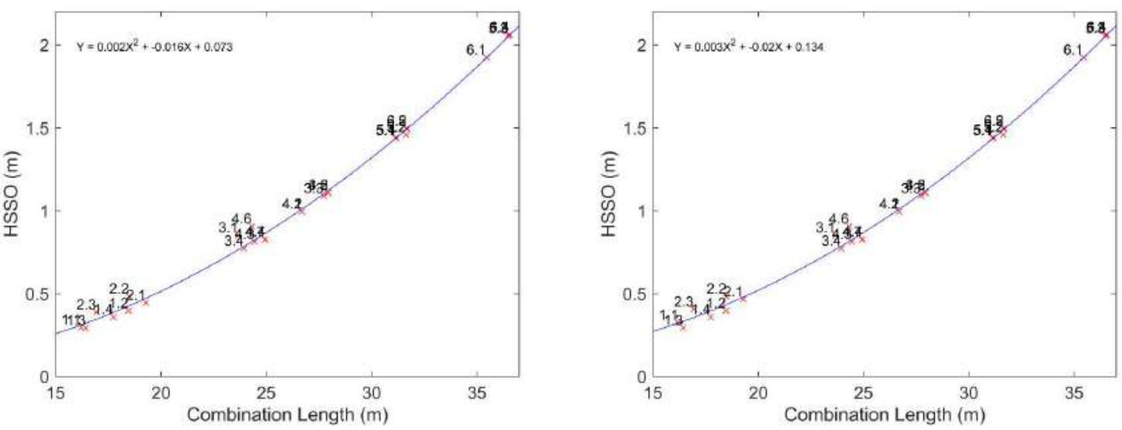

(a) (b)

*Figure 93: Correlation between HSTO and RA: (a) representative loading, (b) critical loading*



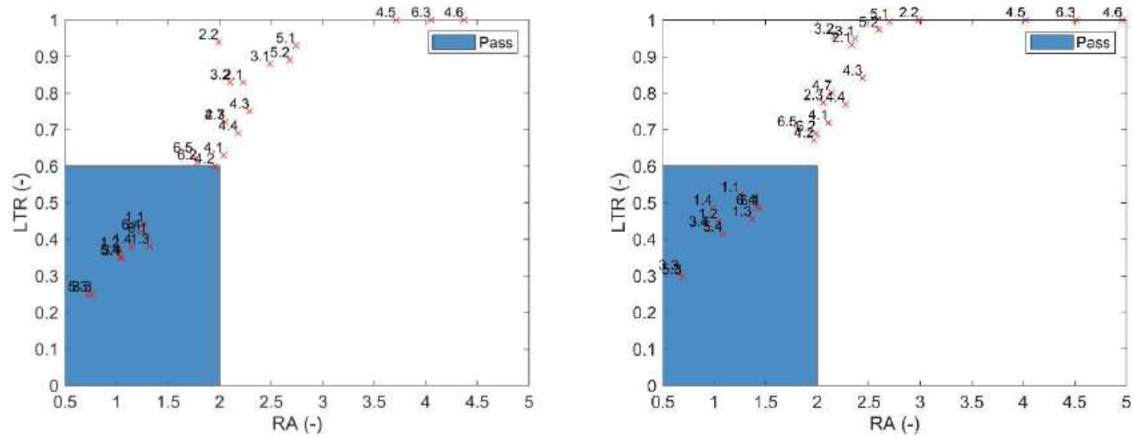

(a) (b)

*Figure 94: Correlation between HSSO and RA: (a) representative loading, (b) critical loading*



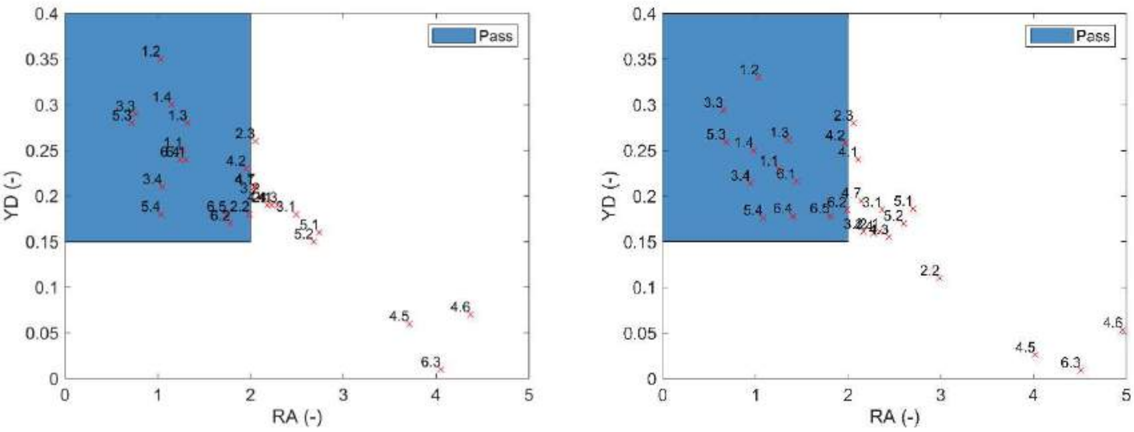

(a) (b)

*Figure 95: Correlation between HSSO and length: (a) representative loading, (b) critical loading*




(a) (b)

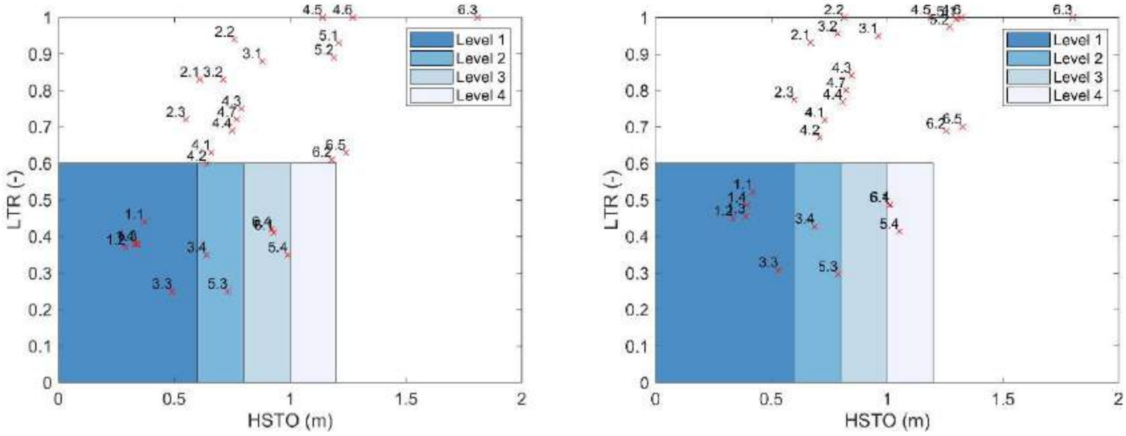
*Figure 96: Correlation between LTR and RA: (a) representative loading, (b) critical loading*




(a) (b)

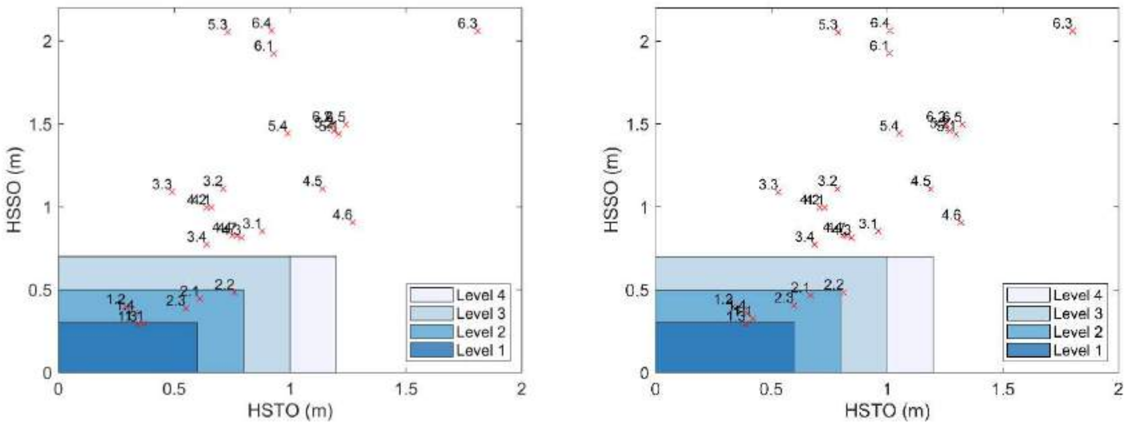
*Figure 97: Correlation between YD and RA: (a) representative loading, (b) critical loading*

Figure 98 (LTR vs. HSTO) shows little correlation, and quite a wide spread of performance. Many vehicles fail LTR while passing Level 2 HSTO for both loading cases. Figure 99 (HSSO vs. HSTO) exhibits a small level of correlation, though with combinations 5.3, 6.1 and 6.4 the most notable outliers. These combinations are amongst the longer combinations. Figure 100 (YD vs HSTO) shows a reasonable correlation, more so in the representative loading case that the critical loading case.



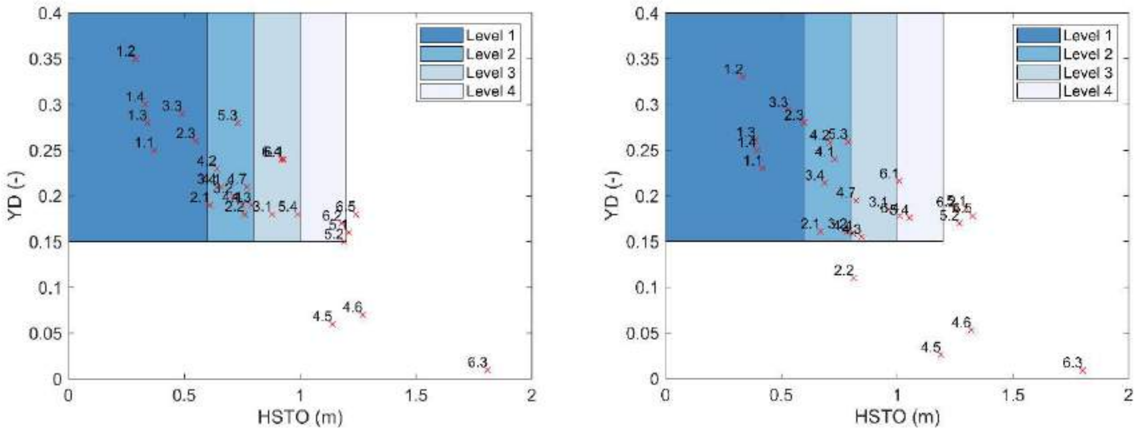

(a) (b)

*Figure 98: Correlation between LTR and HSTO: (a) representative loading, (b) critical loading*




(a) (b)

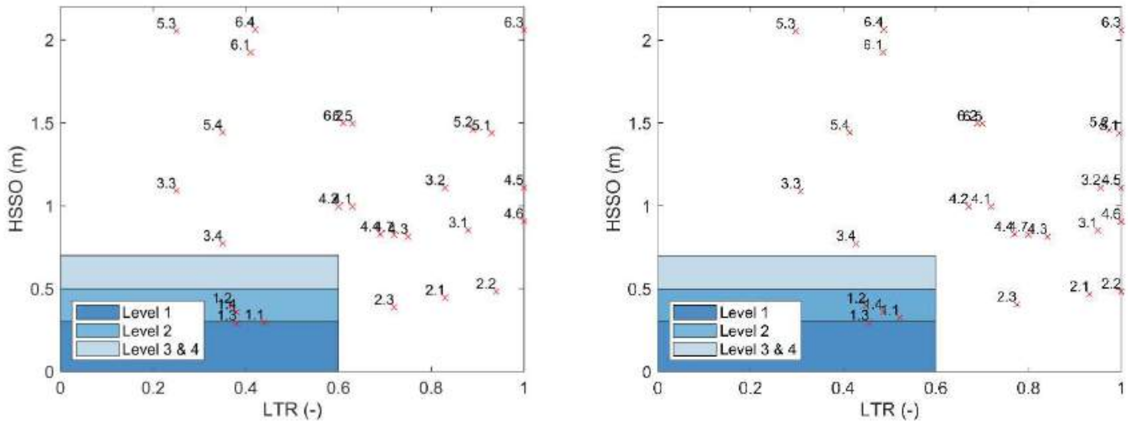
*Figure 99: Correlation between HSSO and HSTO: (a) representative loading, (b) critical loading*




(a) (b)

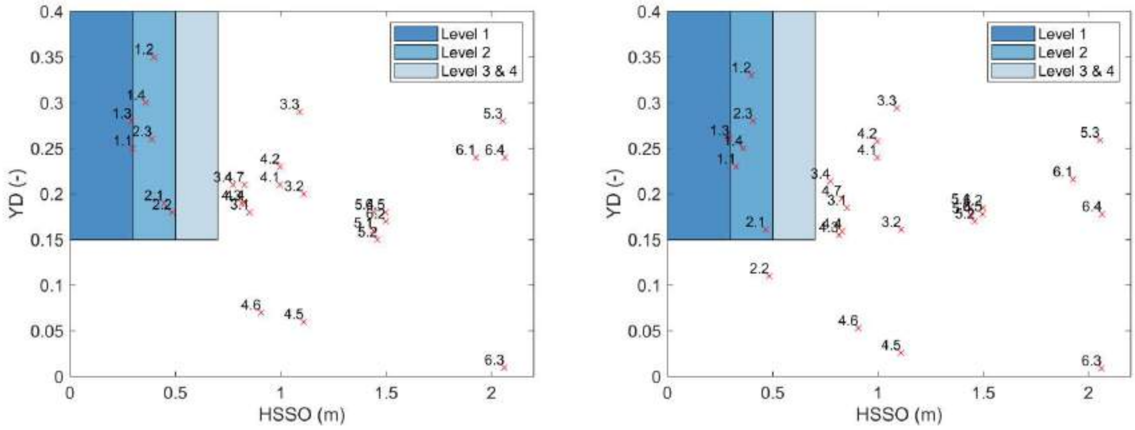
*Figure 100: Correlation between YD and HSTO: (a) representative loading, (b) critical loading*

Figure 101 (HSSO vs LTR) shows no correlation, as does Figure 102 (YD vs. HSSO). Figure 103 (YD vs. LTR) exhibits a small level of correlation, but not enough to exclude either standard going forwards.




(a) (b)

*Figure 101: Correlation between HSSO and LTR: (a) representative loading, (b) critical loading*




(a) (b)

*Figure 102: Correlation between YD and HSSO: (a) representative loading, (b) critical loading*

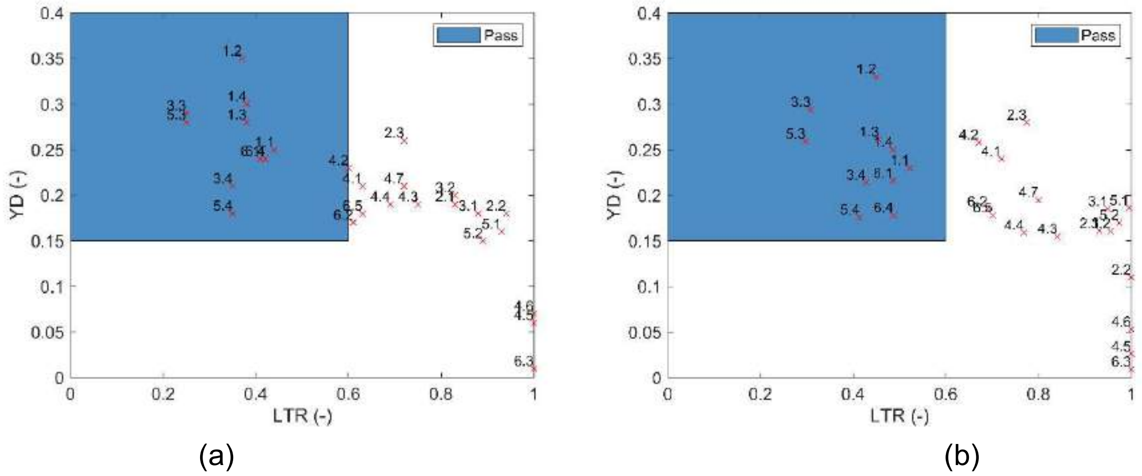



*Figure 103: Correlation between YD and LTR: (a) representative loading, (b) critical loading*

# Appendix E *Winter Simulation Results*

*Table 86. Data from transient manoeuvre simulation*

| Veh | RA_r 88 | RA_r 70 | RA_r 60 | RA_ay 88 | RA_ay 70 | RA_ay 60 | HSTO 88 | HSTO 70 | HSTO 60 |
|---|---|---|---|---|---|---|---|---|---|
| **11** | 1.06 | 0.83 | 0.76 | 1.25 | 1.03 | 0.89 | 0.22 | 0.33 | 0.22 |
| **12** | 0.93 | 0.72 | 0.64 | 1.07 | 0.84 | 0.73 | 0.18 | 0.22 | 0.11 |
| **13** | 1.01 | 0.81 | 0.74 | 1.23 | 1.01 | 0.87 | 0.21 | 0.31 | 0.20 |
| **14** | 0.96 | 0.76 | 0.68 | 1.18 | 0.93 | 0.80 | 0.20 | 0.26 | 0.15 |
| **21** | 1.47 | 1.34 | 1.22 | 2.08 | 1.41 | 1.31 | 0.49 | 0.74 | 0.52 |
| **22** | 2.48 | 3.55 | 2.30 | 2.47 | 1.63 | 1.62 | 0.64 | 1.11 | 0.77 |
| **23** | 1.38 | 1.34 | 1.23 | 1.85 | 1.35 | 1.19 | 0.37 | 0.62 | 0.44 |
| **31** | 1.74 | 1.45 | 1.19 | 2.03 | 1.63 | 1.30 | 0.53 | 0.85 | 0.53 |
| **32** | 1.93 | 1.22 | 1.04 | 2.20 | 1.47 | 1.26 | 0.77 | 0.97 | 0.64 |
| **33** | 1.41 | 0.98 | 0.79 | 1.08 | 0.72 | 0.58 | 0.54 | 0.67 | 0.41 |
| **34** | 1.29 | 0.97 | 0.81 | 1.51 | 1.21 | 0.95 | 0.40 | 0.59 | 0.37 |
| **41** | 1.74 | 1.54 | 1.30 | 1.39 | 1.08 | 0.87 | 0.70 | 1.10 | 0.69 |
| **42** | 1.80 | 1.66 | 1.39 | 1.31 | 1.12 | 0.87 | 0.68 | 1.12 | 0.69 |
| **43** | 1.65 | 1.45 | 1.24 | 1.91 | 1.42 | 1.22 | 0.53 | 0.87 | 0.57 |
| **44** | 1.87 | 1.66 | 1.39 | 1.83 | 1.50 | 1.30 | 0.55 | 1.00 | 0.66 |
| **45** | 2.44 | 2.16 | 1.51 | 2.77 | 1.75 | 1.50 | 0.92 | 1.42 | 0.93 |
| **46** | 2.50 | 3.43 | 2.14 | 3.06 | 1.98 | 1.74 | 0.75 | 1.63 | 1.03 |
| **47** | 2.03 | 1.69 | 1.42 | 1.48 | 1.78 | 1.34 | 0.55 | 1.13 | 0.74 |
| **51** | 2.10 | 1.53 | 1.18 | 2.29 | 1.64 | 1.40 | 0.76 | 1.20 | 0.72 |
| **52** | 2.20 | 1.52 | 1.26 | 2.22 | 1.66 | 1.43 | 0.73 | 1.32 | 0.73 |
| **53** | 1.62 | 1.09 | 0.80 | 1.29 | 0.87 | 0.64 | 0.75 | 0.91 | 0.51 |
| **54** | 1.61 | 1.15 | 0.89 | 1.84 | 1.44 | 1.06 | 0.60 | 0.88 | 0.52 |
| **61** | 1.97 | 1.54 | 1.14 | 1.74 | 1.03 | 0.94 | 1.12 | 1.70 | 1.08 |
| **62** | 1.88 | 1.09 | 1.00 | 2.28 | 1.22 | 1.13 | 0.91 | 1.34 | 0.91 |
| **63** | 10.48 | 2.96 | 2.62 | 5.85 | 2.02 | 1.85 | 1.60 | 3.87 | 1.91 |
| **64** | 2.19 | 1.87 | 1.44 | 1.62 | 1.16 | 0.87 | 0.95 | 1.58 | 0.85 |
| **65** | 2.14 | 2.07 | 1.39 | 2.33 | 1.71 | 1.39 | 0.79 | 1.40 | 0.86 |

*Table 87. Data from friction demand simulation*

| Veh | FD_steer high | FD_steer low | FD_drive high | FD_drive low |
|---|---|---|---|---|
| **11** | 0.20 | 0.11 | 0.45 | 0.24 |
| **12** | 0.21 | 0.12 | 0.40 | 0.22 |
| **13** | 0.07 | 0.05 | 0.15 | 0.08 |
| **14** | 0.07 | 0.05 | 0.12 | 0.07 |
| **21** | 0.10 | 0.06 | 0.29 | 0.16 |
| **22** | 0.16 | 0.09 | 0.36 | 0.20 |
| **23** | 0.08 | 0.06 | 0.25 | 0.14 |
| **31** | 0.19 | 0.11 | 0.48 | 0.27 |
| **32** | 0.19 | 0.11 | 0.46 | 0.26 |
| **33** | 0.20 | 0.12 | 0.47 | 0.27 |
| **34** | 0.19 | 0.11 | 0.50 | 0.28 |
| **41** | 0.11 | 0.07 | 0.47 | 0.27 |
| **42** | 0.12 | 0.07 | 0.47 | 0.27 |
| **43** | 0.14 | 0.09 | 0.48 | 0.27 |
| **44** | 0.16 | 0.09 | 0.48 | 0.27 |
| **45** | 0.12 | 0.08 | 0.47 | 0.27 |
| **46** | 0.32 | 0.15 | 0.48 | 0.22 |
| **47** | 0.34 | 0.15 | 0.48 | 0.22 |
| **51** | 0.19 | 0.11 | 0.48 | 0.27 |
| **52** | 0.19 | 0.11 | 0.48 | 0.27 |
| **53** | 0.20 | 0.11 | 0.48 | 0.27 |
| **54** | 0.19 | 0.10 | 0.51 | 0.28 |
| **61** | 0.16 | 0.10 | 0.47 | 0.27 |
| **62** | 0.16 | 0.10 | 0.47 | 0.26 |
| **63** | 0.12 | 0.08 | 0.47 | 0.27 |
| **64** | 0.25 | 0.11 | 0.46 | 0.22 |
| **65** | 0.37 | 0.16 | 0.53 | 0.25 |

# Appendix F *Bridge Loading Impact Methodology*

## Methodology

*Static effect of truck on bridge*

The effect on moving loads is given by the convolution of these moving loads with the influence line of the effect. In particular, a moving vehicle with N axles would be considered as N moving loads, with given axle loads and given distance between the axles.

If $I_i(x)$ is the value of the influence line of effect $i$ at coordinate $x$ and we consider truck $j$, the global effect at coordinate x $E_i(x)$ is given by the sum of the effects of all axles:

$$E_{i,j}(x) = \sum_{n=1}^{N} P_{j,n} I_i\left(x - d_{j,n}\right), \tag{17}$$

where:

- $P_{j,n}$ is the axle load on axle $n$ of truck $j$,
- $d_{j,n}$ is the distance between axle 1 and axle $n$ for truck $j$ (so by definition, $d_{j,1} = 0$).

The values of $P_{j,n}$ and $d_{j,n}$ are given by the vehicle configurations and the function $I_i(x)$ is representative of the chosen infrastructure. The effect $E_{i,j}(x)$ is generally a stress (in MPa or kN/m$^2$) or a strain (in µm/m) in the structure.

*Extreme effect*

The maximum of this effect $E_{i,j}(x)$ is then assessed for various vehicle configurations. Two vehicle configurations can then be compared in terms of extreme effects by calculating the ratio of the effect $E_{i,j}(x)$.

More precisely, to compare the extreme effects induced by two different vehicles, the ratio of each vehicle is given by:

$$R_{i,j} = \frac{E_{i,j}}{E_{i,ref}}, \tag{18}$$

where :

- $R_{i,j}$ depends on the type of effect $i$ and the vehicle $j$,
- $E_{i,j}$ is the maximum effect $i$ of vehicle $j$,
- $E_{i,ref}$ is the maximum effect $i$ of the reference vehicle (for example, the 40-t conventional trailer).

By definition, for all effects, $\forall i$, $R_{i,ref} = 1$.

*Fatigue*

Fatigue is a slow damaging process affecting mainly steel bridges, or steel elements of composite bridges. It consists of a progressive and localized structural damage identified by crack propagation in a material is subjected to cyclic loading. Fatigue is governed by GVW and/or axle loads, depending on the span length and the active load effect.

The lifetime in fatigue of a structure is either the total number of stress cycles to failure, or the duration to get them. The number of cycles to failure N for repeated loads of constant amplitude depends on the stress amplitude $\Delta\sigma$ as given by the S-N (Woehler) curves (Figure 104):

$$\begin{cases} N \times \Delta\sigma^3 = 5.10^6 \Delta\sigma_D^3 \; if \; \Delta\sigma \geq \Delta\sigma_D \;, \\ N \times \Delta\sigma^5 = 5.10^6 \Delta\sigma_D^5 \; if \; \Delta\sigma_D \; > \Delta\sigma \geq \Delta\sigma_L \;, \\ N = \infty \; if \; \Delta\sigma < \Delta\sigma_L \;, \end{cases} \tag{19}$$

where :

- $\Delta\sigma$ is the stress cycle amplitude,
- $\Delta\sigma_L$ is the fatigue limit (depends on the material and the structural element shape, and is given in the Eurocode 3 or other standards),
- $\Delta\sigma_D$ is the endurance limit (depends on the material of the structural element).

The elementary damage induced by one cycle of amplitude $\Delta\sigma$ is 1/N, and for a series of n cycles of this amplitude, the cumulated damage is n/N. For a series of cycles with variable amplitudes, counted with the “rain-flow” method, represented by an histogram (ni, $\Delta\sigma_i$ ), the total damage induced is given by the Miner’s law: d=$\Sigma$ ($n_i/N_i$). Finally, the lifetime is: T=t/d, where t is the duration to get the series of cycles considered.
The aggressiveness of a given vehicle is proportional to the elementary damage caused to a detail (a structural element) by this vehicle crossing a bridge and is generally given by an equivalent number of standard vehicles (to be defined) causing the same damage.

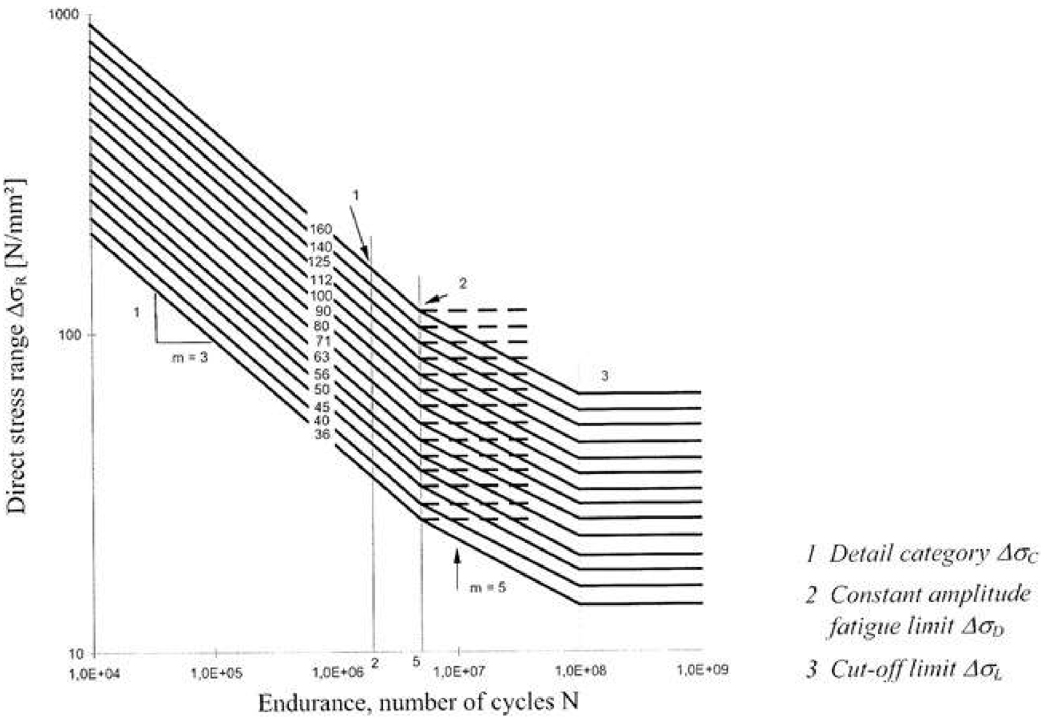



*Figure 104: S-N Woehler curves (extracted from Eurocode 3, EN1993).*

This damage phenomena makes it possible to compare the effect of different vehicles. But to design bridges, one would use the load models of Eurocode 1.

# Appendix G *Literature Digest for Road Wear Impact*

## Mechanisms and models

The load of a heavy vehicle is transferred into the road structure and generates stresses and strains. The recurrent application of loads will eventually lead to failure of the materials in the road structure.
Fatigue appears in different ways for different materials. Therefore, the models used for flexible, semi-rigid and rigid pavements, asphalt concrete and cement concrete are different. Fatigue will lead to the appearance of cracks in the different layers of the road structure.
In particular, multilayer models of the road structure are used for the evaluation of

- vertical strain at the top of the layer of unbound materials and/or of the subgrade;
- transverse strain at the bottom of each of the layers of bound materials;
- transverse stress on the base of each of the layers of bound materials.

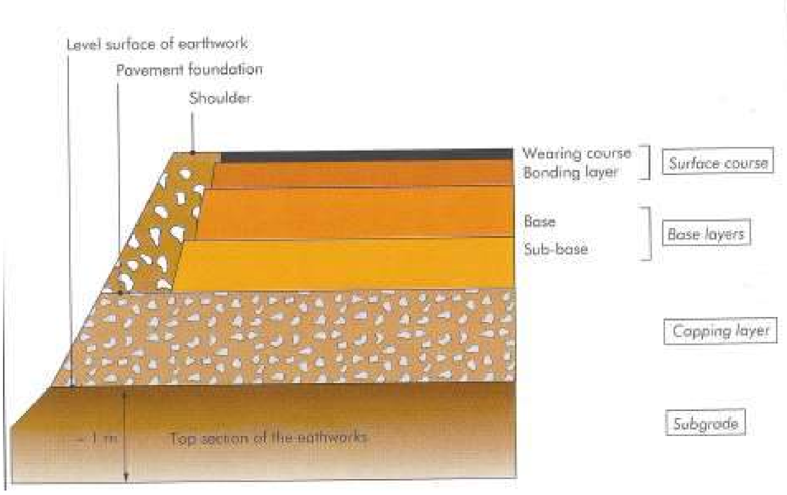



*Figure 105: Multi-layer model of a road structure*

For different materials different models are used throughout the world and within Europe: the number of layers vary, and also the location where strains and stresses are considered differ.

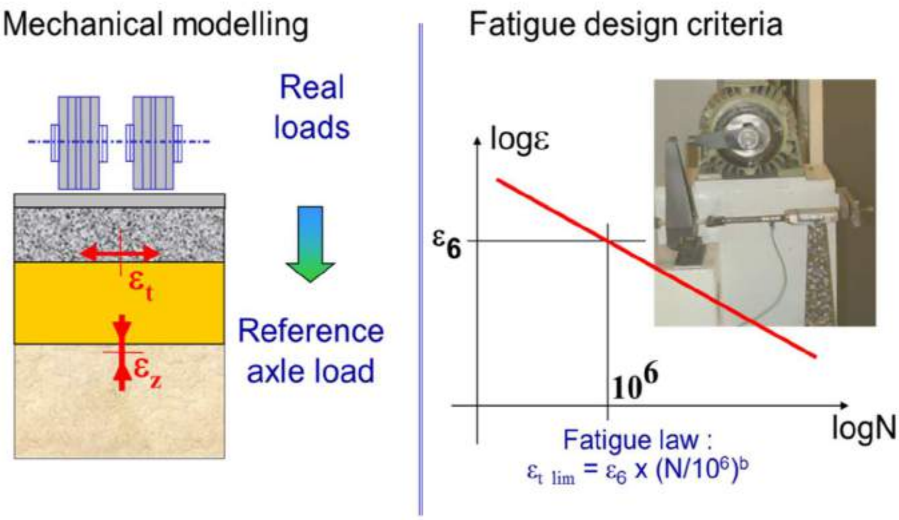



*Figure 106: Illustration of strain and stress generated by a traffic load*

For asphalt concrete pavements the appearance of rutting (permanent vertical deformation in the wheel tracks) is an additional issue. Rutting may even appear in the base course over time. According to [61], an investigation of the effect of traffic loading showed that an increase in wheel load would result in a proportional increase in rutting. Therefore, rutting per unit of goods moved would be lowest for vehicles with the highest ratio of payload to maximum permitted weight. For this it may sometimes be more favourable to use a LHV but will also depend on the design of the vehicle.

In [62] (pages 10-13), another evaluation is made of rutting. In this reference the hypothesis that a reduction of rest periods between load applications by consecutive axles can be considered as a potential risk for more rapid increase of rutting is discussed. From the results of several laboratory studies it is concluded that it is unlikely that the LHV configurations increase the risk of rutting and it is added that the risk may even decrease due to the different load and freight distributions over a large number of axles.

In the ROADEX network countries (Finland, Sweden, Norway, Scotland) LHV's are in use and studies are performed on their influence on the condition of the road network. It is to be noted that these countries have harsh winters and frost thaw is an important issue. Also, the roads the LHV's use in these countries have often unbound material in the subgrade and the upper part of the pavement is often a rather thin layer of asphalt (of about 100mm). In a pre-study by [63], it is stated that there are three factors that reduce pavement lifetime if the number of axles per vehicle is increased:

1. the pore water pressure in the road structure can rise, especially in spring during the frost thaw and after freeze-thaw cycles, inducing a decrease of the stiffness of unbound structural materials: this may lead to rapid plastic deformation (rutting);
2. weak subgrades do not behave in a fully elastic way, hence deflections or temporary deformations cannot recover in time (before the arrival of a next axle load on the same spot): this increases pore water pressure in the subgrade and weakens it, with faster plastic deformation (rutting);
3. less wander causes more tyres to load the same wheel path: faster rutting.

It is illustrated in the report that axle load (10t rather than 8t), tyre pressure (1000kPa rather than 800kPa) and tyre types (super single tyres rather than dual tyres) have a big influence on the pavement lifetime. Thin (less than 100mm) pavements are very much exposed to an increase in rutting when super single tyres are used. Tyre pressure influences strains and stresses in the upper part of the pavement structure: higher pressure increases fatigue and risk of rutting in the upper layer. In the conclusions of this pre-study it is said that one of the best methods to improve bearing capacity is to use a thicker pavement. Also, the road drainage system should be as efficient as possible. Although this pre-study concentrates on particular road structures in the ROADEX countries it should be noted that its conclusions are of interest for one of the pavement structures under consideration: in the study presented here the flexible pavement with a layer of only 50mm of bituminous concrete on top of unbound granular material.

For roads with concrete slabs potential weaknesses near the joints between adjacent slabs is studied as well. Near joints, the weakness may be most important. As shown in [64], a good approximation of edge stress ($\sigma_{free\ edge}$) and joint stress ($\sigma_{loaded\ joint}$) can be deduced from the central stress ($\sigma_{centre}$), using following relations:

$$\sigma_{free\ edge} \cong 2\,\sigma_{centre} \qquad (20)$$

$$\sigma_{loaded\ joint} = (2-\gamma)\,\sigma_{centre} \qquad (21)$$

where γ is the amount of shear transferred at the joint from the loaded slab to the unloaded slab. In the Walloon Region (Belgium) the following values are used: γ = 0.8 for CRCP, γ = 0.5 for dowelled slabs and γ = 0.2 for undowelled slabs.

The stress at the joint can also be determined from the stress at the free edge and the ratio *w* of the deflection at the unloaded side of the joint to the deflection at the loaded side of the joint. The formula of this relation varies in the literature (see [65]). In the Walloon Region (Belgium), in absence of other information the following formula is used [66]:

$$\sigma_{loaded\ joint} = \frac{\sigma_{free\ edge}}{1 + w} \tag{22}$$

With the model described in [67] for concrete slabs, the stresses in the centre and at the free edge can be determined. This approach has been implemented in the software “DimMET”, now renamed to “Qualidim”.
Usually, a road is designed for a period of 20 to 40 years and for the traffic that is expected to use the road over this period. Only the heavy loads from vehicles such as trucks, busses and agricultural vehicles are considered when it comes to fatigue and bearing capacity. Indeed, these vehicles produce loads that are far more important than the light vehicles (motorcycles, cars, delivery vans, etc.). Moreover, the impact of a load on the road structure is expressed in a law with a power 4 factor which significantly increases the aggressiveness of heavy vehicles over light vehicles. The spectrum of the traffic is quite large and is composed of vehicles with very different loads and very different axle configurations. In order to simplify the analysis, the loads generated by individual vehicles are usually translated in equivalent standard axle loads. It is common practice to inforce a maximum allowed axle load per vehicle axle. The effect of an “overloaded” axle can be illustrated by the evaluation and comparison of the aggressiveness of different axle loads.
In theory, a moving wheel will temporarily apply a load to the road structure at a particular position and will then move on: on a particular position the load is applied and then relaxed. At a particular position, the load will temporarily deform the road structure. This means that after a while the road structure will regain its original form. However, the second or third wheel of an axle group (tandem, tridem) will rapidly apply a new load, before the road structure has had the time to regain its original form. Therefore, axle groups are potentially more aggressive than individual axles with the same load. Axle groups are used in order to distribute much larger loads than the maximum allowed axle load over several axles, each of these axles respecting the maximum allowed axle load individually. This is also the main reason for the design of trucks with large axle groups, grouping as much as 8 axles, and the evaluation of their impact on road structures as in [68].

## Similar evaluations presented in literature

The impact of longer and heavier vehicles on the bearing capacity of roads has already been studied and results are available in the literature (e.g. [61], [62], [69], [70]). These studies used different approaches. Some studies are limited to the comparison of the impact of LHVs with the impact of ordinary trucks while other studies evaluate the effect of an LHV on the road structure. In both approaches, not only the impact of the vehicles can be considered but also the amount of goods (and their weights) that can be transported by these vehicles. Some other literature addresses particular vehicles with many axles and large axle groups (e.g. [68], [71]–[73]).
In [61] a simple definition is applied for the effect of road wear by axle loads. It is stated that the structural road wear attributable to vehicles is normally assumed to be proportional to the fourth power of the axle weight (for bituminous pavements). Structural road wear is measured in terms of “standard axles”, where one standard axle is defined (in the UK) as the wear associated with an 8.16 tonne axle and the wearing power of a heavier or lighter axle is calculated as:

$$Road\ wear\ factor\ (standard\ axles) = \left(\frac{axle\ weight\ in\ tonnes}{8.16}\right)^4 \tag{23}$$

The road wear factor is a measure for the aggressiveness of the axle load. This then allows comparing different vehicle types. This simple formula indeed allows illustrating the impact of different loads on road wear: light vehicles have almost no impact compared to heavy vehicles and overloaded vehicles have very high impact because of the “power 4” in the formula. This formula can only be applied to bituminous pavements and does not immediately take the

differences in effect on road wear between the various existing axle configurations into account.
In [69] (page 107), the aggressiveness $A_i$ of an axle $i$ towards a specific layer in the multilayer road structure model is defined as follows:

$$A_i = \left(\frac{s_i}{s_{ref}}\right)^{\alpha} \tag{24}$$

where

$s_i$: the stress on the bottom of the layer, under the considered axle $i$;
$s_{ref}$: the stress on the bottom of the layer due to the reference axle;
$\alpha$: a coefficient of fatigue depending on the material of the layer.

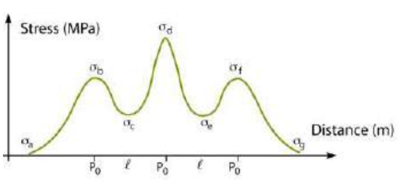
Then for the aggressiveness $A$ of a vehicle on a specific layer, all its axles are combined with the following formula:

$$A = \sum_i A_i, \tag{25}$$

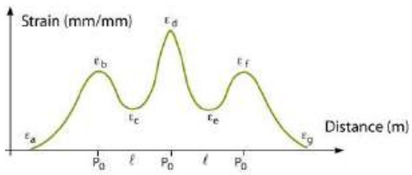
summing over all axles $i$.
Clearly this definition of aggressiveness $A$ depends on the road structure itself, both for the importance of the ratio between stresses $s_i$ and $s_{ref}$, and for the coefficient of fatigue $\alpha$. This approach allows comparing the aggressiveness of different trucks, characterised by different axle configurations and their individual axle loads. In [69] the Alizé-LCPC software was used to model different road structures and to determine the stresses due to loaded axles of different vehicle shapes on these road structures. Computations were made for four types of road structures: a flexible pavement, a bituminous pavement, a thick bituminous pavement and a semi-flexible pavement (as they were called in [69]). The model behind the representation of the road structures in the Alizé-LCPC software is the multilayer model of Burmister [46]. With the Alizé-LCPC software different types of axles were modelled: single, tandem or tridem axles.
In reality, roads are not exposed to the repetitive application of one particular load. Each of the different loads applied to the road contributes at a different extend to the damaging effects of the traffic. Miner's rule is one of the most widely used cumulative damage models for failures caused by fatigue. The damaging effects of various loads $P_i$ with relative frequency $f_i$ in the load spectrum applied to the same road section can be combined using Miner's rule expressed by the following formula:

$$\frac{1}{N} = \sum_i \frac{f_i}{N_i} \tag{26}$$

where failure would occur when load $P_i$ would be the exclusive load that is applied $N_i$ times to the road section and where *1/N* represents the fraction of life consumed by exposure to the cycles at the different load levels.
Stet et al. [74] present an approach for the evaluation of the effect of tandem and tridem axle configurations and applies it to concrete roads.



Tensile stresses at the bottom of the pavement (tridem axle)

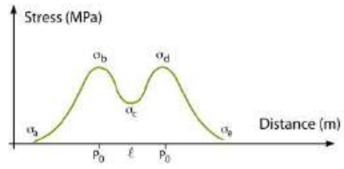


Strains at the bottom of the pavement (tridem axle)

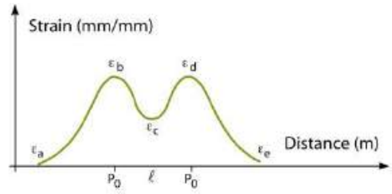
When we consider a tridem axle combination, the effect on the stresses or strains is a sequence of three high values with intermediate partial relaxations. With Miner's rule, the effect of the tridem axle can be decomposed in three parts, by the following formula:

$$3\ N_{TR} = \frac{1}{\frac{1}{3}\frac{1}{N_b} + \frac{1}{3}\frac{1}{N_d} + \frac{1}{3}\frac{1}{N_f}} \tag{27}$$

where $N_{TR}$ is the total number of tridem axle combinations after which failure of the road structure occurs. The total load of the tridem axle combination is a consecutive loadings $P_b$, $P_d$ and $P_f$ from each of the axles that constitute the tridem axle combination. The values for $N_b$, $N_d$ and $N_f$ are the total number of individual axle loads (with a load of respectively $P_b$, $P_d$ and $P_f$) after which failure of the road structure occurs when they are not applied in a combined way. When the only partial relaxation between the loading from the consecutive axles in the tridem combination is not taken into account, $N_b = N_f < N_d$ holds.




Tensile stresses at the bottom of the pavement (tandem axle)




Strains at the bottom of the pavement (tandem axle)

Similarly, for a tandem axle combination, the effect on the stresses or strains is a sequence of two high values with one intermediate partial relaxation. With Miner’s rule, the effect of the tandem axle can be decomposed in two parts, by the following formula:

$$2\ N_{TA} = \frac{1}{\frac{1}{2}\frac{1}{N_b} + \frac{1}{2}\frac{1}{N_d}} \tag{28}$$

where $N_{TA}$ is the total number of tandem axle combinations after which failure of the road structure occurs. The total load of the tandem axle combination is a consecutive loadings $P_b$ and $P_d$ from each of the axles that constitute the tandem axle combination. The values for $N_b$ and $N_d$ are the total number of individual axle loads (with a load of respectively $P_b$ and $P_d$) after which failure of the road structure occurs when they are not applied in a combined way. When the partial relaxation is not taken into account, $N_b = N_d$ holds.

The fatigue law for cement concrete materials for roads in use in The Netherlands and presented in [75] has the virtue of accounting for minimum and maximum stress levels and has the following format:

$$\log N = 13 \left(1 - \frac{\sigma_{bending,max}}{\sigma_{rupture}}\right) \Big/ \left(1 - 0.75\ \frac{\sigma_{bending,min}}{\sigma_{rupture}}\right) \tag{29}$$

With this formula, the value for $N_d$ in the case of the tandem axle combination and the values of $N_b$ and $N_f$ in the case of the tridem axle combination can be increased in function of the partial relaxation that occurs between the application of the consecutive loads of the axle combinations.

In [47] and [76] the same technique as in [74] is applied for both cement concrete and bituminous road materials. As in [74] the aggressiveness of traffic is linked to the road structure through the fatigue laws of the road materials. These laws express fatigue as observed in laboratory conditions on samples. For bituminous materials the fatigue law used in [47] takes the following form:

$$N_i = \left(\frac{0.0016}{\varepsilon_i}\right)^{\alpha} \tag{30}$$

where

- $N_i$: the number of repetitions of load $P_i$ before breaking of the sample;
- $\varepsilon_i$: the deformation of the sample under load $P_i$;
- $\alpha$: the slope coefficient of the fatigue curve, equal to 4.76.

For hydraulically bound materials the fatigue law in [47] is a logarithmic function:

$$\log N_i = b\left(1 - \frac{\sigma_i}{f_{frts}}\right) \tag{31}$$

where

$N_i$: the number of repetitions of load $P_i$ before breaking of the sample;
$\sigma_i$: the stress applied to the sample under load $P_i$;
$f_{frts}$: average flexural (bending) resistance from tensile stress;
$b$: the coefficient of the fatigue curve.

The value for $b$ varies between 11.8 and 20 in the rich literature on the subject. The Laboratoire de Génie Civil of the Université Catholique de Louvain found the value 12 (cf. [77]) for cement concrete and lean concrete used as road materials (in Belgium).

In [47] these fatigue laws are applied to several road structures that are commonly used in Belgium. Also, the load on each of the axles is considered equal because the objective of the computations in [47] is the comparison of the aggressiveness of tandem or tridem axle combinations with the aggressiveness of a single axle. The relative aggressiveness $A_{AC,material}$ in [47] is defined as:

$$A_{AC,material} = \frac{N_{simple,material}}{N_{AC,material}} \tag{32}$$

for *material* equal to *concrete* or *asphalt* and axle combination (*AC*) equal to tandem axle combination (*TA*) or tridem axle combination (*TR*) and with $N_{simple,material}$ the admissible number of passages before road failure of a simple axle with load $P_0$, and $N_{AC,material}$ the admissible number of passages before road failure of axle combination *AC* with loads $P_0$ on each of its axles. The distance between two consecutive axles of an axle combination (tandem or tridem) is set equal to length *l*.

An axle load $Q_i$ is distributed over two wheels, each with a charge of $P_i = Q_i / 2$. When we consider the contact area of the tyre with the road surface to be circular with a radius $\rho_i$ and we consider that the charge is uniformly distributed with pressure $p_i$, then $P_i = p_i \,.\, (\pi.\rho_i^2)$.

For the computation of relative aggressiveness of tandem and tridem axle combinations reference load $P_0$ was chosen as axle load $Q_i = 100kN$, $P_0 = (0.707\ N/mm^2, 150mm)$. Indeed, measurements have shown (see [78]) that for wheel load charges up to 50kN the pressure exercised on the road is constant and equal to 0.707 $N/mm^2$. In that case, the radius $\rho_i$ increases with increasing wheel load charge. For more important charges the radius of the contact area of the tyre stabilises and the pressure increases with increasing wheel load – but this situation is not considered in [47]. Furthermore, the Burmister multilayer model was used for the modelling of 6 different road structures, each for which the aggressiveness of the single axles and the different axle combinations was computed. The global aggressiveness $A_{Total}$ of all traffic on a road section can then be determined with the following formula:

$$A_{Total} = f_{simple}.1 + f_{TA}.\frac{A_{TA}}{2} + f_{TR}.\frac{A_{TR}}{3} \tag{33}$$

where

$f_{simple}$ is the percentage of simple axles in the axle spectrum of the traffic on the road section;
$f_{TA}$ is the percentage of tandem axle combinations in that axle spectrum;
$f_{TR}$ is the percentage of tridem axle combinations in that axle spectrum.

## Realistic traffic loads

In the past it has been observed that the real spectrum of traffic loads on roads changes over time. For instance, on Belgian roads the comparison of data collected during temporary traffic counting campaigns in 1965 and in 1990 showed the appearance of heavy vehicles with new axle combinations (the introduction of tridem axles and the increase of the number of axles per heavy vehicle). The BRRC performed a temporary weigh-in-motion (WiM) data collection

campaign on motorways on weekdays in 1998 and another temporary traffic counting campaign in 2007. From these data it was deduced that the percentage of heavy vehicles with tandem axles decreased while the percentage of heavy vehicles with tridem axles increased over time. Hence, on motorways in Belgium the average number of axles per heavy vehicle increased over time (2.7 axles in 1965, 3.6 axles in 1990, 4.05 axles in 1998, 4.23 axles in 2007, cf. [47] for details). As reported in [47], the same WiM campaign in 1998 showed that the loads on the axles of the real traffic on the roads vary a lot. The statistical distribution of the WiM data shows that for tandem axles 80% of the loads per axle were situated in the range of 30 to 60kN and that there were two peaks for tridem axles around 35 and 65kN, corresponding to different load levels among the heavy vehicles in traffic on the same time. However, the height of the load on a tandem or tridem axle is of little importance when its relative aggressiveness is computed against a single axle with the same load.
An important factor in the aggressiveness of tandem or tridem axle combinations is the distance between consecutive axles within the axle combination. Legislation allows a certain range for this distance and for the evaluation of the stresses and strains in the road structure a road engineer would be tempted to consider only the most damaging configuration of axles within all possible axle combinations. But the constructors of heavy vehicles or trailers do not necessarily produce all axle configurations foreseen as acceptable within the legal frame. From an evaluation on the field in 2007 (counting campaign and observations on parking lots along motorways) a much smaller range of distances was observed for most of the heavy vehicles on the road (see [47]):

- tridem axles: characteristic distance of 1.30m (varying between 1.25m and 1.35m),
- undriven tandem axles: characteristic distance of 1.30m (varying between 1.25m and 1.40m), or less commonly of 1.80m (varying between 1.75m and 1.85m)
- driven tandem axles: characteristic distance of 1.30m (varying between 1.25m and 1.40m).

## Appendix H *A Review of Road Wear Impact Simulation Software*

In the study presented in this document, we used the software Alizé-LCPC. Other software exists that could be used for the same purposes. Here we give a brief, non-exhaustive list of some of the software tools that are currently in use for pavement design and for the evaluation of existing pavements.

*Alizé-LCPC*

The Alizé-LCPC software is one of the commonly used tools for the design of road structures. Additional modules also address back-calculation of deflection measurements for the estimation of the elasticity modules of the different layers of existing roads or the design of the "road" structures on airfields. It is a software that allows the setting of many different parameters and is therefore an especially well-suited for detailed and specialised computations (such as those reported on here).

*PAVERS*

The PAVERS pavement design tool is extensive software including the design of road structures, a module addressing back-calculation of deflection measurements and a module for the evaluation of airfield pavements (see http://www.pavers.nl/).

*CHAUSSÉE*

The CHAUSSEE software is a Canadian software for structural design of flexible roads based on the AASHTO guide (1993). It is adapted to the local situation in Quebec and so that it takes into account the non-linear behaviour of granular materials.
(https://www.transports.gouv.qc.ca/fr/entreprises-partenaires/entreprises-reseaux-routier/chaussees/Pages/logiciel-dimensionnement.aspx)

*VENCON 2.0*

Software by CROW in The Netherlands, dedicated to the design of concrete road structures. It allows to determine the layer thickness of the reinforced or non reinforced concrete layer.

*ELMOD*

This is a software for pavement analysis implemented by the company Dynatest and designed for the evaluation of existing pavements (of roads and airfields) and their rehabilitation (see https://www.dynatest.com/elmod-software).

*Bisar*

BISAR (BItumen Stress Analysis in Roads) is a well-known software used in mechanistic pavement design practices. It was developed by Shell and it is a part of Shell Pavement Design Method (see [79]). The basic assumptions (as given in "Deliverable D3.3 – Mechanical analysis and recommendation for design of PERS" of the EC FP7 project PERSUADE) of this method are:

- the materials are elastic and have a linear stress-strain relationship,
- the system is loaded on top of the structure by one or more circular loads, with a uniform stress distribution over the loaded area.

*Viscoroute*

This software uses a thermo-visco-elastic multi-layer model using the Huet-Sayegh behaviour. By means of the Fast Fourier transform method, it solves the equations of the model in the coordinate system of the moving load. Especially useful for flexible pavements and slowly moving heavy traffic, it was developed in France (cf. [80])

# Appendix I *Simulation Cross-Validation Results*

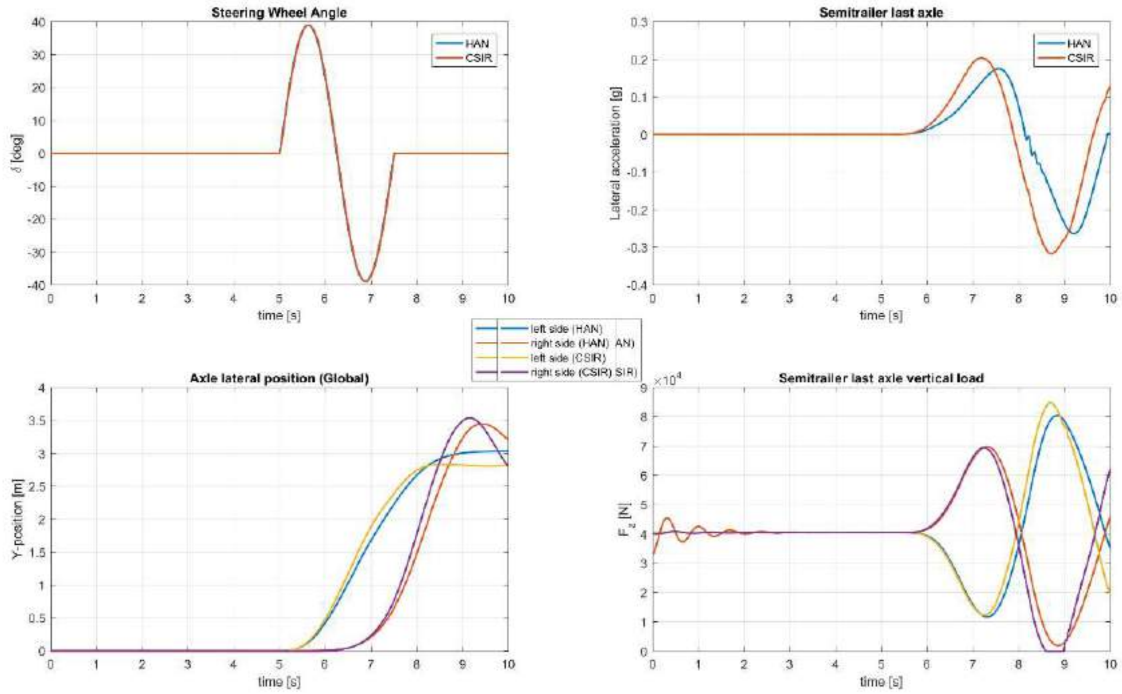



*Figure 107: Cross-validation results, lane change 1*

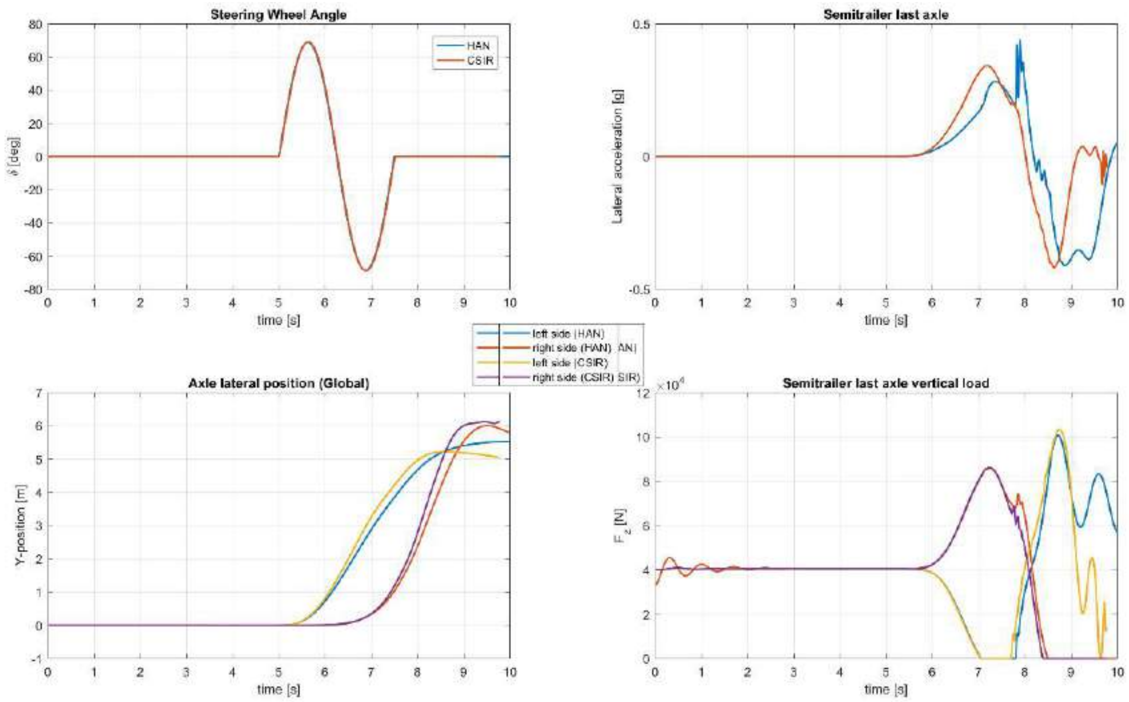



*Figure 108: Cross-validation results, lane change 2*

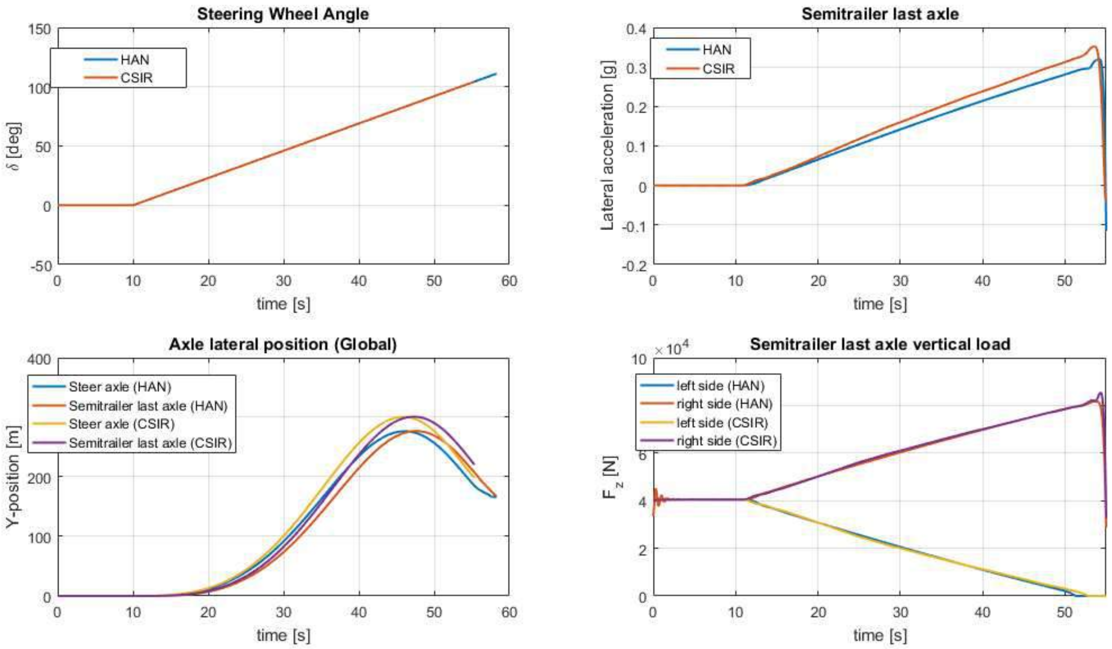
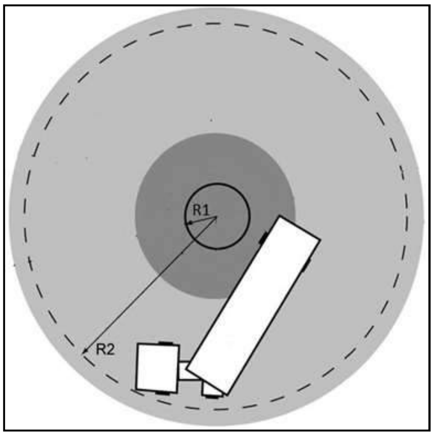



*Figure 109: Cross-validation results, J-turn*

# Appendix J *Manoeuvre Details for SIAP Validation*

## Single Lane Roundabout, dimensions of inner and outer circle

| Sr. No. | Centre Island Radius [m] | Outer Radius R2[m] |
|---|---|---|
| 1 | 2 | 14.00 |
| 2 | 3 | 14.40 |
| 3 | 4 | 14.90 |
| 4 | 5 | 15.40 |
| 5 | 6 | 16.00 |
| 6 | 7 | 16.60 |
| 7 | 8 | 17.30 |
| 8 | 9 | 18.00 |
| 9 | 10 | 18.76 |
| 10 | 11 | 19.55 |
| 11 | 12 | 20.38 |
| 12 | 13 | 21.23 |
| 13 | 14 | 22.12 |
| 14 | 15 | 23.02 |
| 15 | 16 | 23.95 |
| 16 | 17 | 24.90 |
| 17 | 18 | 25.86 |
| 18 | 19 | 26.84 |
| 19 | 20 | 27.83 |
| 20 | 21 | 28.82 |




## Multi Lane Roundabout, dimensions of inner and outer circle

| Sr. No. | Outer Radius R2 [m] | Inner Radius R1 [m] | Sr. No. | Outer Radius R2 [m] | Inner Radius R1 [m] |
|---|---|---|---|---|---|
| 1 | 30 | 24.714 | 12 | 41 | 36.218 |
| 2 | 31 | 25.776 | 13 | 42 | 37.250 |
| 3 | 32 | 26.833 | 14 | 43 | 38.280 |
| 4 | 33 | 27.887 | 15 | 44 | 39.310 |
| 5 | 34 | 28.938 | 16 | 45 | 40.337 |
| 6 | 35 | 29.985 | 17 | 46 | 41.364 |
| 7 | 36 | 31.029 | 18 | 47 | 42.389 |
| 8 | 37 | 32.071 | 19 | 48 | 43.413 |
| 9 | 38 | 33.111 | 20 | 49 | 44.436 |
| 10 | 39 | 34.149 | 21 | 50 | 45.458 |
| 11 | 40 | 35.184 | | | |

# Appendix K *Simulation Results for Determining Road Classes*

*Table 88: Simulation results, safety assessment on road classes*

| Serial No. | Group | Vehicle Combination | Vehicle Description | Radius [m] | Slope [%] | Load Density [kg/m3] | Friction [-] | Lane Width Level 3 [m] | Lane Width Level 2[m] | Lane Width Level 1[m] | Rollover probability[%] | | Jackknife Probability[%] | | Failure to Maintain speed probability[%] | | Crossed Lane Probability[%] | | Road Level | Special Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Data | PDF | Data | PDF | Data | PDF | Data | PDF | | |
| 1 | 1 | 1.1 | TR6x2-ST3 (45ft) | 40 - 150 | ±10 | 62.56 - 312.5 | 0.42-0 | 3.5 | 3.25 | 2.75 | 2.027 | 2.2 | 0 | 0 | 0.869 | 0.57 | 0.217 | 0.21 | 1 | Lower speed limit for radius 125m-150m from 70km/h to 65km/h will reduce probability of rollover from 2.027% 0.796% |
| 2 | | 1.2 | TR6x2-ST3 (2x7.8m) | 50 - 150 | ±10 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | 2.75 | 4.018 | 4.66 | 0 | 0 | 0.464 | 0.55 | 0 | 0 | 1 | Lower speed limit for radius 125m-150m from 70km/h to 65km/h will reduce probability of rollover from 4.018% to 1.08% |
| 3 | | 1.3 | TR4x2-ST3 (13.6m) | 40 - 150 | ±10 | 62.56 - 312.7 | 0.42-2 | 3.5 | 3.25 | 2.75 | 0 | 0.0463 | 0 | 0 | 0.067 | 0.0842 | 0 | 0 | 1 | |
| 4 | | 1.4 | TR4x2-ST3 (14.9m) | 40 - 150 | ±10 | 62.56 - 312.7 | 0.42-2 | 3.5 | 3.25 | 2.75 | 0.692 | 0.92 | 0 | 0 | 0.1538 | 0.21 | 0.0769 | 0.077 | 1 | |
| 5 | 2 | 2.1 | TK6x2-CT2 (2x7.8m) | 40 - 150 | ±10 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 3.409 | 3.72 | 0 | 0 | 0 | 0.00159 | 0 | 0.0482 | 2 | Lower speed limit for radius 125m-150m from 70km/h to 65km/h will reduce probability of rollover from 3.409% to 0% |
| 6 | | 2.2 | TK6x2-FT1+1 (2x7.8m) | 40 - 150 | ±10 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 1.71 | 1.92 | 0 | 0 | 0.498 | 0.49 | 0 | 0 | 2 | |
| 7 | | 2.3 | TK6x2-CT3(2x20ft) | 40 - 150 | ±10 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 1.66 | 1.41 | 0 | 0 | 0.133 | 0.21 | 0 | 0 | 2 | Lower speed limit for radius 125m-150m from 70km/h to 65km/h will reduce probability of rollover from 1.66% to 0.532% |
| 8 | 3 | 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 40 - 150 | ±6 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 0.468 | 0.59 | 0 | 0 | 0.736 | 0.93 | 0.201 | 0.15 | 2 | |
| 9 | | 3.2 | TR6x4-ST3-CT2(3x7.8m) | 40 - 150 | ±6 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 1.12 | 1.06 | 0 | 0 | 2 | Reducing slope to ±5% will bring the failure to maintain speed to below 1% |
| 10 | | 3.3 | TR6x4-LT2-ST3(3x7.8m) | 40 - 150 | ±5 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 2 | |
| 11 | | 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 40 - 150 | ±6 | 62.56 - 312.6 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 1.13 | 1.13 | 0 | 0 | 2 | Reducing slope to ±5% will bring the failure to maintain speed to below 1% |
| 12 | 4 | 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 40 - 150 | ±5 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0.207 | 0.45 | 0 | 0 | 2 | |
| 13 | | 4.2 | TK6x4-FT2+3 (3x7.8m) | 40 - 150 | ±5 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0.401 | 0.64 | 0 | 0 | 2 | |
| 14 | | 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 40 - 150 | ±6 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0.401 | 0.36 | 0 | 0 | 2 | |
| 15 | | 4.4 | TK6x4-FT2+3 (20ft+45ft) | 40 - 150 | ±6 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0.535 | 0.72 | 0.267 | 0.28 | 2 | |
| 16 | | 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 40 - 150 | ±6 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.35 | N/A | 1.2 | 1.81 | 0 | 0 | 0.424 | 0.55 | 2.475 | 2.57 | 2 | Increasing lane width of level 2 by 10cm will reduce probability of failure at level 2 to acceptable levels. Lower speed limit for radius 125m-150m from 70km/h to 65km/h |
| 17 | | 4.6 | TK8x4-CT3-CT3(3x20ft) | 40 - 150 | ±6 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.35 | N/A | 0 | 0.37 | 0 | 0 | 0.154 | 0.13 | 1.156 | 1.43 | 2 | Increasing lane width of level 2 by 10cm will reduce probability of failure at level 2 to |
| 18 | | 4.7 | TK8x4-FT2+3(20ft+45ft) | 40 - 150 | ±6 | 62.56 - 312.7 | 0.42-1 | 3.5 | 3.25 | N/A | 0 | 0 | 0 | 0 | 0 | 0.026 | 0 | 0.0328 | 2 | |
| 19 | 5 | 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0.347 | 0.41 | 0 | 0 | 0.138 | 0.17 | 0 | 0 | 3 | |
| 20 | | 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0 | 0 | 0 | 0 | 0.028 | 0 | 0 | 3 | |
| 21 | | 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0.332 | 0.29 | 0 | 0 | 0.332 | 0.6 | 0 | 0 | 3 | |
| 22 | | 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0 | 0 | 0 | 0 | 0.029 | 0 | 0 | 3 | |
| 23 | 6 | 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0.17 | 0 | 0 | 0.071 | 0.13 | 0.424 | 0.37 | 3 | |
| 24 | | 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0 | 0 | 0 | 0 | 0.031 | 0.316 | 0.46 | 3 | |
| 25 | | 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 16.64 | 16.58 | 0 | 0 | 0 | 0.054 | 0.539 | 1.13 | 3 | Lower speed limit for radius 125m-150m from 70km/h to 65km/h will lower the rollover probability from 16.48% to 0.062% |
| 26 | | 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0.18 | 0 | 0 | 0 | 0.0029 | 0.937 | 0.94 | 3 | |
| 27 | | 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 70 - 150 | ±4 | 62.56 - 312.7 | 0.42-1 | 3.5 | N/A | N/A | 0 | 0 | 0 | 0 | 0 | 0 | 0.685 | 0.9 | 3 | |

| Legend | | | |
|---|---|---|---|
| Road parameters changed from initial estimate | Road parameters same as initial estimate | Unsafe. >1% chance of failure | SAFE. <1% chance of failure |

*Table 89: Probability of exceeding lane limits during highway exits at different road classes*

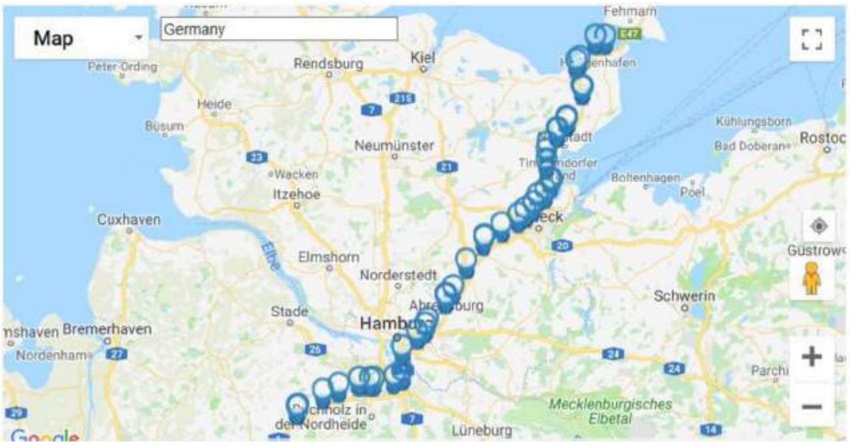
| Serial No. | Group | Vehicle Combination | Vehicle Description | Probability of Leaving the Lane [%] | | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | | Level 1 | Level 2 | Level 3 | |
| 1 | 1 | 1.1 | TR6x2-ST3 (45ft) | 0.21 | 0 | 0 | The vehicles from Group 1 shows a low probabilty of leaving the lane at all road levels. |
| 2 | | 1.2 | TR6x2-ST3 (2x7.8m) | 0 | 0 | 0 | |
| 3 | | 1.3 | TR4x2-ST3 (13.6m) | 0.001 | 0 | 0 | |
| 4 | | 1.4 | TR4x2-ST3 (14.9m) | 0.077 | 0 | 0 | |
| 5 | 2 | 2.1 | TK6x2-CT2 (2x7.8m) | 12.53 | 0.048 | 0 | The vehicles from group 2 have in general high transient offtracking compared to group 1. These vehicles crossess the lane limits on beginning of curved exit. This is why the probability of failure at level 1 is high with respect to relatively narrow lane of this road class being 2.75m. |
| 6 | | 2.2 | TK6x2-FT1+1 (2x7.8m) | 8.77 | 0.0056 | 0 | |
| 7 | | 2.3 | TK6x2-CT3(2x20ft) | 6.36 | 0 | 0 | |
| 8 | 3 | 3.1 | TR6x4-ST3-CT3(45ft+20ft) | 4.01 | 0.15 | 0.0051 | Vehicle 3.3 and 3.4 show a low probability of leaving the lane for level 1 roads. Based on the leaving the lane criteria alone these vehicle should be allowed on level 1. However, these vehicles are restricted from level 1 due to the road grade. At level 1, road grade is ±10%. Vehicles from group 3 cannot maintain a minimum speed of 30km/h beyond 5-6% road grade |
| 9 | | 3.2 | TR6x4-ST3-CT2(3x7.8m) | 3.44 | 0 | 0 | |
| 10 | | 3.3 | TR6x4-LT2-ST3(3x7.8m) | 0.66 | 0 | 0 | |
| 11 | | 3.4 | TR6x4-LT3-ST3(20ft+45ft) | 0.33 | 0 | 0 | |
| 12 | 4 | 4.1 | TK6x4-DY2-ST3 (3x7.8m) | 7.85 | 0 | 0 | Vehicles 4.5 and 4.6 show a probability of failure >1% at level 2. However, out of all the failure cases for these 2 vehicles, 82% of the failed cases crossed the lane by less than 10cm. |
| 13 | | 4.2 | TK6x4-FT2+3 (3x7.8m) | 8.76 | 0 | 0 | |
| 14 | | 4.3 | TK6x4-DY2-ST3 (20ft+45ft) | 12.32 | 0 | 0 | |
| 15 | | 4.4 | TK6x4-FT2+3 (20ft+45ft) | 13.77 | 0.28 | 0.027 | |
| 16 | | 4.5 | TK6x4-CT2-CT2 (3x7.8m) | 18.37 | 2.57 | 0.11 | |
| 17 | | 4.6 | TK8x4-CT3-CT3(3x20ft) | 16.04 | 1.43 | 0.0412 | |
| 18 | | 4.7 | TK8x4-FT2+3(20ft+45ft) | 15.01 | 0.0328 | 0 | |
| 19 | 5 | 5.1 | TR6x4-ST3-DY2-ST3 (2x45ft) | 17.28 | 0.67 | 0.0067 | The vehicles in group 5 show a low probability of failure at level 2. However, these vehicles (Group 5 and 6) have only been simulated for the level 3 radius range of 70m - 150m. The probability of failure is low because radii of 40m-70m have not been included. At these low radius exits these vehicles have a high swept path which will cause the vehicle to leave the lane limits. If these vehicles are simulated for the entire radius range the probability of failure to maintain lane at level 2 will be higher. Therefore group 5 and 6 vehicles are not allowed on level 2 |
| 20 | | 5.2 | TR6x4-ST3-FT2+3 (2x45ft) | 20.27 | 0.0816 | 0 | |
| 21 | | 5.3 | TR6x4-LT2-LT2-ST3 (4x7.8m) | 11.09 | 0.0175 | 0 | |
| 22 | | 5.4 | TR6x4-LT3-LT3-ST3 (2x20ft+45ft) | 15.57 | 0 | 0 | |
| 23 | 6 | 6.1 | TK6x4-DY2-LT2-ST3 (4x7.8m) | 25.22 | 3.05 | 0.37 | |
| 24 | | 6.2 | TK6x4-DY2-LT3-ST3 (2x7.8m+45ft) | 23.9 | 4.92 | 0.46 | |
| 25 | | 6.3 | TK6x4-CT2-CT2-CT2 (4x7.8m) | 31 | 7.06 | 1.13 | |
| 26 | | 6.4 | TK8x4-LT2+2-ST3 (4x7.8m) | 23.54 | 4.08 | 0.99 | |
| 27 | | 6.5 | TK8x4-LT2+3-ST3 (2x20ft+45ft) | 25.66 | 6.14 | 0.9 | |

*Table 90: Radius dimensions of exits on A1 highway - Netherlands*

| Location | Radius [m] |
|---|---|
| Diemen-Noord | 48 |
| Hakkelaarsburg | 100 |
| Bussum | 54 |
| Blaricum | 40 |
| Larren | 43 |
| Hilversum | 42 |
| Knoopunt - Eemnes | 80 |
| Knoopunt - Eemnes | 142 |
| Knoopunt - Eemnes | 70 |
| Eembrugge | 75 |
| Eembrugge | 48 |
| Bunschoten-Spakenburg | 54 |
| Bunschoten-Spakenburg | 45 |
| Knoopunt Hoevelaken | 75 |
| Hoevlaken | 66 |
| Voorthuizen | 56 |
| Voorthuizen | 150 |
| Stroe | 56 |
| Stroe | 62 |
| Kootwijk | 50 |
| Hoenderloo | 53 |
| Apeldoorn-Zuid | 60 |
| Knooppunt-Beekbergen | 84 |
| Voorst | 55 |
| Deventer | 55 |
| Deventer-Oost | 82 |
| Bathmen | 80 |
| Markelo | 59 |
| Knooppunt Azelo | 92 |
| Knooppunt Buren | 75 |
| Westermaat Zuid-Oost | 81 |
| Hengelo Noord | 80 |
| Oldenzaal | 60 |
| Oldenzaal Zuid | 47 |
| De Lutte | 50 |

*Table 91: Radius dimensions of exits on Bundesautobahn 1 highway - Germany*

| Location | Radius [m] |
|---|---|
| Strandhusen | 40 |
| Heiligenhafen - Mitte | 40 |
| Oldenburg iH-Nord | 47 |
| Oldenburg iH-Mitte | 50 |
| Lehnsahn | 139 |
| Lehnsahn | 54 |
| Neustadt iH-Pelzerhaken | 150 |
| Neustadt iH-Pelzerhaken | 51 |
| Neustadt iH-Mitte | 138 |
| Neustadt iH-Mitte | 43 |
| Euten | 130 |
| Scharbeutz | 150 |
| Pansdorf | 135 |
| Ratekau | 138 |
| Ratekau | 45 |
| Sereetz | 62 |
| Bad Schwartau | 77 |
| Lubeck-Zentrum | 83 |
| Lubeck Moisling | 131 |
| Kreuz Lubeck | 72 |
| Reinfield | 150 |
| Bad Oldesloe | 145 |
| Bad Oldesloe | 58 |
| Bargteheide | 57 |
| Ahrensburg | 67 |
| Stapelfeld | 126 |
| Stapelfeld | 59 |
| HH-Ojendorf | 136 |
| HH-Billstedt | 150 |
| HH-Moorfleet | 102 |
| HH-Harburg | 150 |
| Maschener Kreuz | 65 |
| Seevetal-Hittfeld | 51 |
| Dibbersen | 71 |
| Buchholzer Dreieck | 133 |
| Mienenbuttel | 130 |
| Hollenstead | 63 |
| Heidenau | 65 |
| Sittensen | 116 |
| Sittensen | 46 |



## Appendix L *Representative example of road*

Herein we identify a possible route that would comply with the criteria of road level 2, given in Section 7. The route begins at Stockholm Port located at Frihamnen Magasin 2, 115 56 Stockholm, Sweden, and goes to Kleiner Grasbrook Dock located at Asiastrasse 19, 20457 Hamburg, Germany. The road has been selected due to its high inter-modal potential at both destinations, and due to it being a part of the existing Scandinavian-Mediterranean Corridor of the TEN-T road network. The road overview is given in Figure 110. The critical segments of the road will be considered next

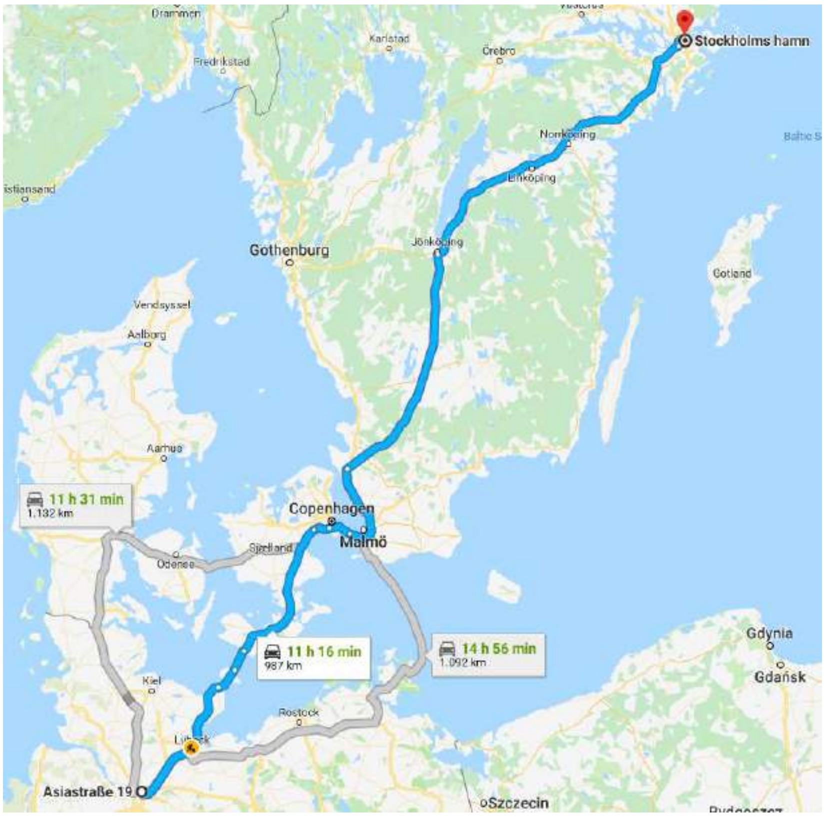



*Figure 110: Route satisfying the criteria of road level 2*

To get onto the highway from Stockholm harbour, a multilane roundabout (crossing of Sodra Hamvagen and Norra Lanken) needs to be navigated, as shown in Figure 111. The roundabout complies with the established limits.


*Figure 111: Multi-lane roundabout satisfying the criteria of road level 2*

Furthermore, the route involves a highway exit near Jonkoping, as shown in Figure 112, which has an exit radius of 40m, which also comply with the requirements.


*Figure 112: Highway exit satisfying the criteria of road level 2*

The longitudinal profile of the route is shown in Figure 113. The maximum slope stays within the tolerance of ±6%.

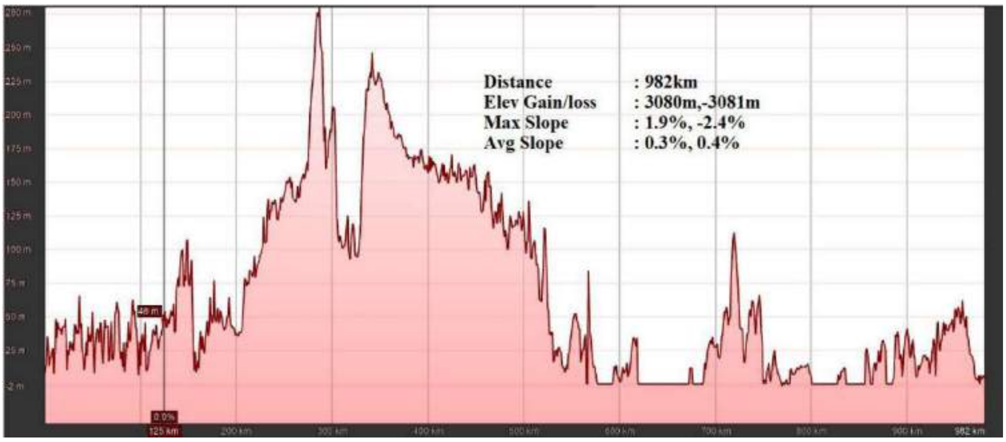



*Figure 113: Longitudinal profile of the route*

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