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PRIMA
PRO-ACTIVE INCIDENT MANAGEMENT

Assessment results of incident management procedures

Deliverable 3.1
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AIT AUSTRIAN INSTITUTE OF TECHNOLOGY
TNO innovation for life
TRL Creating the future of transport
vti FINDING A BETTER WAY

CEDR Call 2013: Traffic Management
PRIMA
Pro-Active Incident Management

Assessment results of incident management procedures

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Executive summary

Non-recurrent events such as road accidents, vehicle breakdowns and extraordinary congestion – henceforth referred to as traffic incidents – affect travel times, safety and the environment, and also generate costs associated with these impacts. Therefore, road administrations must manage incidents in a safe and efficient manner. Typically, every country has its own traffic incident management (TIM) regulations and strategies, but there is a need for transnational practical guidance to achieve an optimal balance of cost and risk factors. In order to develop such practical guidance appropriate tools for assessment need to be defined and applied, and if needed enhanced.

This deliverable presents the approach taken in PRIMA for assessing the effect on incident duration and travel time delay for different incident management techniques. The assessment both considers novel technologies (such as eCall, floating-car vehicle data, Video Incident Detection System etc.) for decreasing the duration of the discovery, verification and initial response phases as well as more traditional scene management techniques, e.g. regarding how many lanes to close, if towing should be done immediately or later during off-peak, if incident screens should be mounted or not, etc.

The assessment was conducted using a scenario-based approach. By using the information from the PRIMA best practice review and the stakeholder consultation as base, a total of four different incident scenarios were developed during a comprehensive workshop held with the project team. The four traffic incident scenarios (all considering motorways) are:

Scenario 1: Car to car collision involving injury, before traffic peak
Scenario 2: Unsafe road conditions due to adverse weather leading to congestion
Scenario 3: Large Goods Vehicle stranded on a motorway
Scenario 4: Unpredictable congestion due to obstruction on a motorway

The assessment was conducted in three different steps. The first step was to assess novel and innovative techniques for incident management. This involved qualitative assessment of solutions for detecting, classifying and verifying incidents based on promising technologies that are likely to be wide-spread in the near future. The assessment showed that given relevant requirements, like communication networks available and appropriate penetration rates, vehicle-based systems provide good capability for the detection of incidents whereas video-based systems provide good capability for the verification of incidents. Potential time savings due to overlapping of phases may result from direct communication links with involved or reporting persons. The actual time savings depend on the baseline conditions, which vary between countries, regions and road types. Urban motorways are in general more densely equipped with detectors and video monitoring compared to rural motorways and general roads. For the two urban motorways scenarios investigated in PRIMA, namely scenario 1 and 3, the time savings were estimated to be around 4-5 minutes (80-97%) while for the interurban motorway scenarios the savings were estimated to be around 10-15 minutes (67-93%). However, these results come with some uncertainty and there is need for further investigation. A problem is that most incident databases commonly only include total incident durations and rarely include information on the duration of the different phases.

The length of the discovery, verification and initial response phase also depends on the type, quality and correctness of the information that novel technologies provide, so in addition also quality indicators were investigated as well as the feasibility of automatic incident severity classification. The assessment shows that an extension of eCall to advanced eCall, i.e. including injury severity estimation, seems promising. To prove its suitability however, an

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extended investigation towards more cases (to account for the variation in human variability), other body regions (not only thorax) and different impact scenarios (not only frontal impacts) is needed. It should also be investigated how the injury risk information can be used in practice, for example to adjust the (emergency) response actions accordingly (is it needed to send and ambulance, or will only a police officer suffice; is specialized medical help required, or maybe even a helicopter), or to estimate the impact of the incident on the traffic, which can in turn be used to take appropriate actions (how long is it expected for the road to be blocked, is redirecting of traffic needed, etc.).

The amount of saved time by using innovative techniques is fed into the second step of the assessment, namely modelling and simulating the incident scenarios in order to estimate the traffic performance (e.g. travel time delay, queue length and incident duration) for different incident management techniques. Two different assessment methods were developed, one more advanced based on macroscopic traffic simulation using the Cell Transmission Model and one simpler but quicker based on a deterministic queue model. The queue model was proven to be useful to conduct quick comparisons for different techniques given the start time of the incident, the travel demand profile, speed limit, number of lanes, etc. The 'GUI' and the implementation needs to be enhanced if the model is to be used in operational incident management, but its simplicity for quick and rough estimates for scene management techniques makes it an interesting candidate as a supportive tool for incident managements centres. In addition the macroscopic cell transmission simulation model was applied to investigate the effect of different scene management techniques in more detail. The cell transmission model has longer execution times but gives a more detailed description of changes in the traffic state due to an incident and different incident management techniques. The simulation model takes on- and off ramps into consideration and can capture variations in the travel demand at a higher level of detail. So for more complex motorway sites with recurrent incidents, a local calibrated macroscopic traffic simulation model would be a more preferable decision support tool for scene management.

The traffic performance assessment shows that alternative scene management techniques as quick clearance involving towing in off-peak, contraflow, and closing a limited number of lanes can decrease delay and incident durations. However, the rank order of techniques depends on the start time of the incident in relation to the traffic peak, the assumptions for the duration of the different phases, the travel demand profiles, etc. The results show that there can be substantial differences between the total delay and the incident duration depending on which technique is applied for a given incident scenario.

The effect on traffic performance (step 2) and the estimated time savings (step 1 & 2) are used in the last step of the assessment (step 3), which aims to estimate the risks and costs of the different incident management techniques given a specific incident scenario. The analysis of the risks, costs and benefits (i.e. the third step) are presented in a separate deliverable, namely PRIMA D3.2 – Description and results of the CBA and risk assessment. In the end, the different assessments are used as input to the development of the PRIMA traffic incident management guidelines.

1 Introduction

Non-recurrent events such as road accidents, vehicle breakdowns and extraordinary congestion – henceforth referred to as traffic incidents – affect travel times, safety and the environment, and also generate costs associated with these impacts. Therefore, road administrations must manage incidents in a safe and efficient manner. Typically, every country has its own traffic incident management (TIM) regulations and strategies, but there is a need for transnational practical guidance to achieve an optimal balance of cost and risk factors. In order to develop such practical guidance appropriate tools for assessment need to be defined and applied, and if needed enhanced.

This deliverable presents the approach taken in PRIMA for assessing the effect on incident duration and travel time delay for different incident management techniques. The assessment both considers novel technologies for decreasing the duration of the discovery, verification and initial response phases as well as more traditional scene management techniques, e.g. regarding how many lanes to close, if towing should be done immediately or later during off-peak, if incident screens should be mounted or not, etc.

1.1 Definitions

In this report the terms incident, technique and scenario are used frequently. In the PRIMA project the following definitions were for these terms (Taylor et al., 2015a):

A **traffic incident** is any unplanned event that may adversely affect the safety or the capacity of a road and hinder traffic flow.

A **technique** is a way of conducting a series of traffic incident management actions (e.g. close lanes, secure workspace, tow vehicle and reopen lanes), eventually by applying a certain **technology** (e.g. Variable Message Signs, Probe Vehicle Data, etc.)

A **scenario** is an internally consistent (verbal) picture of a situation or a sequence of events, based on certain assumption and factors (variables).

In PRIMA the CEDR TIM cycle, (see Figure 1 which originate from CEDR (2011) is used. In CEDR (2011) the different phases are defined in the following way

Discovery is the initial identification by any means of a potential incident by a responsible organisation or its staff.

Verification is the clarification and confirmation of the location, extent, and key details of an incident as far as is possible, enabling appropriate resources to be deployed.

Initial response is the dispatch of appropriate resources to the incident scene, the deployment of information, signing, and control measures to stabilise the scene and prevent escalation, and the securing of the scene for safety and so that immediate attention can be paid to casualties and hazards.

Scene management is the management of activities that need to be completed at the scene before the incident location can be cleared, including protection of the scene, implementation of diversions or other traffic management measures, relief of trapped traffic, further treatment and evacuation of casualties, removal of hazardous chemicals, investigation of the incident, and collection of evidence.

Recovery is the recovery of vehicles, loads, obstacles, and debris from the carriageway and the carrying out of essential repairs to the infrastructure before restoring the normal traffic condition.

Restoration is the restoration of the traffic conditions to those expected at the location for that particular day and time of day.

Normality is the traffic conditions expected at a location on a particular day and at a particular time of day.

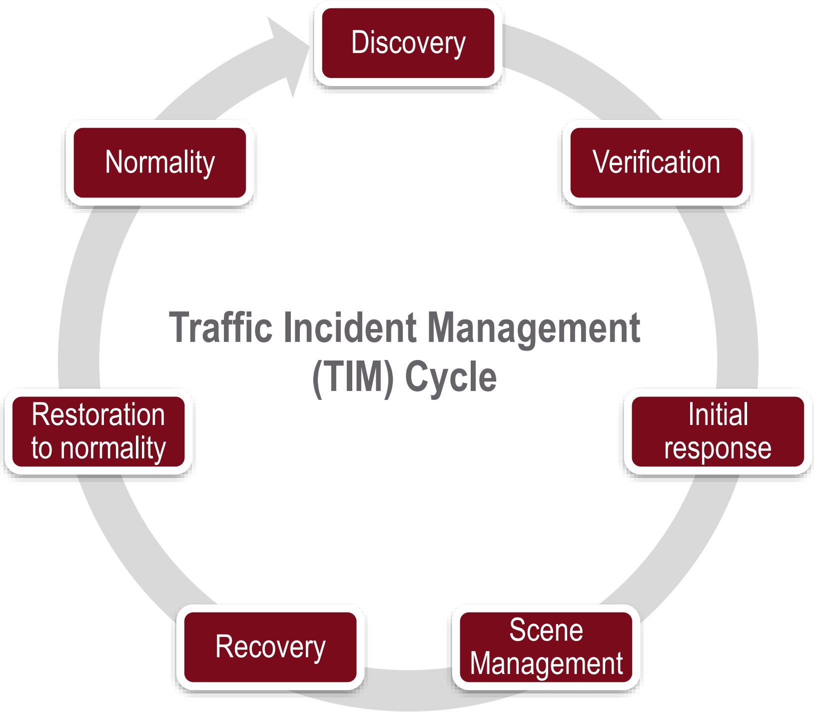


Figure 1: Illustrations of the different phases in incident management (CEDR, 2011)

1.2 Overall assessment methodology

The assessment is conducted using a scenario-based approach. By using the information from the best practice review and the stakeholder consultation as base (see Taylor et al. (2015a)), a total of four different incident scenarios were developed during a comprehensive workshop held with the project team. The main target was to get a large variety of scenarios and at the same time satisfy the desired requests from the stakeholder consultation. Most of the highest ranked incidents and technologies in Taylor et al. (2015a) were covered in the developed scenarios. The four traffic incident scenarios (all considering motorways) are:

- Scenario 1: Car to car collision involving injury, before traffic peak
- Scenario 2: Unsafe road conditions due to adverse weather leading to congestion
- Scenario 3: Large Goods Vehicle stranded on a motorway
- Scenario 4: Unpredictable congestion due to obstruction on a motorway

The assessment is conducted in three different steps according to the flow chart in Figure 2. The process of assessing the feasibility of novel technologies investigates novel technologies and evaluates how much the response time can be reduced by using combinations of different novel technologies to shorten the discovery, verification and initial response phases. The length of these phase also depend on the type, quality and correctness of the information that these novel technologies provide, so in addition also quality indicators are investigated as well as the feasibility of automatic incident severity classification. The amount of saved time is fed into the process of modelling and simulating the incident scenarios, which estimates the traffic performance (e.g. travel time delay, queue length and incident duration) for different incident management techniques. The effect on traffic performance and the estimated time savings are then used to estimate the risks and costs of the different incident management techniques given a specific incident scenario. The analysis of the risk, cost and benefits are presented in a separate deliverable, namely PRIMA D3.2 – Description and results of the CBA and risk assessment (Taylor et al., 2015b). In the end the different assessments are used as input to the development of the PRIMA traffic incident management guidelines.

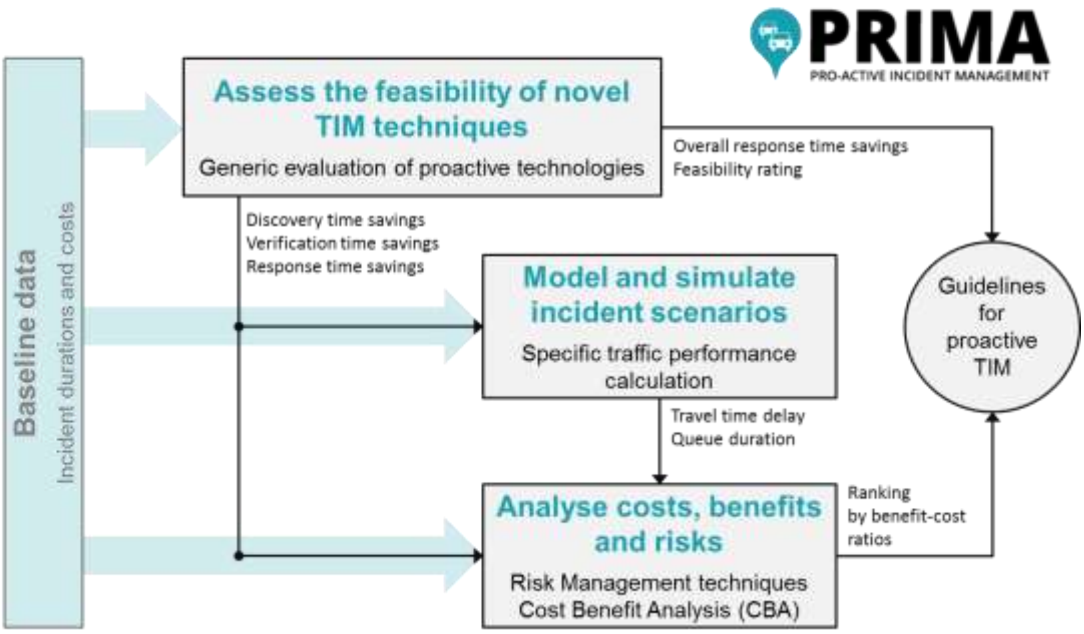


Figure 2: Methodology in PRIMA WP3

1.3 Report outline

The report starts with a description and illustration of the four incident scenarios and the incident management techniques considered for each scenario. Chapter 3 describes the assessment of how novel technologies may reduce the duration of the discovery, verification and initial response phases. Chapter 4 presents a feasibility study on the use of a Human State Estimator to predict injury risk on a real time basis, which could be used to enhance eCall with injury risk information and in the end enhance the incident verification process. Chapter 5 presents how the cost of congestion for different types of incidents and incident management techniques can be estimated by adopting a macroscopic traffic flow simulation model or a faster but less detailed traffic performance assessment method based on queuing theory. Chapter 5 also includes a comparison of the differences and a discussion on advantages and disadvantages of the two traffic performance assessment methods. The overall results and their implications for the PRIMA project, i.e. how the results are fed into the cost-benefit analysis and the guideline development, are given chapter 6.

2 Illustration of incident scenarios and techniques

This chapter contains a brief illustration of the predefined traffic incident scenarios including the main phases of the TIM cycle (see Figure 1). There may be several sub-phases included, where the capacity may vary over time. For example, there may be an initial phase in the scene management including protecting the scene, which requires all lanes blocked. Before presenting the scenarios, a short description of different types of techniques and technologies for discovery and verification considered in PRIMA is given.

2.1 Overview on discovery and verification techniques

Techniques and technologies that can be used for discovering and verifying an incident range from basic ‘low tech’ reports to more ‘high-tech’ and automatized. The following techniques were considered in the PRIMA project:

- **Citizen reports:** This is the most basic type of detection and verification based on travellers calling the traffic management centre or a radio station, or based on dedicated smartphone apps.
- **Professional reports:** With their knowledge from trainings and experiences, professionals can support Incident Management with full and reliable information about the incident. (e.g. Police or Traffic Manager)
- **Sectional (and Network) Traffic Data Measurements:** technology based systems, e.g. ANPR, tolling systems, Bluetooth, WLAN) delivering traffic data for sections in (a) aggregated form, like number of vehicles per time or mean travel time for the section or (b) single vehicle data with more detailed information.
- **Vehicle-based (Trajectory) Data Measurements:** floating vehicle data, with accurate position and time information, typically GPS-based delivered in real-time via mobile phone network (UMTS/3G) or cooperative communication systems (c2x).
- **Video monitoring**: CCTV is often available in busier parts of networks monitored by a Traffic Management Centre, but may depend on detection by a human operator.
- **Vehicle-based Information Report:** eCall and ‘advanced eCall’ are considered especially in scenarios with collisions. eCall is designed to sense severe impacts in case of an accident and automatically call the nearest emergency centre and transmits the exact geographic location of the accident scene and other data.
- **Video Incident Detection System (VIDS):** the category involves algorithms for automatic incident detection based on image recognition in video data.

2.2 Scenario 1 - Car to car collision involving injury, before traffic peak

2.2.1 Description of incident

On a weekday just before the morning peak, a serious crash between two passenger vehicles occurs on an urban motorway with three main lanes plus a hard shoulder, see visualization in Figure 3. The weather conditions are clear and dry when the incident occurs. The crash has caused injuries and is blocking 1-2 lanes in at least one directional (inbound morning commute) lane of travel. At the moment when the incident occurs, the required number of resources is assumed to be available upon request (police, ambulance, fire fighters, and towers).

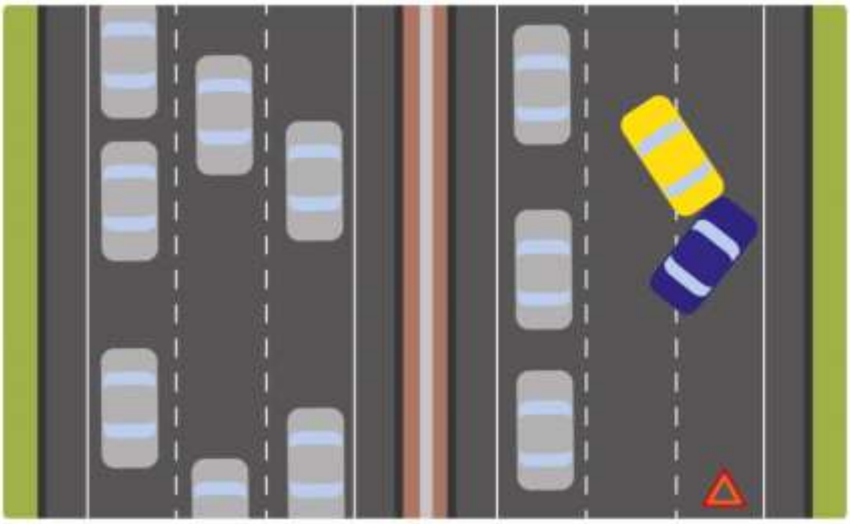


Figure 3: Illustration of the incident scenario with car to car collision involving injury, before traffic peak. Two out of three lanes are blocked in the illustration, but the number of lanes blocked may vary between one and two. Right-hand traffic is assumed.

2.2.2 Considered discovery and verification techniques

As baseline technologies it is assumed that at least citizen reports and cross-sectional data measurements are available. Furthermore, video monitoring (CCTV) is expected to be available since the scenario involves a major urban motorway. In addition to the baseline techniques, the following discovery and verification techniques are considered:

- Professional reports
- Sectional (and Network) Traffic Data Measurements
- Vehicle-based (Trajectory) Data Measurements
- Vehicle-based Information Report
- Video Incident Detection System (VIDS)

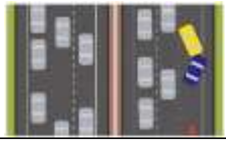
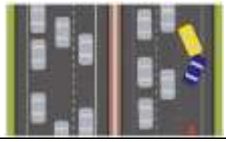
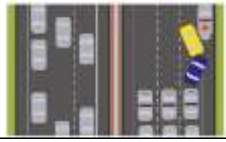
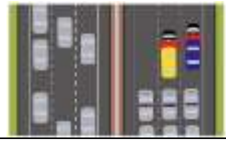
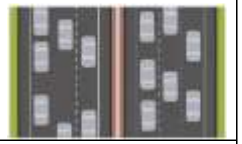
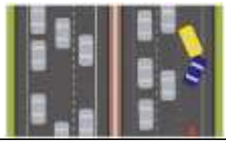
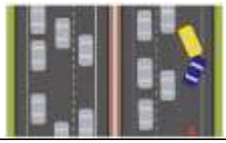
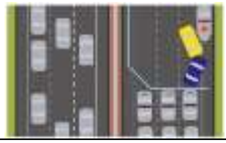
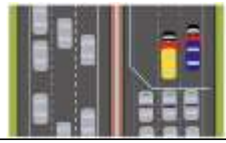
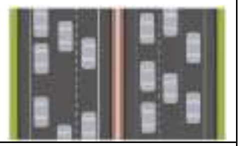
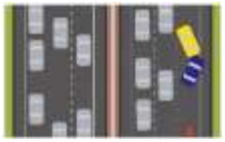
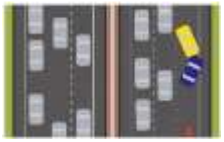
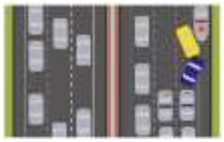
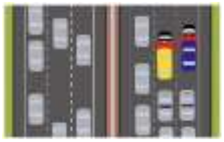
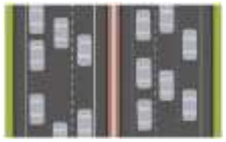
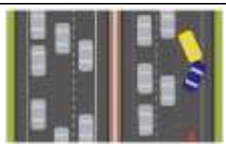
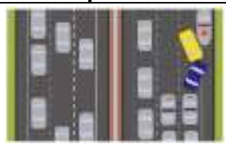
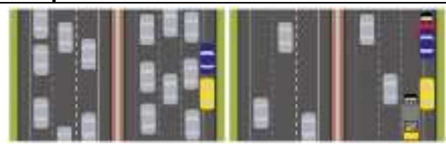
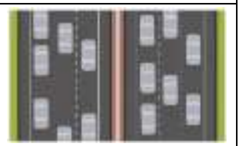
2.2.3 Considered scene management techniques

The different scene management techniques considered for this scenario focus on ensuring a safe operating environment for the emergency responders and at the same time recover the scene to normality and prevent unnecessary delays for remaining traffic. The following techniques are evaluated in PRIMA for restoring the capacity to normality:

1. **Close all lanes:** Close all lanes and clear the incident scene completely before reopening the motorway.
2. **Incident screens:** Close all lanes and clear the incident scene completely before reopening the motorway. Put up incident screens to avoid unnecessary capacity drops due to rubbernecking.
3. **Close some lanes:** Close minimum number of lanes in order to remain as much capacity as possible for remaining traffic. Clear the scene totally before reopening any of the closed lanes.
4. **Tow in off-peak:** Close minimum number of lanes and move the crashed vehicles to the shoulder. Reopen cleaned lanes as fast as possible and tow the vehicles later during off-peak.

All listed techniques are also visualized in Table 1 together with the corresponding duration for each phase. The durations have been estimated utilizing the examples of incident timelines flow chart provided in CEDR (2011).

Table 1. Illustration of the different TIM techniques to be evaluated for traffic incident scenario 1. Right-hand traffic is assumed.

Phase	**Discovery**	**Verification**	**Initial response**	**Scene management**	**Recovery**
Technique 1 – Close all lanes					
Scene					
Duration [min]	6	3	16	66	Until queue dissolves
Technique 2 – Incident screens					
Scene					
Duration [min]	6	3	16	86	Until queue dissolves
Technique 3 – Close some lanes					
Scene					
Duration [min]	6	3	16	66	Until queue dissolves
Technique 4 – Tow in off-peak					
Scene					
Duration [min]	6	3	16	wait until off-peak + 66	Until queue dissolves

2.2.4 Traffic demand

Four different types of traffic demand profiles are considered in the assessment of scenario 1. The four different types are assumed to be representing a

- high and long traffic peak,
- high and short traffic peak,
- Low and long traffic peak and
- low and short traffic peak.

All peaks have been estimated based on measured flows from the motorway network in Stockholm, Sweden. The amplitude and duration of the demand profile is estimated with respect to the different characteristics of the morning and afternoon peak. High peaks are represented by the traffic demand during the morning peak and consequently low peaks are represented by the traffic demand during the afternoon peak. The duration of the long peaks are represented by the duration of the afternoon peak, and short peaks by the morning peak.

Measured demand profiles have been aggregated and smoothed in order to avoid rapid changes in traffic flow, which is assumed to be non-representative. The different demand profiles are illustrated in Figure 4, together with the ramp flow, which is scaled as 10% of the main demand.

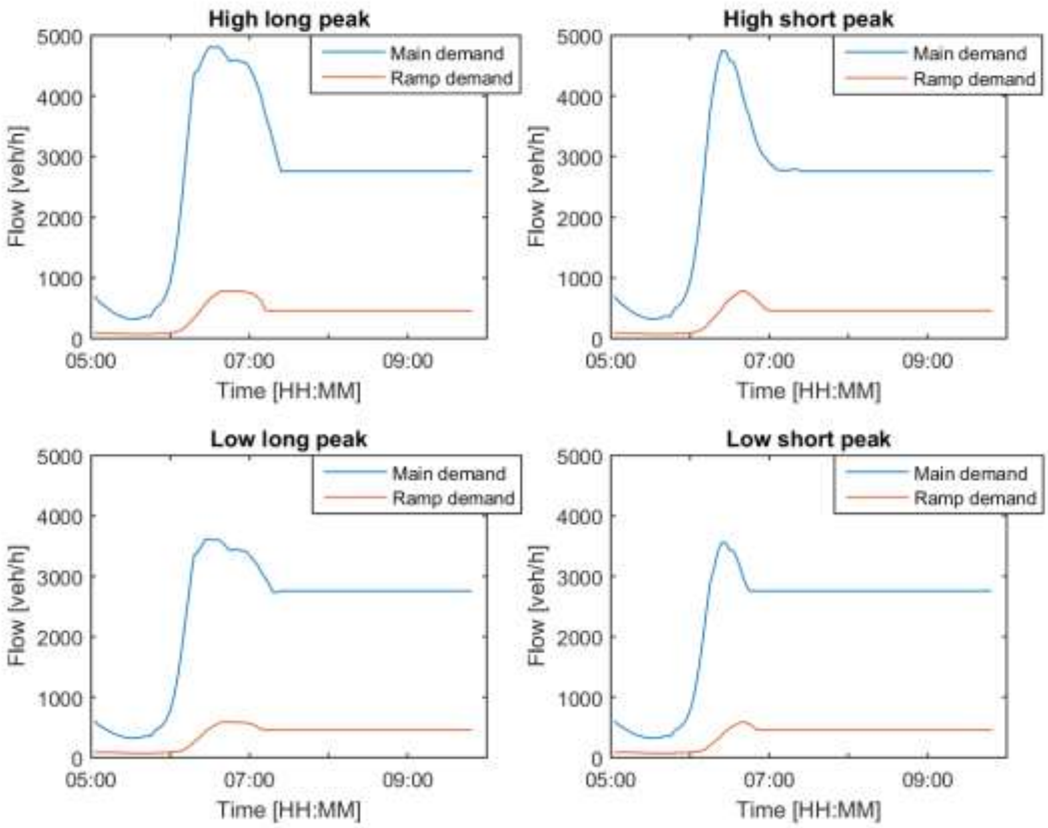


Figure 4: The different traffic demand profiles used in the traffic performance assessment of scenario 1.

2.3 Scenario 2 - Unsafe road conditions due to adverse weather leading to congestion

2.3.1 Description of incident

During daytime, the weather conditions cause reduction of the safe operating speed on an inter-urban motorway with two lanes and hard shoulder. This may be as an effect of e.g. heavy rain causing high risks for aquaplaning, intensive snow in combination with wind causing snowdrifts or a minor landslide causing mud on the road (assumed to affect safe operating speed on both lanes in the influenced direction). See visualization in Figure 5. The reduction of the safe operating speed leads to some upstream congestion. At the moment when the incident occurs the required number of resources are assumed to be available (police, fire fighters, snow ploughs, water pumps, Truck Mounted Attenuator (TMA)[1]).

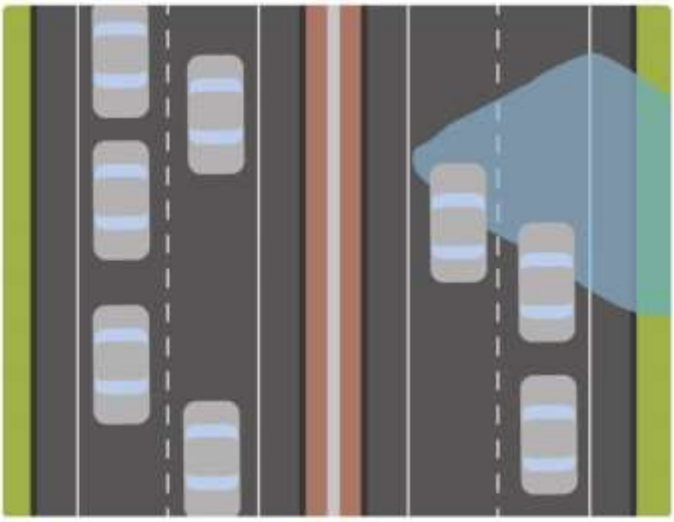


Figure 5: Illustration of the incident scenario with unsafe road conditions due to adverse weather leading to congestion. No lanes are blocked, operating speed is decreased. Right-hand traffic is assumed.

2.3.2 Considered discovery and verification techniques

As baseline technologies it is assumed that at least citizen reports and cross-sectional data measurements are available. In addition to the baseline techniques, the following discovery and verification techniques are considered:

- Professional reports
- Sectional (and Network) Traffic Data Measurements
- Vehicle-based (Trajectory) Data Measurements
- Video Incident Detection System (VIDS)

[1] A TMA is a truck fitted with flashing lights, speed limit and/or lane-closed or change-lane sign. Potentially several TMAs can be deployed across all lanes to create a 'moving block' to slow traffic or create a temporary working space ahead.

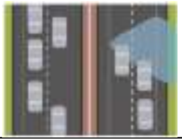
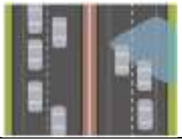
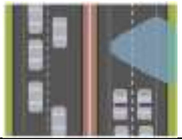
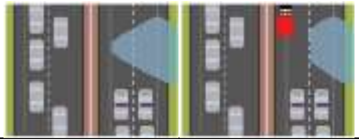
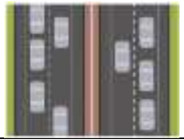
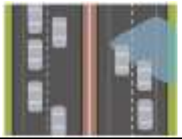
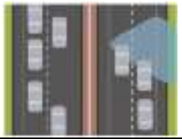
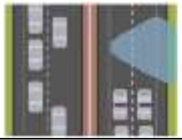
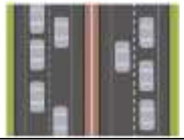
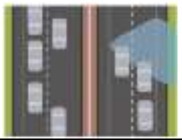
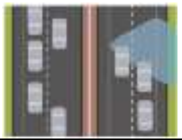
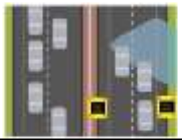
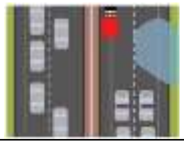
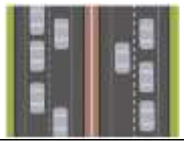
2.3.3 Considered scene management techniques

The different scene management techniques considered for this scenario focus on enabling maximum capacity and at the same time also approve safe operating conditions for the motorists as well as for the emergency responders. The following techniques are evaluated in PRIMA for restoring the capacity to normality:

1. **Close all lanes:** Close all lanes and clear the scene totally. Do not reopen any lane before the scene is totally restored to normality, i.e. all water is pumped away, all mud or snow is removed.
2. **Contraflow:** Close all lanes and clear the scene totally. Do not reopen any lane before the scene is totally restored to normality, i.e. all water is pumped away, all mud or snow is removed. Redirect all traffic to the opposite direction in order to have some remaining capacity at the scene.
3. **VMS and speed limit:** Do not close any lanes. Put out information signs/use VMSs in order to keep the road totally open but decrease the operating speed at the scene by a temporary lower speed limit. Close the road and clear the scene during low traffic/off-peak.

All listed techniques are also visualized in Table 2 together with corresponding duration for each phase. The durations have been estimated utilizing the examples of incident timelines flow chart provided in CEDR (2011).

Table 2: Illustration of the different TIM techniques to be evaluated for traffic incident scenario 2. Right-hand traffic is assumed.

Phase	**Discovery**	**Verification**	**Initial response**	**Scene management**	**Recovery**
Technique 1 – Close all lanes					
Scene					
Duration [min]	6	3	26	26 + 29	Until queue dissolves
Technique 2 – Contraflow					
Scene					
Duration [min]	6	3	26	26 + 29	Until queue dissolves
Technique 3 – VMS and speed limit					
Scene					
Duration [min]	6	3	Until off-peak	66	Until queue dissolves

2.3.4 *Traffic demand*

Three different types of demand profiles are used when simulating incident 1. The different profiles are assumed to be representing

- high traffic peak,
- medium traffic peak and
- low traffic peak

All peaks have been estimated based using the same measured flows from the motorway network in Stockholm, as was used estimating the demand profiles in scenario 1. The amplitude of the demand profile has been estimated with respect to the different characteristics of the morning and afternoon peak. The high peak represents the traffic demand during morning the peak and the low peak represents the traffic demand during the afternoon peak. The medium peak is basically the average between the high and low peak while the duration is based on the duration of the morning peak.

Measured demand profiles have been aggregated and smoothed in order to avoid rapid changes in traffic flow, which is assumed to be non-representative. The different demand profiles are illustrated in Figure 6, together with the ramp flow, which is scaled as 10% of the main demand.

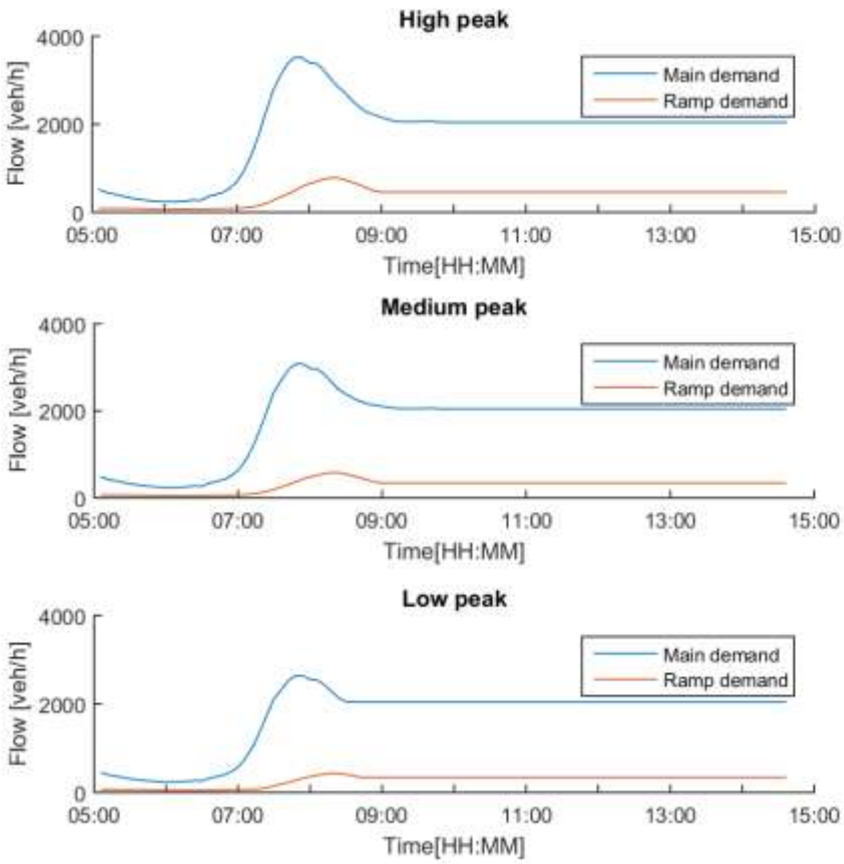


Figure 6: The different traffic demand profiles used in the traffic performance assessment of scenario 2.

2.4 Scenario 3 - Large Goods Vehicle stranded on a motorway

2.4.1 Description of incident

Due to technical failure, a Large Goods Vehicle (LGV) gets stranded on the lane closest to the road side on a major urban motorway with three main lanes without hard shoulder. The incident occurs during daytime when the weather and road conditions are clear and dry. Due to the size and location of the LGV, the capacity is reduced on the motorway, but since the vehicle is not loaded with dangerous goods there is no need of immediate evacuation. The LGV is only blocking one lane, which leads to reduced capacity causing congestion and travel time delays. See visualization in Figure 7. At the moment when the incident occurs, the required number of resources are assumed to be available (police, Truck Mounted Attenuator (TMA), heavy towers, repairs).

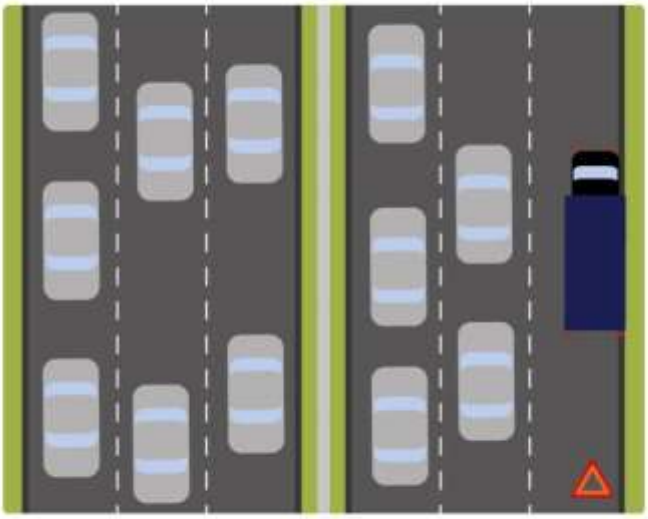


Figure 7: Illustration of the incident scenario with stranded LGV on a motorway. 1 of 3 lanes are blocked. Right-hand traffic is assumed.

2.4.2 Considered discovery and verification techniques

As baseline technologies it is assumed that at least citizen reports and cross-sectional data measurements are available. Furthermore video monitoring (CCTV) is expected to be available since the scenario involves a major urban motorway. In addition to the baseline techniques, the following discovery and verification techniques are considered:

- Professional reports
- Sectional (and Network) Traffic Data Measurements
- Vehicle-based (Trajectory) Data Measurements
- Video Incident Detection System (VIDS)

The listed novel technologies are summarized in order to cover international technology readiness levels and typical penetration rates. They are categorized based on their type of traffic data and measurements to involve general technical capabilities and limitations as well as the field of application but exclude details, like measurement technology and requirement for mounting and operation.

2.4.3 Considered scene management techniques

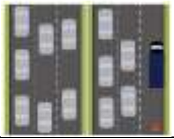
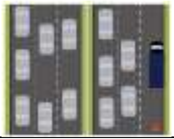
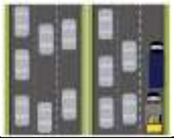
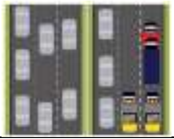
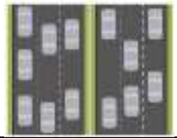
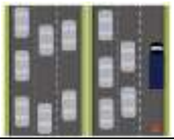
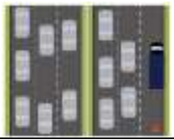
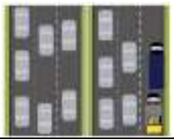
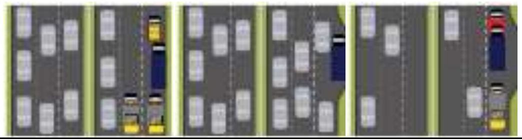
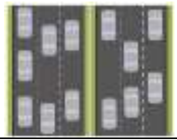
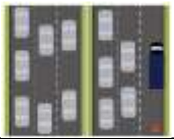
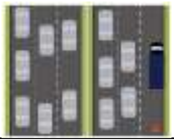
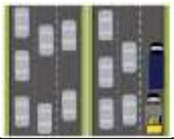
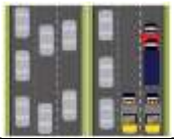
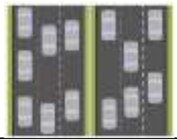
The techniques considered for this scenario focus on maintaining the highest level of service and capacity at the roadway, motorists will probably not attempt any major diversion or change of plan due to the stranded LGV, since this kind of incident is quite common.

The main purpose is to minimize distraction for the motorists, in order to maximize the capacity at the scene, since the largest risk concerns rear end collisions as a consequence of decreased operating speed at the scene. The truck driver is assumed to remain inside the cabin of the truck, after he or she has put up the warning triangle. In case towing is necessary, the risk level for the road works has to be minimized, which requires closing additional lanes. The following techniques are evaluated in PRIMA for restoring the capacity to normality:

1. **Close extra lane:** Close the blocked lane and the centre lane and tow the stranded heavy goods vehicle to the nearest downstream off-ramp
2. **Repair on-site:** Close the blocked lane and the centre lane in order to repair the vehicle so that it can drive to the next safety pocket or downstream off-ramp. Wait and tow the vehicle during off-peak.
3. **Tow in off-peak:** Close the blocked lane using a TMA and wait to close additional lanes and conducting towing to off-peak (and then close the blocked lane and the centre lane in order to tow the stranded vehicle)

All listed techniques are also visualized in Table 3 together with corresponding durations for each phase. The durations have been estimated utilizing the examples of incident timelines flow chart provided in CEDR (2011).

Table 3: Illustration of the different TIM techniques to be evaluated for traffic incident scenario 3. Right-hand traffic is assumed.

Phase	**Discovery**	**Verification**	**Initial response**	**Scene management**	**Recovery**
Technique 1 – Close extra lane					
Scene					
Duration [min]	3	5	24	29	Until queue dissolves
Technique 2 – Repair on site					
Scene					
Duration [min]	3	3	20	19 + wait until off-peak + 29	Until queue dissolves
Technique 3 – Tow in off-peak					
Scene					
Duration [min]	3	3	Wait until off-peak	29	Until queue dissolves

2.4.4 Traffic demand

Four different types of demand profiles are used when simulating scenario 3. These profiles are identical compared to the ones used in scenario 1 (see Figure 4 in section 2.2.4):

- High and long traffic peak
- High and short traffic peak
- Low and long traffic peak
- Low and short traffic peak

2.5 Scenario 4 - Unpredictable congestion due to obstructions on a motorway

2.5.1 Description of incident

During dry and good road conditions, an obstruction appears on the motorway as a consequence of e.g. spilled load, debris or tire cap. The obstruction objects are blocking one lane on a two lane Inter-urban motorway with hard shoulders, which causes reduction of the safe operating speed and the consequence is reduced capacity. See visualization in Figure 8. At the moment when the incident occurs, the required number of resources are assumed to be available (police, tractors, loaders, TMA).

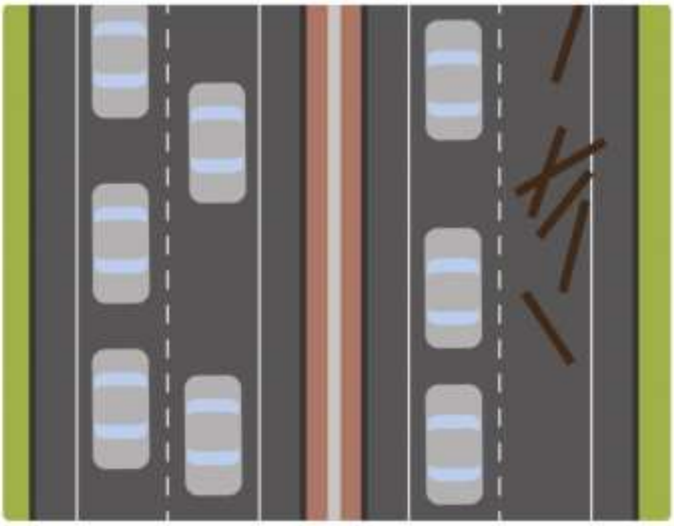


Figure 8: Illustration of the incident scenario with unpredictable congestion due to obstructions on a motorway. 1 of 2 lanes are blocked. Right-hand traffic is assumed.

2.5.2 Considered discovery and verification techniques

As baseline technologies it is assumed that at least citizen reports and cross-sectional data measurements are available. In addition to the baseline techniques, the following discovery and verification techniques are considered:

- Professional reports
- Sectional (and Network) Traffic Data Measurements
- Vehicle-based (Trajectory) Data Measurements
- Video Incident Detection System (VIDS)

2.5.3 Considered scene management techniques

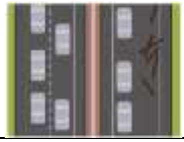
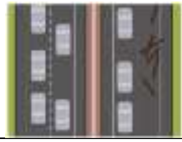
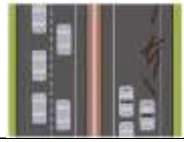
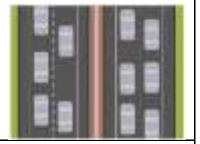
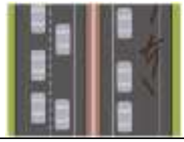
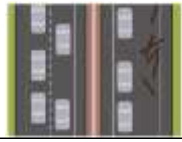
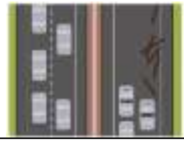
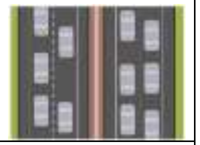
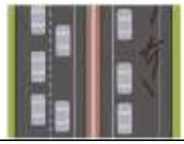
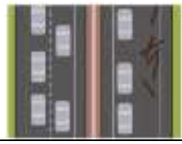
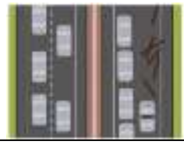
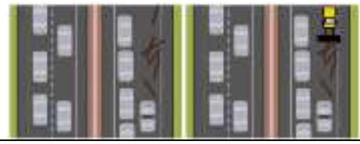
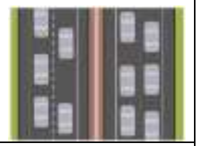
The techniques considered for this scenario focus on maintaining the highest level of service and capacity at the roadway.

The main purpose is to minimize distraction for the motorists, in order to maximize the capacity at the scene, since the largest risk concerns rear-end collisions as a consequence of decreased operating speed at the scene. Where road works are needed to remove the obstruction, the risk level for the road works has to be minimized, which requires closing additional lanes. The following techniques are evaluated in PRIMA for removing the obstruction and restoring the capacity to normality:

1. **Close all lanes:** Close all lanes and clear the scene totally before reopening any lane.
2. **Contraflow:** Redirect all traffic to the opposite direction in order to maintain some capacity at all times.
3. **Close blocked lane:** Close the blocked lane and immediately clear the scene.

All listed techniques are also visualized in Table 4 together with corresponding durations for each phase. The durations have been estimated utilizing the examples of incident timelines flow chart provided in CEDR (2011).

Table 4: Illustration of the different TIM techniques to be evaluated for traffic incident scenario 4. Right-hand traffic is assumed.

Phase	**Discovery**	**Verification**	**Initial response**	**Scene management**	**Recovery**
Technique 1 – Close all lanes					
Scene					
Duration [min]	6	3	26	26 + 29	Until queue dissolves
Technique 2 – Contraflow					
Scene					
Duration [min]	6	3	26	26 + 29	Until queue dissolves
Technique 3 – Close blocked lane					
Scene					
Duration [min]	6	3	26	26 + 39	Until queue dissolves

2.5.4 Traffic demand

This scenario assumes a constant off-peak demand, which simply corresponds to the off-peak demand used in scenario 1 – 3 in the previous description. This means that the constant demand used in scenario 4 is based on the average demand between the morning and afternoon peak measured at the Stockholm motorway network. The constant demand is measured as 2048 vehicles per hour.

3 Qualitative assessment of novel technologies

3.1 Aim and scope

The aim of this task is to assess novel and innovative techniques for incident management. This involves solutions for detecting, classifying and verifying incidents based on promising technologies that are likely to be wide-spread in the near future. Especially the early stages of the incident management cycle can be enhanced by technology. Based on the 'cycle of phases' for traffic incident management the relevant phases for the assessment of technologies were defined as Discovery, Verification and Initial Response.

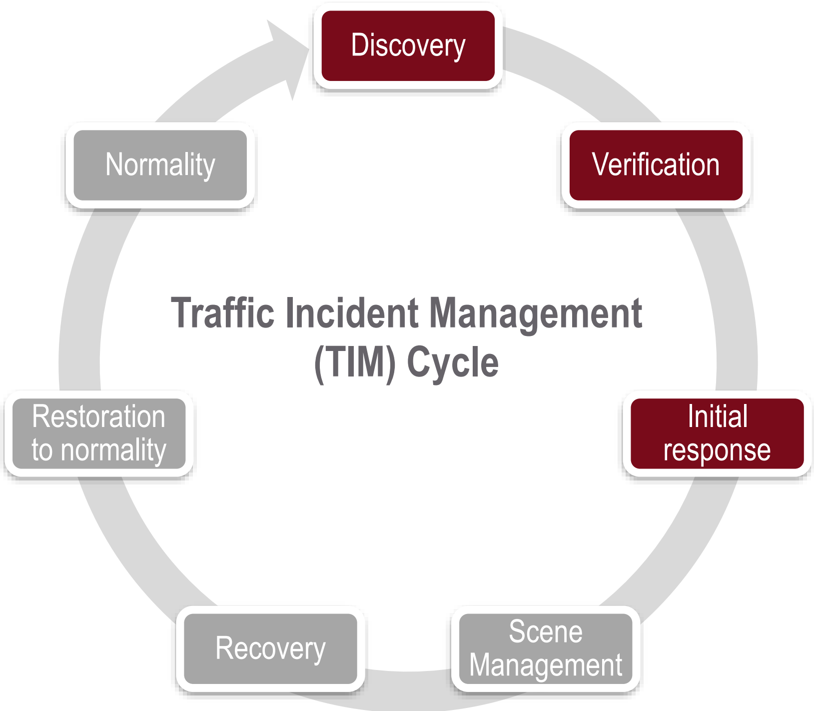


Figure 9: Traffic Incident Management 'cycle of phases (CEDR, 2011) with highlighted phases for the assessment of novel technologies

The CEDR (2011) report describes that the management of an incident can be broken down into a cyclic sequence of phases (see Figure 9), progression through which constitutes the timeline of an individual incident. There is general agreement on the objectives during the TIM phases. The diagram shows the phases as a cycle that starts and finishes with a state of normality.

3.2 Method

3.2.1 Performance Indicators for Incident Management

In order to identify and define the most critical performance indicators for incident management the relevant phases with their tasks and constraints were analysed. The description of the phases Discovery, Verification and Initial Response (from CEDR (2011)) are listed below and were used to specify indicators, separated in quality and time-related indicators.

TIM actions in the Discovery phase:
- Implement immediate safety measures
- Initiate early actions to protect the lives of road users
- Initiate early actions to prevent an escalation of the incident
- Obtain sufficient detail to enable an informed decision on the responder
- Organisations to be involved and the type and level of response required
- Establish initial command, control, and coordination of the incident

The following performance indicators given in Table 5 were specified for the discovery phase.

Table 5: Performance indicators for the discovery phase

Quality-related Indicators	DR (Detection Rate)	Ratio or percentage of the number of detected incidents to the total number of actual incidents during a given time period.
	FAR (False Alarm Rate)	Ratio or percentage of false positive detections per unit of road length and unit of time, as a measure of operator work load; i.e. [number of false alarms / km / day].
Time-related Indicators	Detection Time t_D	The Detection time is the time between the occurrences of the incident until the time that agencies become aware of the incident. The average Value is denoted by MTTD (Mean Time To Detect).

TIM actions in the Verification phase:
- Verify the nature and location of the incident
- Identify the resources and organisations required for an initial response to the incident
- Implement immediate safety measures
- Identify and tackle the aspects that require immediate attention
- Supply responders and their organisations with essential information
- Establish initial command, control, and coordination of the incident scene
- Plan the 'initial response' phase
- Initial response
- Protect the scene
- Save lives
- Protect and preserve the lives of others
- Preserve the scene for investigation
- Safeguard property and infrastructure
- Protect the environment
- Commence initial investigation
- Mitigate congestion
- Plan the Scene Management' phase

The following performance indicators given in Table 6 were specified for the verification phase.

Table 6: Performance indicators for the verification phase

Quality-related Indicators	FCR (False Classification Rate)	The Ratio or percentage of false Classifications to the total number of actual incidents during a given time period.
	Number of Vehicles	The capability to identify the number of vehicles involved.
	Vehicle Class	The capability to distinguish between light vehicles such as passenger vehicles and light commercial vehicles, and heavy goods vehicles.
	Injury Risk / Injury Level	The capability to get information or estimations on injury risk or injury level
Time-related Indicators	Verification Time t_V	This is the time period from when the Traffic Management Center (TMC) is first noticed to when the incident is verified.

TIM actions in the Initial Response phase:

- Protect the scene
- Save lives
- Protect and preserve the lives of others
- Preserve the scene for investigation
- Safeguard property and infrastructure
- Protect the environment
- Commence initial investigation
- Mitigate congestion
- Plan the 'scene management' phase

The following performance indicators given in Table 7 were specified for the initial response phase.

Table 7: Performance indicators for the initial response

Quality-related Indicators	Response Performance	The response performance covers questions like: was the right initial response actions launched, was the needed resources (ambulances, tow vehicles, police, etc.) activated/sent and were there enough number of resources?
Time-related Indicators	Initial Response Time t_{IR} (Initial Response Team Preparation and Travel Time)	Describes the time till first action forces arrive at the scene, covering the two parts of: the response teams preparation delay t_p, which is related to the response resource availability and the incident type, and the IRTs travel time t_t, which depends on the travel distance and the traffic condition.

3.2.2 Categorization and pre-selection of promising novel techniques and technologies

Promising technologies, such as eCall, floating vehicle data or cooperative systems were discussed and integrated in the further process of assessment. Confirmed by the stakeholder consultation of PRIMA WP2 (Taylor et al., 2015a) the traffic data and traffic monitoring systems are in many cases in use or planned to implement in the near future, see Figure 10.

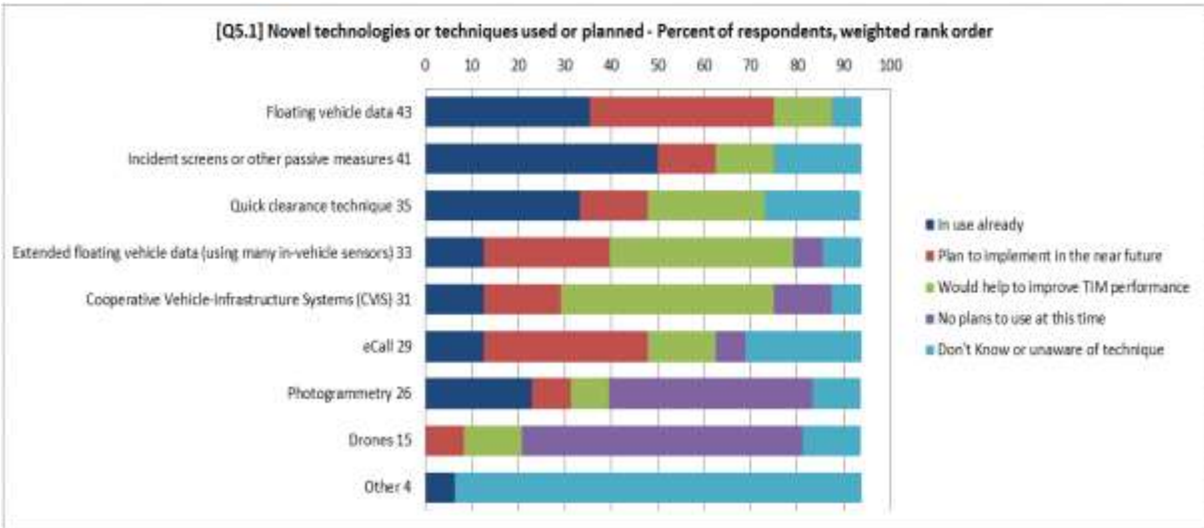


Figure 10: Stakeholder answers regarding the use of novel technologies in incident management (Taylor et al., 2015a)

The technology categories used in PRIMA (as introduced in chapter 2.1) are ordered from basic to advanced technologies, starting from simple and widely used technologies, such as citizen reports via phone call or app and loop detectors (Cross-sectional Traffic Data Measurements) to the more advanced technologies such as Floating Vehicle Data (FCD), cooperative systems (c2x) and eCall (as Vehicle-based Information Report) and automated Video Incident Detection Systems.

3.2.3 The feasibility of novel techniques and technologies

In order to elaborate on the feasibility of novel and innovative technologies for incident detection and prevention a qualitative assessment was performed. The assessment involved mainly the time-related indicators describing the duration of specific TIM phases. According the definition of time indicators in section 3.2.1 the time line in Figure 11 shows the Discovery Time ($\mathrm{t_D}$), Verification Time ($\mathrm{t_V}$) and Initial Response Time ($\mathrm{t_{IR}}$).

Some technologies provide the highest potential by interleaving different TIM phases. Hence, although the single discovery and verification time stays unchanged, the overlapping of the phases enables substantial time saving. This is reflected by the introduction of $t_{D\&V}$ and $t_{V\&IR}$ (see Figure 11).

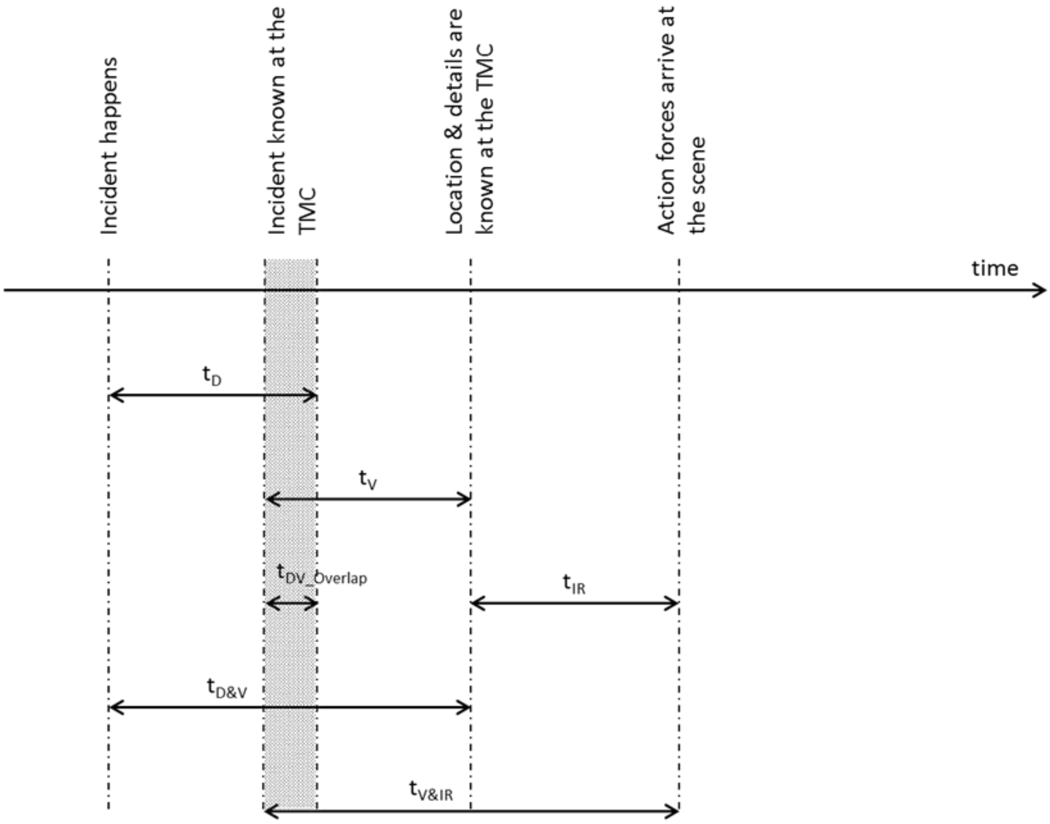


Figure 11: Definition of Time Durations in Traffic Incident Management

3.3 Results

The assessment consisted of an evaluation of quality-related and time-related indicators for discovery, verification and initial response. From previous studies, like the RAIDER Project, suitability of technologies for incident detection could be derived. Table 8 summarizes the assessment results for the indicators with an appropriate 3-colour-code from best (green), medium (yellow) and lowest suitability.

The assessment of the quality-related indicators shows best capability of vehicle and video-based systems for incident discovery. Full and reliable verification of incidents can be expected by professional reports on the scene or via video. The assessment has also shown that good response performance is enabled by high quality in verification.

Table 8: Assessment Results for quality-related indicators for discovery, verification and initial response (partly derived from Netten et al., 2013)

		Discovery			Verification			Initial Response
Nr	**Subcategory**	DR[1]	FAR[1]	FCR	Vehicle Class[1]	Nbr. of Vehicles	Injury Risk/ Injury Level	Response Performance
1	Citizen Report (partial and draft Information)	medium	medium[2]	low	yes	yes	partly (via direct communication link)	high (depends on verification quality)
2	Professional Report (full and reliable Information)	low	low	low	yes	yes	yes (via direct communication link)	high (depends on verification quality)
3	Cross-sectional Traffic Data Measurements	NA	NA	NA	NA	NA	NA	NA
4	Sectional Traffic Data Measurements – overall	NA	NA	NA	NA	NA	NA	NA (could be used for travel time estimation)
5	Sectional Traffic Data Measurements –single veh.	low	high	NA	NA	partly (indication by missing vehicles)	NA	NA (could be used for travel time estimation)
6	Vehicle-based (Trajectory) Data Measurements	low	low	high	yes	no	NA	NA (could be used for travel time estimation)
7	Video Monitoring (visual , CCTV)	medium	low	low	yes	yes	partly (visual monitoring)	high (depends on verification quality)
8	Vehicle-based Information Report (eCall)	medium	low	low	yes	yes	partly (direct communication link to driver) yes (advanced eCall with in-car sensors)	medium (information from involved vehicles, but no scene overview)
9	Video Incident Detection System (VIDS)	high	medium[2]	low[3]	yes	yes	partly (visual monitoring)	high (depends on verification quality)

Abbreviations: NA… not applicable; [1]derived from RAIDER project, [2]average FAR different system characteristics (phone and app based citizen report systems, degree of automatization of VIDS), [3]visual verification expected

For the assessment of time-related indicators, a 4 level classification was defined with low, medium, high and very high estimated duration (see Table 9). The resulting time categories are based on previous studies (e.g. Netten et al., 2013 and CEDR, 2011) and aligned to empiric data and the corresponding TIM phase.

Table 9 indicates the time category as a typical duration using the correlated technology to support the tasks of the relevant TIM phase. Empiric incident data was analysed to obtain representative values for the range of TIM phase durations. The available incident data indicates total durations and delays for incidents. A separation into phases is not available and the distribution of whole incident duration is not applicable for single phases. Furthermore the general impact of the use of technology on the distribution of the phase time cannot be estimated. The time categories are colour-coded and used to describe possible improved timelines for the phases of incident management.

Table 9: Definition of Time Categories for Phases and Overlaps

TIM Phase	Symbol	Low Time	Medium Time	High Time	Very High Time
Detection Time (Accident/Breakdown) (Scenario 1,3)	t_D	< 10 sec	10 sec < t < 1 min	1 min < t < 5 min	>= 5 min
Detection Time (Congestion) (Scenario 2,4)	t_D	< 1 min	1 min < t < 5 min	5 min < t < 15 min	>= 15 min
Verification Time	t_V	< 1 min	1 min < t < 3 min	3 min < t < 10 min	>= 10 min
Initial Response Time	t_{IR}	< 5 min	5 min < t < 10 min	10 min < t < 30 min	>= 30 min
Overlapping of TIM Phases:					
Detection and Verification	$t_{D\&V}$	< 5 min	5 min < t < 10 min	10 min < t < 15 min	>= 15 min
Verification and Initial Response	$t_{V\&IR}$	< 5 min	5 min < t < 10 min	10 min < t < 30 min	>= 30 min

Table 10: Assessment Results with color-coded time categories for the relevant phases and scenarios

		Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Nr	**Subcategory**	Det.	Ver.	I.R.	Det.	Ver.	I.R.	Det.	Ver.	I.R.	Det.	Ver.	I.R.
1	Citizen Report (partial and draft Information)	<- $t_{D\&V}$ ->			<- $t_{D\&V}$ ->			<- $t_{D\&V}$ ->			<- $t_{D\&V}$ ->		
2	Professional Report (full and reliable Information)		<- $t_{V\&IR}$ ->		NA	<- $t_{V\&IR}$ ->		NA	<- $t_{V\&IR}$ ->		NA	<- $t_{V\&IR}$ ->	
3	Cross-sectional Traffic Data Measurements		NA			NA			NA			NA	
4	Sectional Traffic Data Measurements – overall		NA			NA			NA			NA	
5	Sectional Traffic Data Measurements –single veh.		NA			NA			NA			NA	
6	Vehicle-based (Trajectory) Data Measurements												
7	Video Monitoring (visual , CCTV)				NA			NA			NA		
8	Vehicle-based Information Report (eCall)	<- $t_{D\&V}$ ->			NA	NA		NA	NA		NA	NA	
9	Video Incident Detection System (VIDS)												

Abbreviations: NA… not applicable; I.R. … Initial Response

The assessment table for time-related indicators (see Table 10) relates the list of technology categories to the pre-selected phases for the PRIMA Scenarios as:

- Scenario 1 - Car to car collision involving injury, before traffic peak
- Scenario 2 - Unsafe road conditions due to adverse weather leading to congestion
- Scenario 3 - Stranded Large Goods Vehicle on a motorway
- Scenario 4 - Unpredictable congestion due to obstructions on a motorway

The expert discussions concluded with a position, that there is no direct support for the phase of ‘Initial Response’ by using traffic data acquisition and monitoring technologies. A possible overlapping of the duration for Verification and Initial Response was identified for the operation of traffic managers or similar persons providing professional reports and trainings to also take actions for Initial Response.

The assessment tables for time-related (see Table 10) and quality-related indicators (see Table 8) indicate the feasibility of technologies to shorten incident detection and management. Assuming the relevant requirements, such as available communication networks and appropriate penetration rates, vehicle-based systems provide good capability for the detection of incidents whereas video-based systems provide good capability for the verification of incidents. Potential time savings due to overlapping of phases may result from direct communication channels with involved or reporting persons.

Based on the idea to present a minimum resulting service level for stakeholders to estimate the effects of implementing and/or using more advanced technologies, the upper bound of time categories will be used as reference value for further tasks in PRIMA. Table 9 shows that the type of incident is reflected by separate time categories for discovering accidents/ breakdowns as in scenario 1 and 3 and for discovering extraordinary congestion relevant for scenario 2 and 4. The upper bound of the assigned time categories are recalculated to relative time savings when moving from the High time category (which is assumed to be the baseline) to the Medium or Low time category, see resulting relative time savings in Table 11. This approach allows covering the whole time category and traffic performance. Furthermore, CBA results can be interpreted as ‘at least possible service level’ with more planning reliability for decision makers.

The resulting time savings are further used in the traffic performance assessment. Complemented by the results of a CBA this will lead to recommendations to support decisions regarding the implementation or upgrade of novel technologies for incident management.

Table 11: Duration savings in percent for moving from the High time category to the Medium time category or from the High time category to the Low time category

Scenario	TIM phase	High→Medium Time	High→Low Time
1	Detection	80%	97%
	Verification	70%	90%
	Initial response	67%	83%
2	Detection	67%	93%
	Verification	70%	90%
	Initial response	67%	83%
3	Detection	80%	97%
	Verification	70%	90%
	Initial response	67%	83%
4	Detection	67%	93%
	Verification	70%	90%
	Initial response	67%	83%

With regard to the severity of incidents, especially in case of accidents, information on casualties and injuries is essential. This information can be provided from direct communication channels (voice) with involved or reporting persons or estimated from visual video monitoring. The objective of eCall is to make use of in-vehicle sensors to detect when a vehicle is involved in a (serious) accident. The following chapter discuss a method to estimate injury severity based on eCall in order to speed up this essential part of verification.

4 Injury severity estimation using Advanced eCall

4.1 Aim and scope

eCall is a system installed in a vehicle, that automatically dials the emergency services in the event of a serious road accident. Next to the GPS coordinates of the vehicle, other sensor information can be transmitted as well, such as airbag deployment. It is expected that, by reducing the response time of the emergency services, eCall will reduce the number of fatalities in the European Union as well as the severity of injuries caused by road accidents. Moreover, it is expected that eCall will bring savings to society by improving incident management and by reducing road congestion and secondary accidents. The European Commission decided in 2014 that from 2015 on, all new cars should be equipped with an eCall system (The European Parliament, 2014).

In Advanced eCall, injury risk information is added to the eCall message. This has the potential to further improve emergency response, both in quality and time. A prerequisite for adding injury risk information to eCall, is that a real time injury risk estimator is available, which can be used to estimate the risk of injury based on sensor input from the vehicle. In this project, a first step towards Advanced eCall is made by performing a feasibility study on the use of TNO’s Human State Estimator to predict injury risk on a real time basis.

4.2 Method

The methodology used in the feasibility study can be split in several steps. First, car crashes are selected from the GIDAS database (Geman In-Depth Accident Study, 2015). For these cases, the injuries from which the occupants suffered are known and documented. Next, the injury severity is estimated using the Human State Estimator. This will show if the Human State Estimator is capable of distinguishing between the various injury severity levels seen in the GIDAS cases. The paragraphs below describe the methodology used in this study in more detail.

4.2.1 Human State Estimator

The Human State Estimator (HSE) is a linearized numerical model of the Hybrid III 50th percentile dummy in a small family car, subject to a frontal crash. The HSE (Laan, 2009) is capable of measuring loads, moments and displacements in the neck, spine and chest (see Figure 12). The current version of the HSE is developed based on a scenario with statistically the largest fatality risk; injury in the thoracic region for an adult occupant in a passenger, involved in a frontal impact (Laan, 2009). Due to this focus on frontal impacts, the influence of the seat belt is more accurately validated compared to the seat behaviour. This study will therefore also focus on thoracic injuries caused by frontal impacts between passenger cars. In future research, both this study and the HSE should off course be extended towards other impact scenarios as well.

Various parameters can be measured in the HSE (see Figure 12), of which chest compression (Δx_{chest}) is the most important in this study. Furthermore, belt roll-out can be measured and even prescribed (for optimization purposes). In this study however, no belt optimization is used, since it is assumed that there is no optimization algorithm implemented in the investigated vehicles.

To evaluate chest compression with the HSE, two inputs to the system are required:

- Acceleration pulse of the crash (a_{veh} in Figure 12)
- Seat and belt system properties

In the GIDAS cases used for this project (section 4.2.2), both these inputs are not given. Therefore, they have to be estimated from known crash data. The estimation of acceleration pulses is described in more detail in section 4.2.3. The seat and belt properties are estimated using a validation method as described in 4.2.4.

The chest compression measured by the HSE can be translated to an injury risk using injury risk functions. This is described in more detail in paragraph 4.2.5.

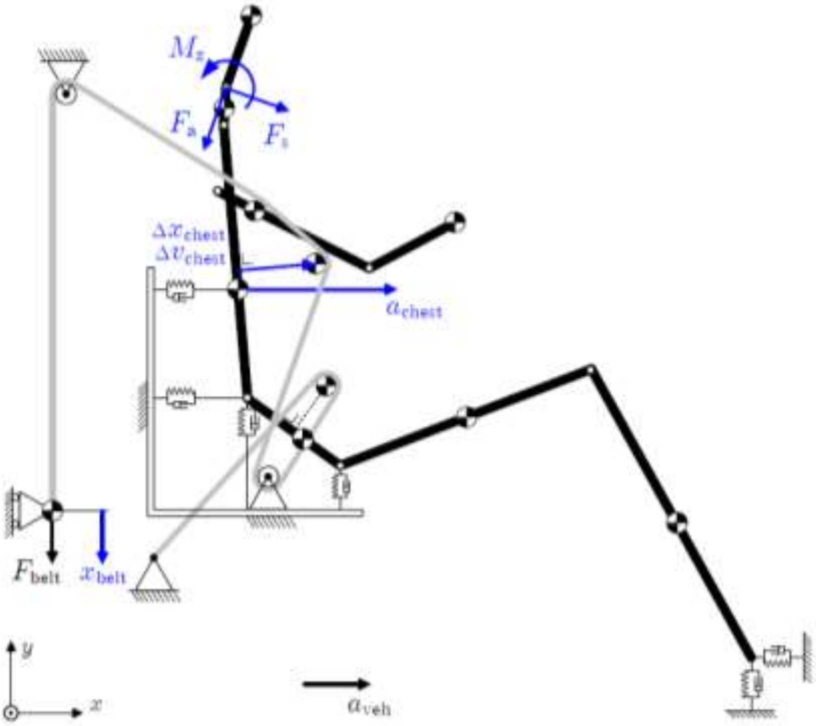


Figure 12: Schematic overview of the human state estimator, including the forces, moments and displacement variables that are measured within

4.2.2 GIDAS cases

As already mentioned in the previous section, this feasibility study focusses on thoracic injuries in frontal car to car crashes. To best evaluate the ability of the HSE to distinguish between injury severity levels, this should be the main altering parameter in the cases, meaning the other (environmental) parameters should be kept as constant as possible.

The selected GIDAS cases are described in Table 12. More details on each case are given in the sub-sections below.

Table 12: Overview of selected GIDAS cases

Case	Impulse angle	Overlap [%]	delta-v (kph)	collision speed	Collision with:	Injury severity	Sex (driver)	Height (driver; cm)	Road type	Max. speed limit	AIS Thorax (w/o spine)	Comment
1	180	100	30	72	passenger car	severe	male	unknown	motorway, 3 lanes	130	2	
2	175	81	37	70	passenger car	severe	male	178	motorway, 3 lanes	no limit	1	Multi collision accident (4 cars)
3	-176	77	39	70	car	slight	male	183	motorway, 3 lanes	no limit	0	Multi collision accident (6 cars)
4	-172	80	31	95	passenger car	slight	male	unknown	motorway, 3 lanes	100	1	steering short before collision

4.2.2.1 GIDAS Case 1 – Nissan Almera

The first GIDAS case describes a collision between a Nissan Almera (build year 1995) and an Audi A6 (build year 2001), where the Nissan impacted the rear of the Audi (so frontal impact for the Nissan) with a collision speed of approx. 72 km/h. The overlapping area of the front of the Nissan and rear of the Audi is 100% (full overlap). The driver of the Nissan suffered from a AIS 2 thorax injury (more details on AIS levels (injury severity levels) in paragraph 4.2.4). A picture of both cars is shown in Figure 13.

Figure 13: Picture of the Nissan (left) and Audi (right) after the collision in GIDAs case 1

4.2.2.2 GIDAS Case 2 – Audi A8

The second GIDAS case describes a collision between an Audi A8 (build year 1996) and a BMW M3 (build year 2002), where the Audi impacted the rear of the BMW with a collision speed of approx. 70 km/h. The overlapping area between the cars at collision was approx. 81%. The driver of the Audi suffered from a AIS 1 thorax injury. The accident is a multi-collision accident, where 4 cars are involved. The Audi and BMW are at the end of the pile-up. A picture of both cars is shown in Figure 14

Figure 14: Audi A8 (top left) and BMW M3 (bottom left) involved in the multi-collision accident of the third GIDAS case.

4.2.2.3 GIDAS Case 3 – Lexus RX

The third GIDAS case describes a collision between a Lexus RX (build year 2009) and a VW T5 (build year 2005), where the Audi impacted the rear of the VW with a collision speed of approx. 70 km/h. The overlapping area between the cars at collision was approx. 77%. The driver of the Lexus suffered no thorax injury (AIS 0). The accident is a multi-collision accident, where 6 cars are involved. The Lexus and VW are at the end of the pile-up. A picture of both cars is shown in Figure 15.

Figure 15: Lexus RX (left) and VW T5 (right) in GIDAS case 4

4.2.2.4 GIDAS Case 2 – VW New Beetle

The fourth GIDAS case describes a collision between a Volkswagen New Beetle (build year 2000) and a Mercedes Sprinter (build year 2004), where the New Beetle impacted the rear of the Sprinter with a collision speed of approx. 95 km/h. The overlapping area between the cars at collision was approx. 80%. The driver of the New Beetle suffered from a AIS 1 thorax injury. A picture of both cars is shown in Figure 16.

Figure 16: Picture of the VW New Beetle (left) and Mercedes Sprinter (right) from the second GIDAS case

Just before the impact, the driver of the New Beetle intended to avoid the standing traffic at the left most lane and steered to the right, thereby hitting the Sprinter at the rear. Due to the impact, the Sprinter spinned and toppled over. The New Beetle ended at the incline on the roadside. This is schematically shown in Figure 17. Since the impact pulse for this case is difficult to predict due to the complex kinematics in the crash, this case is not used in this study. Note that this case would have been usable in case the impact acceleration pulse was measured with on board sensors, as is the case for most eCall equipped vehicles.

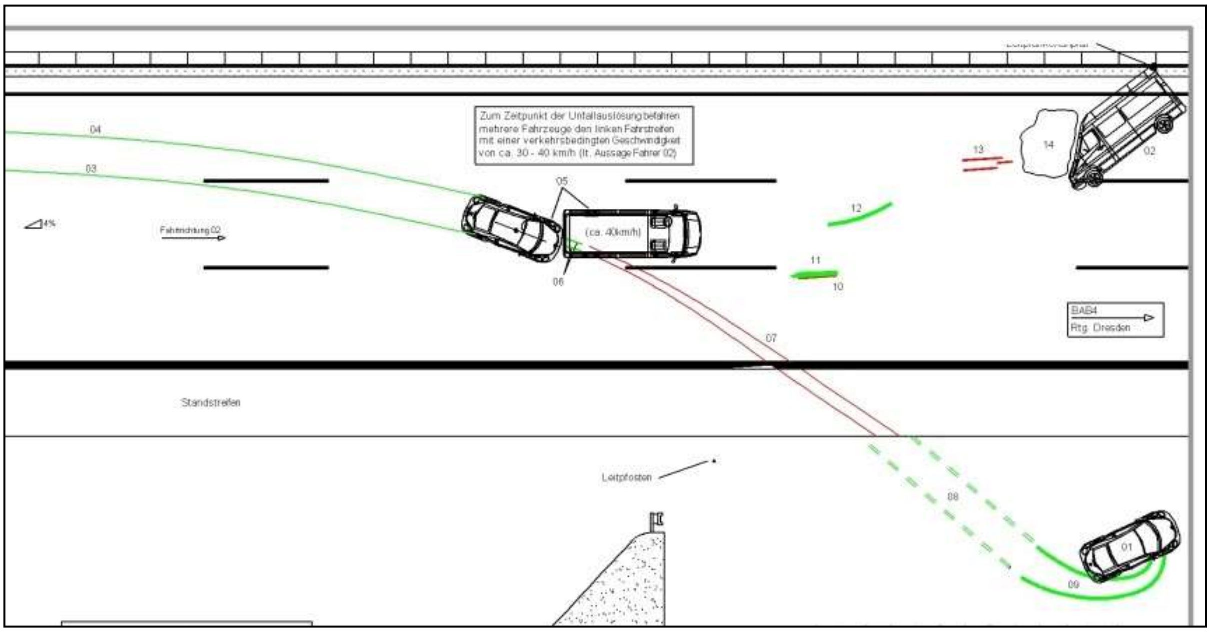


Figure 17: Schematic overview of accident scenario of GIDAS case 2

4.2.3 Crash pulse estimation

The GIDAS cases described in the previous paragraph to not contain information on the acceleration crash pulse. Since this is a required input to the HSE, the acceleration is estimated. Note that the acceleration pulse is of significant influence to the output of the HSE and therefore the estimated injury risk. Though the estimated pulse is sufficient for the goal of this study, which is to give an indication on the feasibility of Advanced eCall. Using a recorded acceleration crash pulse would obviously be preferred above this estimation step. In its application in Advanced eCall however, it is assumed that the acceleration of the vehicle is recorded and can therefore be used in the risk estimation.

Typical crash acceleration pulses follow a triangular shape, which is the shape that is used for the estimated impact pulses (see Figure 18). The variables for this impact pulse are pulse duration (t_2), the peak magnitude (a_1) and peak timing (t_1). In this simplified pulse, the acceleration at $t = 0$ and t_2 is assumed to be 0.

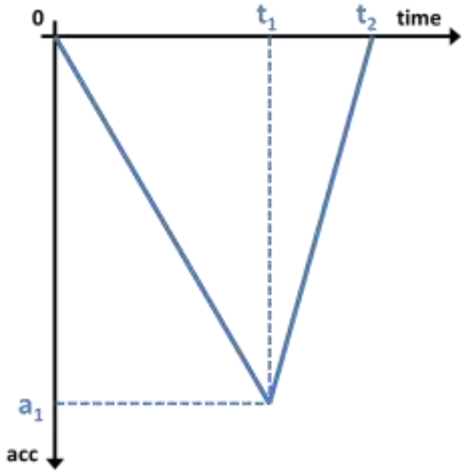


Figure 18: Simplified acceleration pulse, where the acceleration on the vertical axis is plotted against the time on the horizontal axis. Pulse acceleration peak (a_1), peak timing (t_1) and pulse duration (t_2) alter based on impact conditions.

The following parameters are taken into account when estimating the variables a_1, t_1 and t_2:

- Mass ratio between impacting cars
- Overlap between impacting cars

For this purpose, known crash pulses from two types of barrier impact tests are used from the FIMCAR project (FIMCAR Project, 2012). In these tests, among others, the acceleration during the impact is measured.

The first set of data consists of Moving Progressive Deformable Barrier (MPDB) tests with three types of cars (car A, B and C, an average, small and large size vehicle respectively). The MPDB is "Moving", since it can move with a chosen velocity. It contains a "Deformable" part that impacts with the vehicle. "Progressive" in MPDB refers to the fact that the barrier gets stiffer with increasing impact distance. An example of an MPDB test is shown in Figure 19. In the MPDB tests the vehicle under tests and the barrier move towards each other with the same speed. The velocity used in the MPDB tests is comparable to the delta-v (change in velocity of vehicle during impact), however, since both barrier and vehicle are approaching with this speed, the impact velocity is double, resulting in a higher and shorter crash pulse. The overlap in the MPDB tests is 50%, however, resulting in a less severe and slower crash pulse. These two effects are assumed to compensate, and it is therefore assumed that the MPDB tests can be used to derive the crash pulse shape for a 100% overlap frontal car-2-car impact.

Figure 19: Example of an MPDB test

The acceleration pulses for the MPDB tests with car A, B and C are shown in Figure 20.

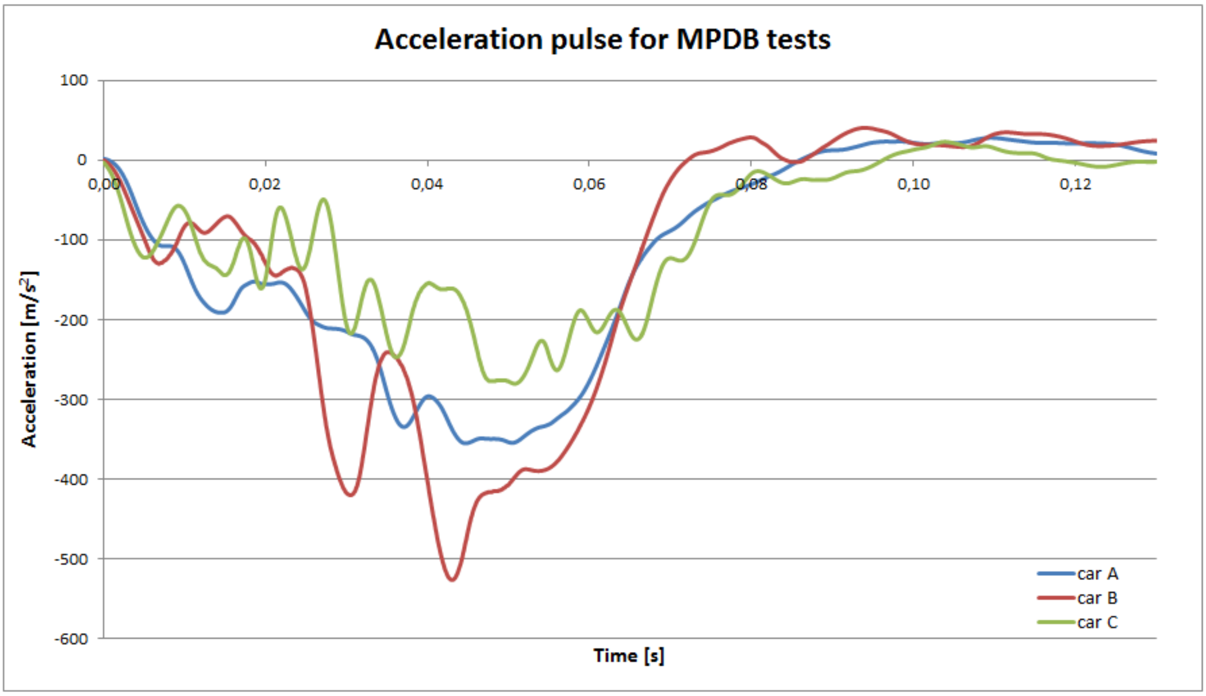


Figure 20: Impact acceleration pulses for three MPDB tests: car A (blue), car B (red) and car C (green).

A triangular shape is fitted through the acceleration curves, such that the shape of the pulse is adequately captured. These fits are plotted as solid lines in Figure 21. From these triangular fits, the variables a_1, t_1 and t_2 are derived. These values, together with the mass ratios between MPDB and vehicle under test are summarized in Table 13.

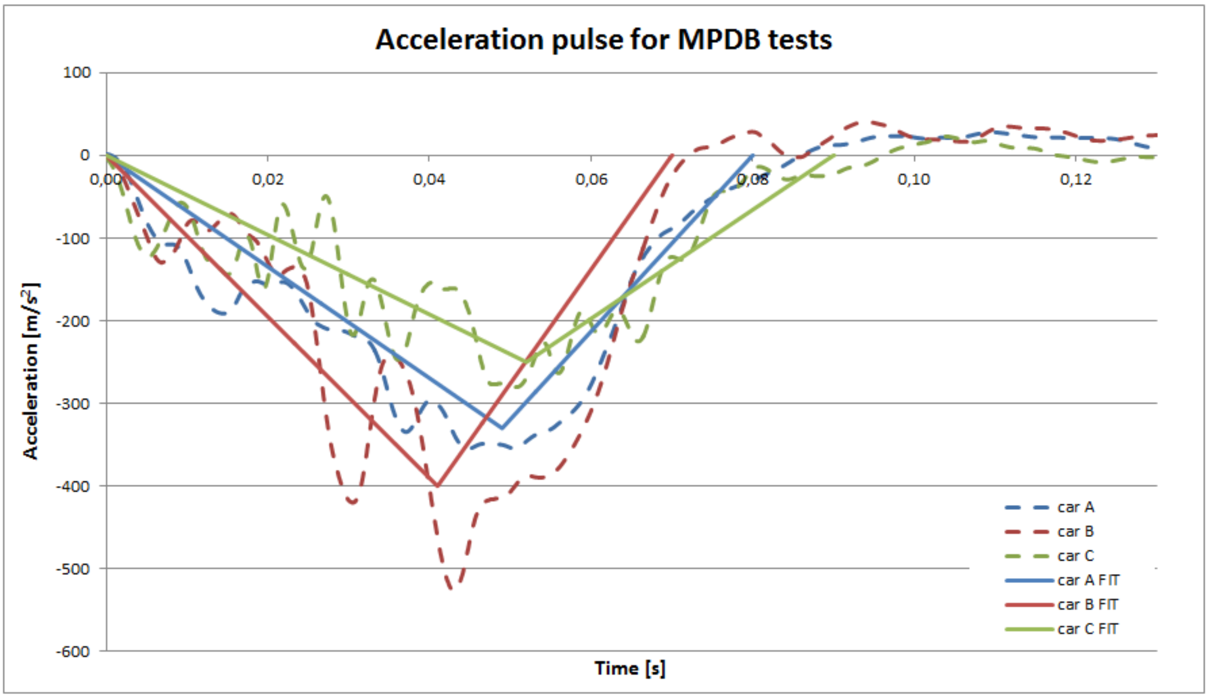


Figure 21: Impact acceleration pulses for three MPDB tests (dashed lines), including triangular fit (solid lines), for car A (blue), car B (red) and car C (green)

Table 13: Properties of 3 MPDB tests used to derive a relation between the pulse shape and mass ratio

MPDB case	mass vehicle [kg]	mass MPDB [kg]	mass ratio [-]	peak acc (a_1) [m/s²]	peak time (t_1) [s]	pulse length (t_2) [s]
Car A	1405	1500	0,94	330	0,049	0,08
Car B	1250	1487	0,84	400	0,041	0,070
Car C	2169	1507	1,44	250	0,052	0,09

The relation between the mass ratio and variables a_1, t_1 and t_2 is visualized in Figure 22 as well. A trend line is fitted through the known MPDB data points (linear fit for the timing parameters, power fit for the peak acceleration parameter). Subsequently, this trend line is used to derive the values for a_1, t_1 and t_2 for the GIDAS cases (where the mass ratios are known). The resulting values for the GIDAS cases are listed in Table 14.

Table 14: Estimated pulse shape values for the GIDAS cases, based on relation between mass ratio and pulse shape as shown in Figure 22

GIDAS case	mass vehicle [kg]	mass MPDB [kg]	mass ratio [-]	peak acc (a1) [m/s2]	peak time (t1) [s]	pulse length (t2) [s]
Nissan Almera	1055	1565	0,67	456	0,042	0,068
Audi A8	1275	1635	0,78	406	0,043	0,072
Lexus RX	2085	1980	1,05	318	0,047	0,079

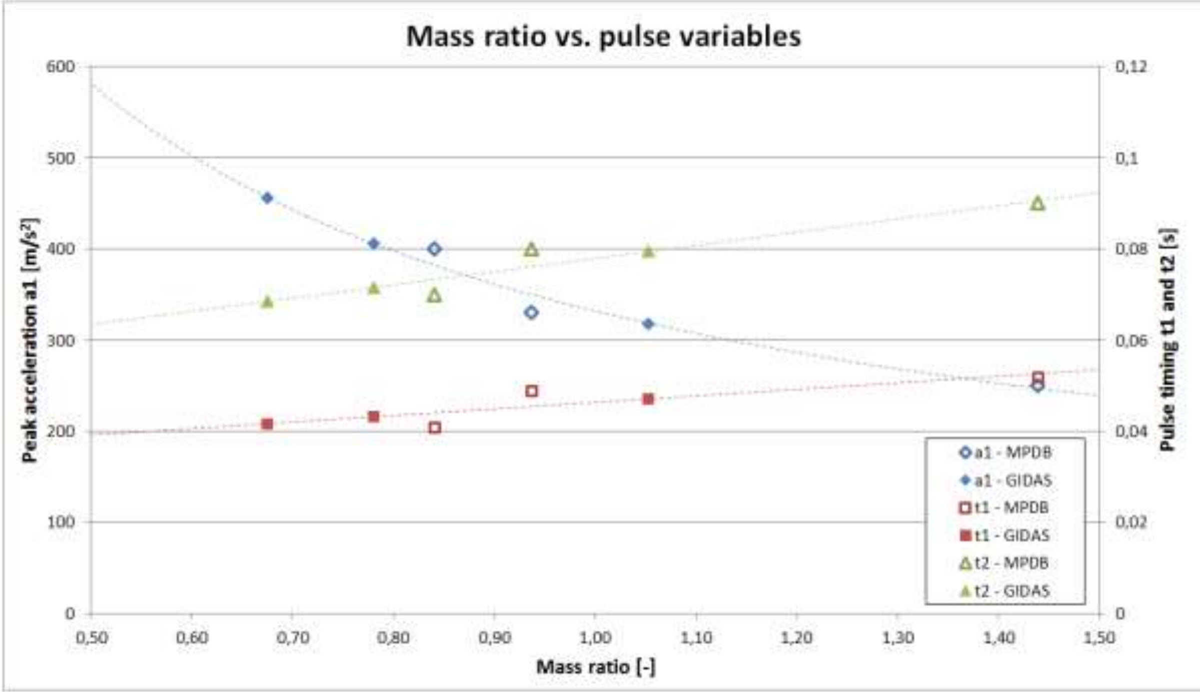


Figure 22: Plot of the relation between the mass ratio and pulse shape parameters a_1, t_1 and t_2. The trend lines through the known MPDB data (open markers) is used to determine the pulse shape variable values for the GIDAS cases (solid markers).

The next step is to account for the influence of the overlap between impacting objects. For this purpose, two known crash pulses are used with a similar car in different overlap configurations; an Offset-Deformable Barrier (ODB) test and a Full-Width Deformable Barrier (FWDB) test with car A. In the ODB tests, the overlap between barrier and vehicle is 40%. For the FWDB test the overlap is 100%. The impact pulses measured during these tests is plotted in Figure 23.

From Figure 23 it can be derived that decreasing the overlap with 60% (FWDB → ODB), decreases the peak value by approx. 30% (a_1 → – 30%), delays the peak time with approx. 70% (t_1 → +70%) and increases the pulse duration with approx. 60% (t_2 → + 60%). This relation can be used to scale the parameters from Table 14 (100% overlap) towards the real overlap as stated in the GIDAS case information. Table 15 lists the resulting pulse shape variables. Figure 24 shows the time history plot for the resulting GIDAS case crash pulses. These pulses can subsequently be used in the Human State Estimator to evaluate injury risk.

Table 15: Estimated pulse shape values for the GIDAS cases after correcting for overlap

GIDAS case	Overlap [%]	peak acc (a_1) [m/s²]	peak time (t_1) [s]	pulse length (t_2) [s]
Nissan Almera	100	456	0,0416	0,0685
Audi A8	81	363	0,0527	0,0854
Lexus RX	77	278	0,0597	0,0981

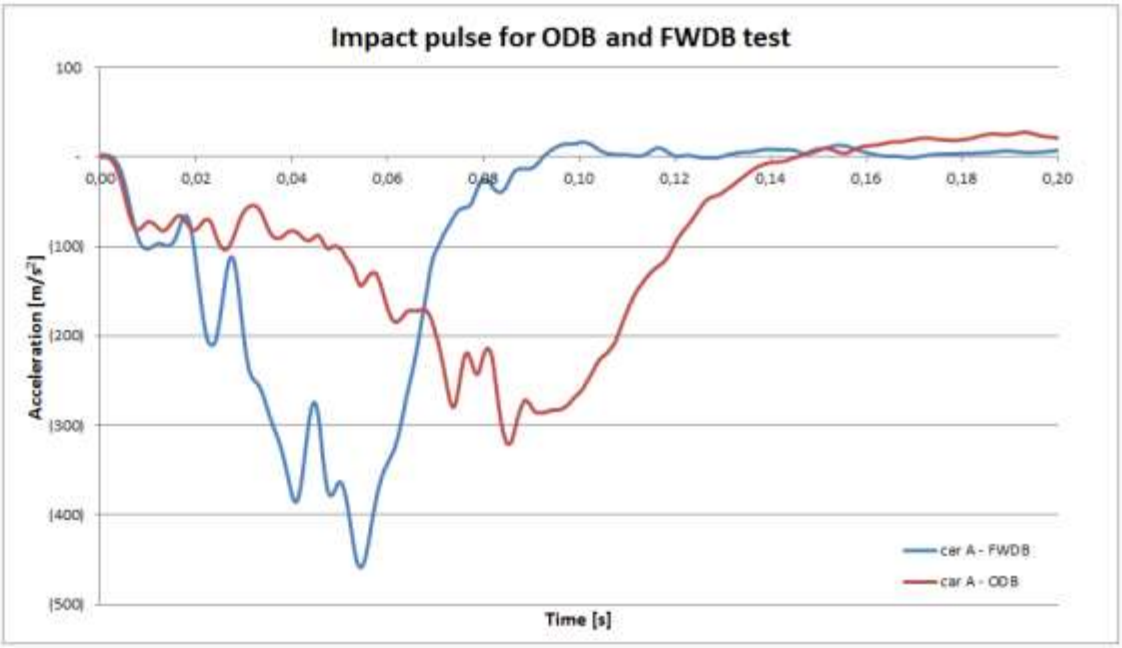


Figure 23: Impact acceleration pulse for ODB (red) and FWDB (blue) test with an Opel Astra

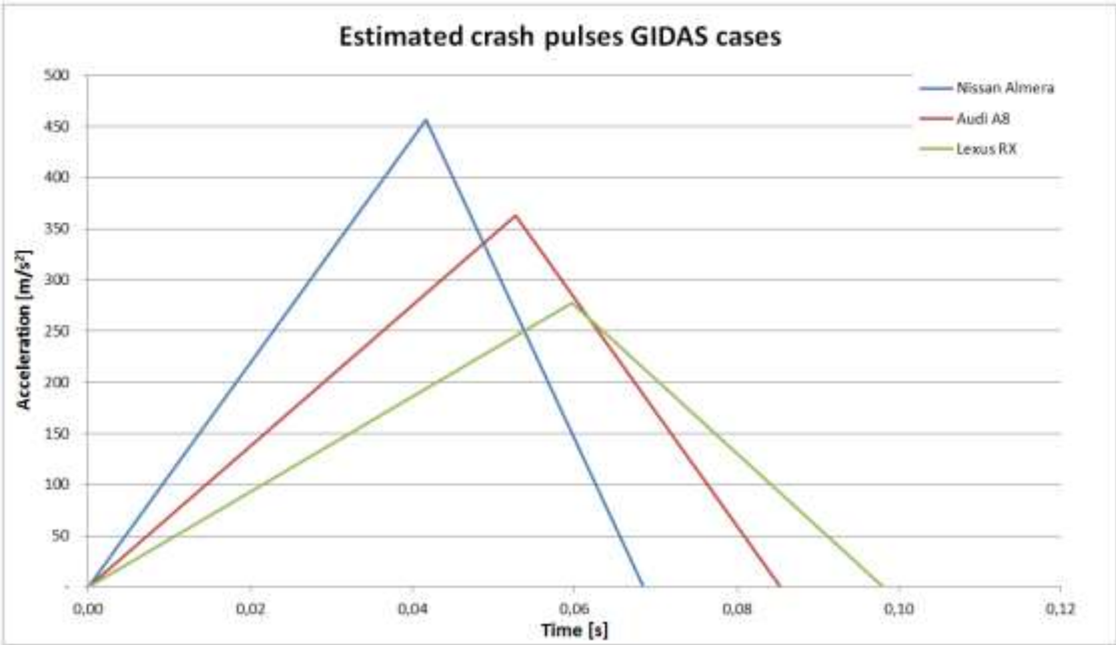


Figure 24: Estimated crash pulses for the GIDAS cases, derived by the pulse estimation steps as described in this paragraph

4.2.4 Validation seat belt system HSE

Various parameters in the Human State Estimator, such as stiffness, damping, elastic characteristics of the seat and belt system can be tuned to fit the situation as good as possible. For this feasibility study however, the seat and belt characteristics are not known. Similar to what is done for the crash pulse estimation, the seat and belt characteristics are tuned based on known impact test data. The tests include a Hybrid III dummy, enabling injury metrics to be used as well to tune the seat and belt characteristics. Two tests are used for this purpose: an ODB and MPDB test with car A. It is assumed that the same characteristics can be applied to the GIDAS cases. Again, this is assumed to suffice for a feasibility study. If Advanced eCall is implemented though, the real seat and belt characteristics for the specific vehicle should be implemented in the HSE.

The signals produced by the HSE together with the measured data during the tests are show in Figure 25 and Figure 26. The behaviour of the measured and simulated signals are comparable, with similar peak values (especially for the chest compression, which is the parameter of interest in this feasibility study).

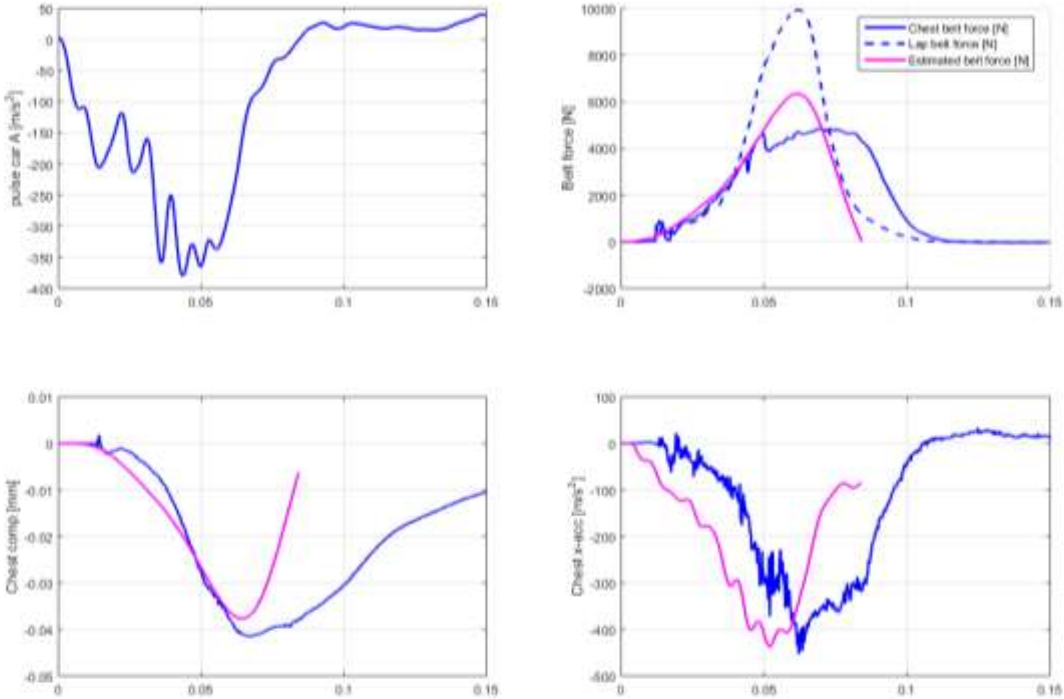


Figure 25: Measure data in car A - MPDB test in blue, data obtained from HSE in magenta. Top left: crash pulse acceleration, used as input for the HSE. Top right: belt forces measured. In the test, both the chest belt and lap belt forces ae measured. The HSE measures the belt force only at the belt roll-out. Bottom left: Chest compression [m] measured in the dummy during the test (blue) and by the HSE (magenta). Bottom right: chest acceleration in measured during test and in HSE.

The belt force measured by the HSE (magenta line in upper right plot of Figure 25 and Figure 26) is plotted up to the moment where the acceleration drops below 0 m/s^2. Due to linearization of the model, the calculated belt force can become both positive (pulling force) and negative (pushing force), while in reality a seat belt will never induce a negative (pushing) force. For this reason, the belt force is only calculated up to the moment where the acceleration < 0 m/s^2. Since this effect occurs after the impact peak, it will not influence the injury results.

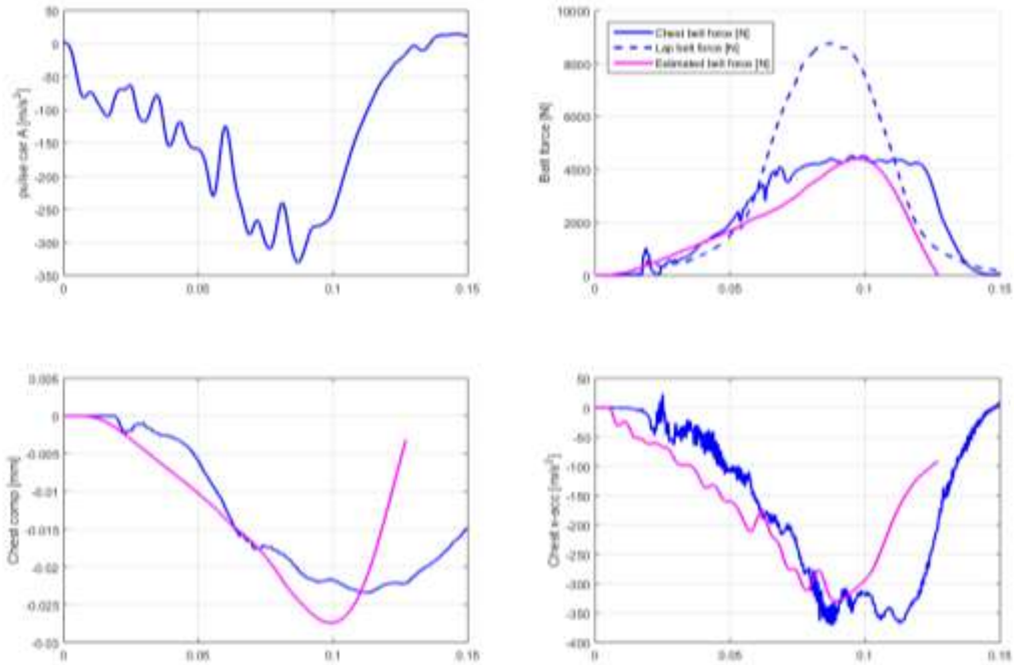


Figure 26: Measure data in car A – ODB test in blue, data obtained from HSE in magenta. Top left: crash pulse acceleration, used as input for the HSE. Top right: belt forces measured. In the test, both the chest belt and lap belt forces ae measured. The HSE measures the belt force only at the belt roll-out. Bottom left: Chest compression [m] measured in the dummy during the test (blue) and by the HSE (magenta). Bottom right: chest acceleration in measured during test and in HSE.

4.2.5 Injury risk function

As mentioned before, the output of the HSE that is under investigation in this feasibility study is chest compression. Chest compression measured by the HSE (or a hardware or numerical dummy) can be related to injury risk using so called injury risk functions.

In short, an injury risk function describes the relation between a measurable parameter (force, moment, acceleration, displacement, etc.) and the risk of obtaining an injury on a specific body region. For various injury severity levels, separate functions can be derived. Injury severity is expressed in AIS levels; the Abbreviated Injury Scale, which runs from AIS 0 (no injury) to AIS 6 (immediate death). Examples of thorax injuries for the different AIS levels are listed in Table 16.

Table 16: Overview of AIS injury severity levels and relating thorax injury examples

AIS level	Severity injury	Example
AIS 0	No injury	-
AIS 1	Minor injury	Superficial laceration
AIS 2	Moderate injury	Fractured sternum
AIS 3	Serious injury	Bilateral long contusion
AIS 4	Severe injury	Flail chest
AIS 5	Critical injury	Aortic laceration
AIS 6	Maximum injury	Crushed chest

The derivation of injury risk functions generally starts with Post Mortum Human Subject (PMHS, i.e. cadaver) tests. A load (force / moment / acceleration / displacement) is applied to a certain body part. Afterward, the severity of injury (if any) is evaluated. In some tests it is possible to measure the load within the specific body part of the PMHS directly. If not, the same test is repeated with a Anthropomorphic Test Device (ATD, or dummy), which is capable of measuring the load internally. An example of an PMHS and dummy chest impact test is shown in Figure 27.

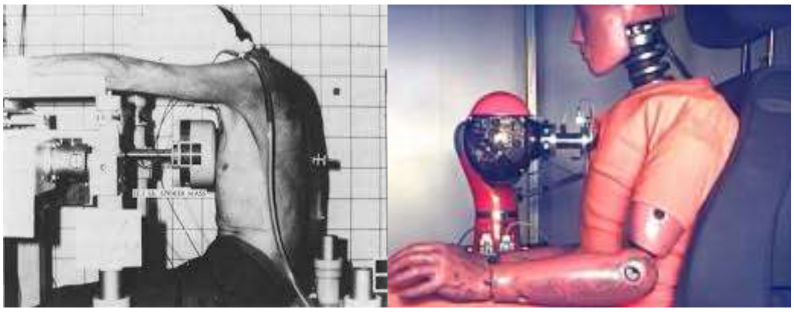


Figure 27: Chest impact test with PMHS (left) and Hybrid III dummy (right)

The impact tests result in a list of various measured load values that can be related to either injury (1) or no injury (0) of a certain severity level. A s-curve fit (for example binominal logistic regression) is used to create a continuous curve from this discrete data. In Figure 28 the impact measurements of an artificial dataset are represented by the red asterisks, and the fitted s-curve by the dark blue line.

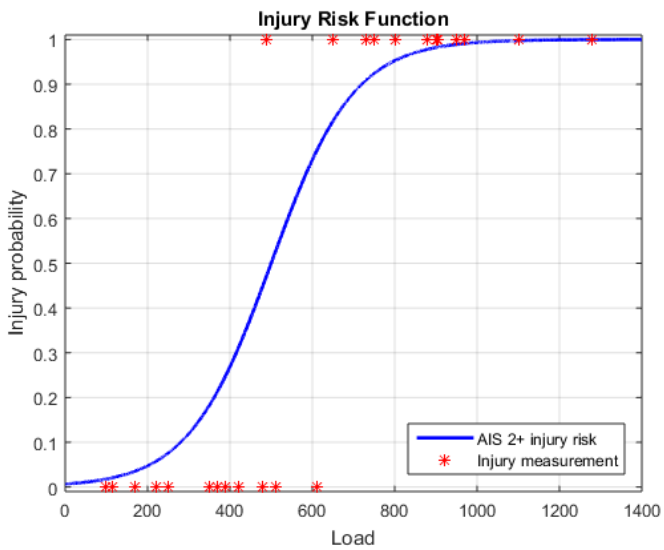


Figure 28: Example of an injury risk curve. The red asterisks represent the various impact tests with a certain load (horizontal axis), and either injury (1 on the vertical axis) or no injury (0 on the vertical axis). The fitted s-curve represents the continuous distribution of injury probability over the load variable (blue line).

The injury risk curves used for this study are those for the chest compression in the Hybrid III 50^{th} percentile dummy as shown in Figure 29. The functions are derived from PMHS data (Somers et al., 2014) which are scaled to fit for the Hybrid III (Broos, 2016 (to be published)).

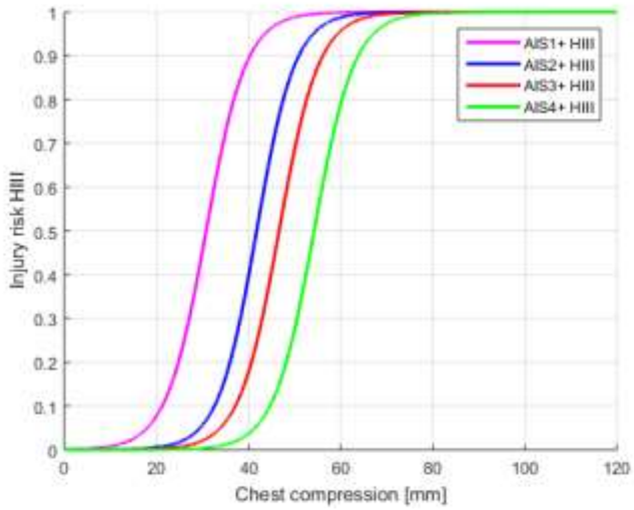


Figure 29: Hybrid III chest compression injury risk curves used in the HSE in this study

4.3 Results

4.3.1 Injury risk results

The impact pulses for the GIDAS cases shown in Figure 24 result in chest compression time history plots as shown in Figure 30 below. The absolute maximal values in these plots are related to injury risk using the injury risk functions from Figure 29. This results in injury risk summarized in Table 17 and Table 18.

Table 17: Cumulative injury risks for various severity levels for the GIDAS cases, as subtracted from the injury risk curves given in Figure 29.

Case	Real Thorax AIS (GIDAS)	Chest comp [mm]	% AIS 1+	% AIS 2+	% AIS 3+	% AIS 4+
Nissan	2	50.5	97	72	45	12
Audi	1	40.4	81	25	10	2
Lexus	0	28.8	33	3	1	0

Table 18: Overview of injury risks of various severity levels for the GIDAS cases. % AIS4+ summarizes the chances on an AIS4 injury or higher.

Case	Real Thorax AIS (GIDAS)	Chest comp [mm]	% AIS 0	% AIS 1	% AIS 2	% AIS 3	% AIS 4+
Nissan	2	50.5	3	25	27	33	12
Audi	1	40.4	19	56	15	8	2
Lexus	0	28.8	67	30	2	1	0

These results show that the HSE is capable of distinguishing between the various injury severity levels in the GIDAS cases. The driver in the first GIDAS case (Nissan Almera) suffered from an AIS2 injury. For this case, the HSE estimated an 27% and 33% risk on such an AIS2 and AIS3 injury, respectively. In the second GIDAS case (Audi A8), an AIS1 injury risk was observed. The HSE estimated the chance on an AIS1 level thorax injury on 56% (AIS0 only 19%, AIS2 only 15%). In the third case (Lexus), the chance on an injury was estimated only 33% by the HSE.

Note that injury risk functions results in chances on a certain injury level. The exact resulting injury will depend on individual properties (age, health, etc.). To a certain extent, human variability and repeatability / reproducibility of the test method is taken into account in the injury risk curve, by testing various PMHS subjects, although PHMS data is generally scarce.

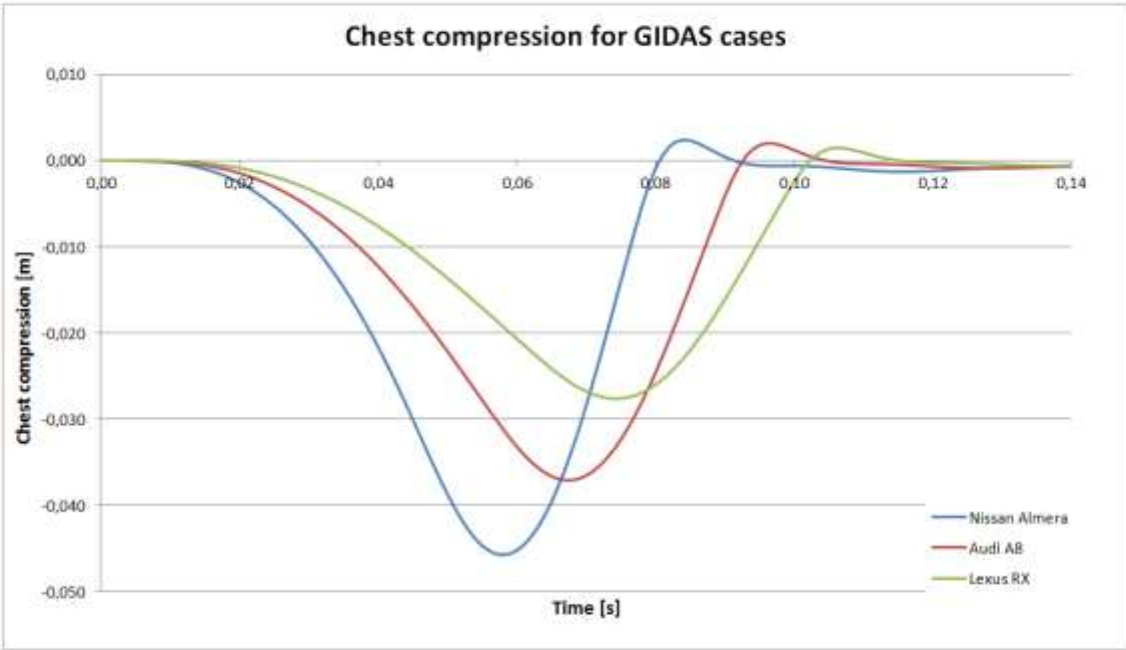


Figure 30: Chest compression time history plots for the three GIDAS cases. The maximum chest compression (absolute value) is used to determine the injury risk.

4.3.2 Discussion and future research

Since not all required data was available for this feasibility study, input data to the HSE, such as belt characteristics and crash pulse, is estimated. To do so, assumptions are made regarding pulse severity and timing. In the real-life application of Advanced eCall, this data is known (seat / belt characteristics) or measured by in-car sensors (crash pulse). This reduces the uncertainties introduced by the assumptions made in this study. It is expected that the results will benefit substantially from the known seat/belt characteristics and crash pulse.

This study provides a first glimpse on the feasibility of the use of the HSE for Advanced eCall. To prove it suitability however, this investigation should be extended towards more cases (to account for the variation in human variability), other body regions (not only thorax) and different impact scenarios (not only frontal impacts).

This study did not focus on the implementation of Advanced eCall, which is of course necessary to prove its worth for Traffic Incident Management. It should be investigated how the injury risk information can be used in practice, for example to adjust the (emergency) response actions accordingly (is it needed to send and ambulance, or will only a police officer suffice; is specialized medical help required, or maybe even a helicopter), or to estimate the impact of the incident on the traffic, which can in turn be used to take appropriate actions (how long is it expected for the road to be blocked, is redirecting of traffic needed, etc.). More elaborate research, potentially followed by pilot studies are required to gain trust in the injury risk prediction and to gain insight in the effect of response scenarios based on the Advanced eCall information.

5 Modelling and simulation of incident scenarios

5.1 Aim and scope

The aim of the modelling and simulation of incident scenarios was to develop or adapt traffic models so that they can be used to estimate cost of congestions, here in terms of traffic performance costs. The developed methodology was then applied to estimate the total delay, queue length and incident duration for different combinations of incident scenarios and TIM techniques, both different scene management techniques and novel technologies.

The aim was to find a traffic modelling approach that correctly describes the queue build up and discharge due to different types of incidents but that is fast enough to allow for estimation of a large set of combinations of scenarios, scene management techniques, novel technologies, travel demands, etc. Two different approaches have been investigated: 1) a macroscopic traffic simulation and 2) a deterministic queue model. The macroscopic traffic simulation model allows a more detailed modelling of how the traffic characteristics (density, speed, and flow) varies over space and time, while the queue modelling approach offers fast estimations. The different models are described in section 5.2 and compared for a subset of the scenarios and techniques in section 5.3.

5.2 Method

Figure 31 shows a schematic illustration of a road stretch without enter or exit points and with an incident blocking some parts of the road stretch. Traffic arrives to the road stretch at section (a) on its way towards the incident location it catches the queue (b), which might build up due to the reduced capacity through the incident location. At the incident location (c), the traffic throughput depends on the number of open lanes and the remaining capacity. Downstream of the incident location (d), the vehicles can accelerate and the traffic conditions are assumed to be non-congested.

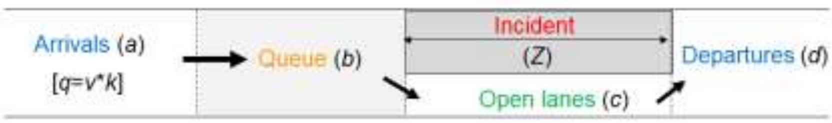


Figure 31: System layout

The queue build up and discharge processes for an incident implying a total road blockage are illustrated in Figure 32. At the time when the incident occurs, a queue will start to form and propagate upstream of the incident location (given that the travel demand exceeds the remaining capacity). When the incident is cleared, the queue will be discharged from the incident location. The time it takes to clear the queue is called the Recovery phase. In the figure, the queue reaches the maximum queue extent at the end of the Clearance phase, while the most upstream position reached by the queue is reached at the end of the Recovery phase.

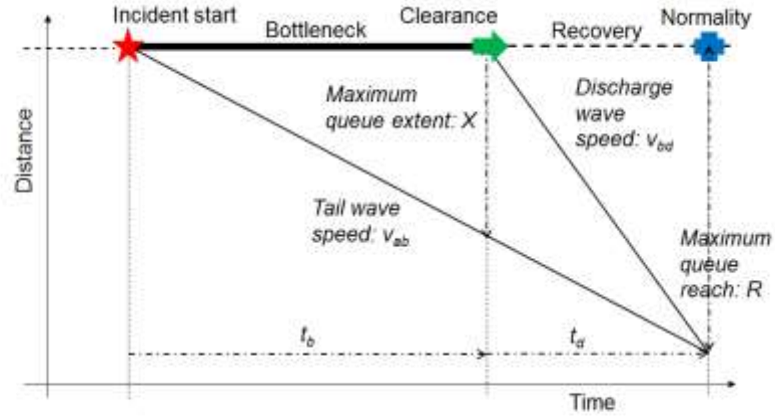


Figure 32: Sketch of queue development

The speed of the tail wave and the discharge wave as well as the queue extent and the total delay can be modelled in several ways. In PRIMA, two main approaches have been evaluated, namely a macroscopic traffic simulation using the Cell Transmission Model (described in section 5.2.1) and a deterministic queue model (described in section 5.2.2 and Section 5.2.3). Section 5.2.2 describes a single section and single time period queue model, which considers one road section and in which the capacity reduction due to the incident is constant during the duration of the incident and the clearance. Section 5.2.3 describes a further enhanced queue model still considering a single section but in addition it considers several time periods, for which the capacity reduction may differ depending on which the scene management actions that are taken.

5.2.1 Macroscopic simulation using the Cell Transmission Model

In order to perform traffic simulation of the different incident scenarios, a macroscopic traffic simulation has been used. The macroscopic model is a velocity-based cell transmission model (CTM) (Daganzo, 1994) used in the Mobile Millennium Stockholm project[2], originally developed by within the Mobile Millennium project at UC Berkeley (Bayen et al., 2011).

The cell transmission model utilizes the relation between speed (u), flow (q) and density (ρ) in order to estimate the average traffic state at a specific stretch. The traffic state

The relation between speed, density and flow can be expressed by the continuity equation (1). The continuity equation is used in order to relate the local characteristic flow to the instantaneous characteristic density.

$$q = \rho \cdot u \tag{1}$$

The fundamental diagrams illustrates the relation between flow, density and speed. The fundamental diagram used in the traffic incident scenarios is illustrated in Figure 33. Important information visualized in the fundamental diagram is actual road capacity, critical density (ρ_c) (where the maximum flow appears), critical speed (u_c) (where the maximum flow appears), jam density (ρ_{max}) (when operating speed is zero) and free flow speed (u_f).

[2] http://www.mobilemillenniumstockholm.se/

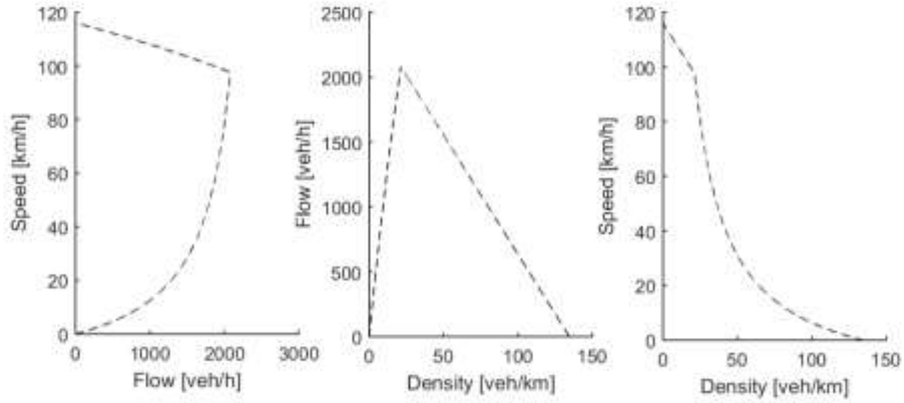


Figure 33: The fundamental diagrams used in the PRIMA traffic simulation

The traffic estimation is based on the partial differential equation (PDE) by Lighthill-Whitham-Richards (LWR) (Lighthill and Whitham, 1955, Richards, 1956). The LWR PDE is given in equation (2) and (3) and describes the traffic density at a specific road stretch with length *L*, over a given time period denoted *T*.

$$\frac{\partial \rho(X,t)}{\partial t} + \frac{\partial Q\big(\rho(X,t)\big)}{\partial X} = 0 \quad (X,t) \in (0,\mathrm{L}) \times (0,T) \tag{2}$$

$$\rho(X,0) = \rho_0(X), \;\; \rho(o,t) = \rho l(X), \;\; \rho(L,t) = \rho_r(X) \tag{3}$$

In equation (2) and (3), ρ_0, ρ_r and ρl denote the initial density, right boundary density and left boundary density, respectively. *Q* denotes the flux function which represents the flow of vehicles as a function of density defined between 0 and the jam density ρ_{max}. Equation (4) illustrates flow of vehicles (*Q)* as a function of density (ρ), also known as the fundamental diagram. This assumes velocity ca be expressed as a function of density, $V(\rho)$**,** also defined between 0 and ρ_{max}.

$$Q(\rho) = \rho \cdot V(\rho) \tag{4}$$

The traffic state may be expressed in terms of velocity by inverting the function in equation (4). This means that the partial differential equation can be expressed for velocity instead of the typical traffic state, which is density. The velocity function used the CTM is a hyperbolic linear approximation of the Daganzo-Newell velocity function (see e.g. Work et al. (2010)). The hyperbolic-linear approximated function of the Daganzo-Newell may be inverted as illustrated in equation (5). The inverted hyperbolic-linear function is expressing the density as a function of velocity.

$$\rho = V_{HL}^{-1}(v) = \begin{cases} \rho_{\max}\left(1 - \dfrac{v}{v_{max}}\right) & if\ v \geq v_c \\ \rho_{max}\left(\dfrac{1}{1 + \dfrac{v}{w_f}}\right) & otherwise \end{cases} \tag{5}$$

The most important characteristic of the velocity function used in the CTM is that it has to be invertible. The importance of an invertible velocity function is related to the fact that model uses a CTM with velocity as the state.

To construct a nonlinear time dynamic system, the LWR PDE can be discretized by using the Godunov discretization scheme (Godunov, 1959).

A discrete time step ΔT (indexed by $n \in \{0,\cdots,n_{max}\}$) and a discrete space step ΔX (indexed by $i \in \{0,\cdots,i_{max}\}$) is used for discretization over time and space. Application of the Godunov scheme onto the LWR PDE results in the formulation stated in equation (6). The estimated traffic state at time step n and space i is denoted ρ.

$$\rho_i^{n+1} = \rho_i^n - \frac{\Delta T}{\Delta X}\left(G(\rho_i^n, \rho_{i+1}^n) - G(\rho_{i-1}^n, \rho_i^n)\right) \tag{6}$$

G denotes the Godunov flux function, defined in equation (7).

$$G(\rho_i, \rho_{i+1}) = \begin{cases} Q(\rho_{i+1}) & \text{if } \rho_c \leq \rho_{i+1} \leq \rho_i \\ Q(\rho_c) & \text{if } \rho_{i+1} \leq \rho_c \leq \rho_i \\ Q(\rho_i) & \text{if } \rho_{i+1} \leq \rho_i \leq \rho_c \\ \min\left(Q(\rho_i), Q(\rho_{i+1})\right) & \text{if } \rho_i \leq \rho_{i+1} \end{cases} \tag{7}$$

The equation (6) and (7) constitutes the framework of a cell transmission model (CTM) with the state based on density. To ensure numerical stability the values of space and time steps are chosen such as that the link length cannot be traversed faster than if using the The maximum characteristic speed, denoted α_{max}. The condition in equation (8) is used to ensure this.

$$\alpha_{max}\frac{\Delta T}{\Delta X} \leq 1 \tag{8}$$

Speed can be expressed in terms of flow and density since the hydrodynamic relation is invertible. This holds that the equation (6) and (7) can be rewritten and express the CTM with a state based on velocity instead of density. Equation (9) and (10) represent the framework of this cell transmission model, also is known as the CTM-v model (Work, 2010).

$$v_i^{n+1} = V\left(V^{-1}(v_i^n) - \frac{\Delta T}{\Delta X}\left(\bar{G}(v_i^n, v_{i+1}^n) - \bar{G}(v_{i-1}^n, v_i^n)\right)\right) \tag{9}$$

$$\bar{G}(v_i, v_{i+1}) = \begin{cases} Q(v_{i+1}) & \text{if } v_c \geq v_{i+1} \geq v_i \\ Q(v_c) & \text{if } v_{i+1} \geq v_c \geq v_i \\ Q(v_i) & \text{if } v_{i+1} \geq v_i \geq v_c \\ \min\left(Q(v_i), Q(v_{i+1})\right) & \text{if } v_i \geq v_{i+1} \end{cases} \tag{10}$$

With use of the hyperbolic-linear model, the Godunov scheme in equation (10) can be expressed according to equation (11).

$$\bar{G}(v_i, v_{i+1}) = \begin{cases} v_{i+1}\rho_{max}\left(\dfrac{1}{1+\dfrac{v_{i+1}}{w_f}}\right) & \text{if } v_c \geq v_{i+1} \geq v_i \\ v_c\rho_{max}\left(1-\dfrac{v_c}{v_{max}}\right) & \text{if } v_{i+1} \geq v_c \geq v_i \\ v_i\rho_{max}\left(1-\dfrac{v_1}{v_{max}}\right) & \text{if } v_{i+1} \geq v_i \geq v_c \\ \min(V_{HL}^{-1}(v_i)v_i, V_{HL}^{-1}(v_{i+1})v_{i+1}) & \text{if } v_i \geq v_{i+1} \end{cases} \tag{11}$$

All the discrete points at the velocity field is represented by the equation (9) and (10) except for the starting and ending points of the network, denoted v_0^n and $v_{i_{max}}^n$. These points are expressed according to equation (12) and (13). Note that v_{-1}^n and $v_{i_{max}+1}^n$ are ghost points representing the continuation of the physical road stretch.

$$v_0^{n+1} = V\left(V^{-1}\left(v_0^n\right) - \frac{\Delta T}{\Delta X}\left(\bar{G}(v_0^n, v_1^n) - \bar{G}(v_{-1}^n, v_0^n)\right)\right) \tag{12}$$

$$v_{i_{max}}^{n+1} = V\left(V^{-1}\left(v_{i_{max}}^n\right) - \frac{\Delta T}{\Delta X}\left(\bar{G}\left(v_{i_{max}}^n, v_{i_{max}+1}^n\right) - \bar{G}\left(v_{i_{max}-1}^n, v_{i_{max}}^n\right)\right)\right) \tag{13}$$

An update algorithm needs to be added in order to estimate the traffic state in a network using the CTM-v model. The CTM-v update algorithm is obtained by sequentially applying the CTM-v and solving the linear programming in equation (14) scheme for each separate link in the entire network.

$$\begin{gathered} \max: 1^T\xi \\ st: A_j \leq \gamma_{O_j^{max}} \\ 0 \leq \xi \leq \gamma_{I_j^{max}} \end{gathered} \tag{14}$$

The parameters $\gamma_{I_j^{max}}$ and $\gamma_{O_j^{max}}$ represents the upper bound of the flux functions for the edges where vehicles enters and exits the system. *A* denotes the allocation matrix and the exiting fluxes for junction *j* is denoted ξ. By solving equation (14) to its optimal solution (ξ^*) the Godunov function in (11) reaches the values corresponding in equation (15) for the incoming links e_{in} and the outgoing links e_{out} for the specific junction *j*. The ratio of vehicles exiting junction *j* at the specific link e_{out} is denoted α.

$$\bar{G}_{e_{in}}\left(v_{i_{max}}^n, v_{i_{max}+1}^n\right) = \xi_{e_{in}}^* \qquad \bar{G}_{e_{out}}(v_{-1}^n, v_0^n) = \sum_{e_{in}\in I_j} \alpha_{j,e_{out},e_{in}}\,\xi_{e_{out}}^* \tag{15}$$

The network is thereby marched in time and consists in a discrete dynamical system. By knowing the velocity field in equation (16) for all discrete points $i \in \{0, \dots, \mathrm{i_{max}}\}$ at all edges it becomes possible to estimate the traffic state for the next time step.

$$v^n\left[v^n_{0,e_0},\ldots,v^n_{e_{max},e_0},\ldots,v^n_{0,e_{|\varepsilon|}},\ldots,v^n_{e_{max},e_{|\varepsilon|}}\right] \tag{16}$$

Equation (17) enables estimation of the velocity in the next time step $t = (n+1)\Delta T$ by using the CTM-v network update algorithm denoted *M.*

$$v^{n+1} = M[v^n] \tag{17}$$

The CTM-v update network algorithm contains several steps estimating the traffic state. The different steps are summarized as follows:

1. For all junctions j in network J:

   a) Compute the maximum admissible outgoing and incoming flux using the hyperbolic linear function in equation (5).

   b) Solve the linear program in equation (14) to its optimal solution (ξ^*) and compute $\bar{G}_{e_{in}}$ and $\bar{G}_{e_{out}}$ using equation (15).

2. Update the velocity field according to equation (9), (12) and (13). The calculation is performed by estimating the velocities in the next time step $v^{n+1}_{i,e}$ $\forall \in \{1,\ldots,\mathrm{i}_{\mathrm{max,e}}\}$ for all edges in the network ($e \in \varepsilon$).

Modelling of capacity reductions were required in order to capture the effects of traffic incidents in the macroscopic traffic simulation. Reductions have been applied according to the Highway Capacity Manual 2010 (Transportation Research Board, 2010) including utilization of remaining capacity, as stated in Table 19.

Table 19: Utilization of remaining capacity

Lanes on freeway	No incident	Rubbernecking Small	Rubbernecking Large	Shoulder disable	Shoulder accident	1 lane blocked	2 lanes blocked	3 lanes blocked
2	100%	95%	75%	95%	81%	70%	0%	N/A
3	100%	95%	75%	99%	83%	74%	51%	0%

The effect of the capacity reduction has been modelled by changing the number of lanes available (fraction of lanes are allowed here) in combination with changed parameter values in the fundamental diagrams. The implementation applies the fundamental diagram to each individual lane. The changes in the fundamental diagram was made in order to remain the same critical density and jam density. The changes includes decreased free flow speed and overall decreased flow at each speed. The effect of capacity reductions on the lane utilization of the remaining capacity is presented in Table 19 and the effects on the fundamental diagram is illustrated in Figure 34.

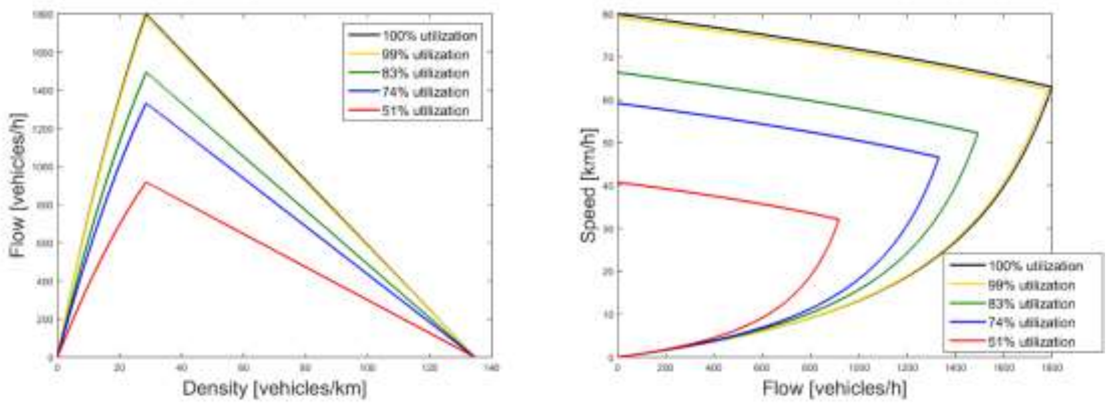


Figure 34: Density-flow (left) and flow-speed (right) relationships for different capacity utilizations, used in scenario 1 and 3

The traffic simulation was performed at networks specifically defined for the PRIMA project. The networks were defined to fit the incident scenarios, having the following characteristics:

Network 1 (used for scenario 1 and 3)

- Length: ~100 km
- Length of cells (ΔX): 243 m
- Distance between ramps: 2 km
- Speed limit: 120 km/h
- Number of lanes: 3

Network 2 (used for scenario 2 and 4)

- Length: ~100 km
- Length of cells (ΔX): 243 m
- Distance between ramps: 4 km
- Speed limit: 80 km/h
- Number of lanes: 2

5.2.2 A single section single period queue model

The queue model developed calculates the speed/flow slope based on the *normal capacity of one lane*, then adjusts the result according to the actual number of lanes, *n*, and a factor to allow for a flatter initial trajectory. While *capacity* at the bottleneck is determined by the number of lanes available there, *m*, the dynamics of the queue depend on the number of lanes available upstream of the bottleneck because the queue forms upstream of the obstruction. This is by default equal the normal number of running lanes, but could be different, e.g. if the hard shoulder were opened giving extra space for the queue. The queue model use a large set of different variables and parameters and we therefore start with a definition of terms.

Definition of terms:

Configuration input parameters:

n = number of lanes

μ = normal capacity of one lane

V_f = free-flow speed

Scenario input variables
Q_a = flow of arriving traffic
T_b = duration of incident (up to clearance)
m = number of lanes available during incident

Circumstantial input parameters
β = overreach factor (maximum free-flow capacity / capacity with bottleneck)
χ = 'build-up' remaining lane capacity factor (during incident)
δ = 'decline' remaining lane capacity factor (after clearance)
λ = jam spacing (same distance units as in speed)
τ = response time (same time units as in speed, flow and capacity)

Output parameters:
α = slope of uncongested speed/flow relationship
q_x = flow of traffic: a arriving, b queuing, c passing incident, d departing
v_x = speed of traffic (…)
k_x = density of traffic (…)
v_{ab} = speed of tail wave of queue (positive=downstream)
v_{bd} = speed of discharging head wave of queue
w = upstream 'shock' wave speed = $-\lambda/\tau$
X = maximum physical extent of queue
t_d = time to discharge queue after clearance
r = upstream reach of a queue segment or tail wave
R = maximum upstream reach of queue
S = total space-time occupied by queue
D = total delay in queue corrected for normal travel time
N = number of vehicles delayed (by any amount)
d = average queuing delay per vehicle

Traffic conditions at the arriving section

For the upstream section (a) the arriving flow Q_a is an input to the model while the average speed v_a is modelled using a linear speed-flow relationship in which the speed is calculated as

$$v_a = V_f - \alpha Q_a \, , \tag{18}$$

where V_f is the free flow speed and the parameter α is calculated based on the free flow speed, the normal capacity per lane and a overreach factor β (maximum free-flow capacity / capacity with bottleneck) as

$$\alpha = \frac{V_f - \dfrac{\lambda\mu}{1-\tau\mu}}{n\beta\mu} \, . \tag{19}$$

The parameter λ represents the jam spacing and τ is the response time. The density is calculated using the general relationship between flow, speed and density as

$$\rho_a = \frac{Q_a}{v_a}. \tag{20}$$

Traffic conditions in the queue and at the incident location

The traffic flow in the queuing part (b) is the same as the throughput flow at the incident location (c) which is calculated based on the normal capacity per lane, number of lanes available and remaining lane capacity as

$$q_b = q_c = \chi m \mu. \tag{21}$$

Speed and density within the queue are estimated using a model derived from the assumption that a minimum safe braking distance is maintained, which results in a constant upstream wave speed. This is arguably the simplest of many alternative speed-density models. The speed is calculates as

$$v_b = \frac{\lambda q_b}{n - \tau q_b}. \tag{22}$$

and the density is calculated as

$$\rho_b = \frac{q_b}{v_b} = \frac{n - \tau q_b}{\lambda}. \tag{23}$$

Traffic conditions downstream of the incident location

For the traffic conditions downstream of the incident location (d) we assume that common free-flow relationship applies, i.e. we assume the same relationship between speed, flow and density. The flow depend on the normal capacity per lane, number of available lanes, and a remaining lane capacity factor (after clearance), which gives

$$q_d = \delta n \mu. \tag{24}$$

The speed in section *d* follows the same relationship as for the arriving flow, i.e.

$$v_d = V_f - \alpha q_d. \tag{25}$$

The density in section *d* is given by

$$\rho_d = \frac{q_d}{v_d}. \tag{26}$$

Queue build up and discharge

The speed at which the queue propagates upstream is calculated as

$$v_{ab} = \frac{Q_a - q_b}{k_a - k_b} . \tag{27}$$

How far upstream the queue reach depend on the queue propagation speed and the period of the queueing T_b. The maximum queue extend happens just before the recovery starts and can be calculated as

$$X = v_{ab} T_b . \tag{28}$$

The speed at which the queue is discharged is calculated as

$$v_{bd} = \frac{q_b - q_d}{\rho_b - \rho_d} . \tag{29}$$

In practice the head wave speed is equal to the 'shock' wave speed, i.e.

$$w = -\frac{\lambda}{\tau} . \tag{30}$$

This applies within the queue because both sides of the boundary are governed by the same congested speed/flow/density relationship. It also applies between the queue and discharging flow because the flows are the same, there being no source of additional traffic, whereas at the tail of the queue of course the flows are different. This gives that the duration of the recovery t_d can be estimated as

$$t_d = \frac{X}{v_{ab} - v_{bd}} . \tag{31}$$

The maximum upstream reach of the queue R is where the queue build up wave meets the queue discharge wave, which can be calculated as

$$R = v_{bd} t_d . \tag{32}$$

The total space-time region S that the queue occupied is calculated as

$$S = \tfrac{1}{2} R t_b . \tag{33}$$

The total delay D can then be calculated based on the space-time region that the queue occupied, the density in the queue and the relation between the speed of the arriving vehicles (undisturbed flow) compared to the speed in the queue, which gives

$$D = S\rho_b \left(1 - \frac{v_b}{v_a}\right) . \tag{34}$$

The number of delayed vehicles N are calculated as

$$N = Q_a(t_b + t_d). \tag{35}$$

and the delay per vehicle d is then given by

$$d = \frac{D}{N}. \tag{36}$$

There can also be delay from reduced speed in the incident zone, but this can be neglected on the assumption that the zone is short, differing from work zones and abnormal loads.

5.2.3 A single section multi-period queue model

In the multi-period model the output from the queue in one period contributes to the input in the next, and the number of lanes available may change.

Assuming ambient traffic arrival rate remains constant, we need five event times t_i representing the start and end times of the phases, and the number of lanes available through the bottleneck in each phase m_i and available to the queue n_i. Figure 35 illustrates the four phases given by the five event times t_i. The number of lanes available upstream of the bottleneck could be changed, for example, if the hard shoulder were opened, and would reduce the density of arriving traffic and thereby reduce the upstream speed of the tail wave. A problem with describing the sequence of events is that, because the speed at which changes propagate through the queue is finite, changes at its tail do not occur at the same times as causative changes at its head.

The tail wave will move upstream as long as the arriving flow does not fall below the flow in the queue. This flow reflects earlier capacity reduced below the arrival rate, and is assumed to persist as long as the queue lasts, although some diffusive density change might occur. If the capacity stays below the flow in the queue, then the head of the queue remains attached to the bottleneck. Otherwise, it moves upstream at approximately the wave speed. These details are difficult to model using constant values in finite time periods because each basic time period in effect has to be divided into several phases in which some values are different.

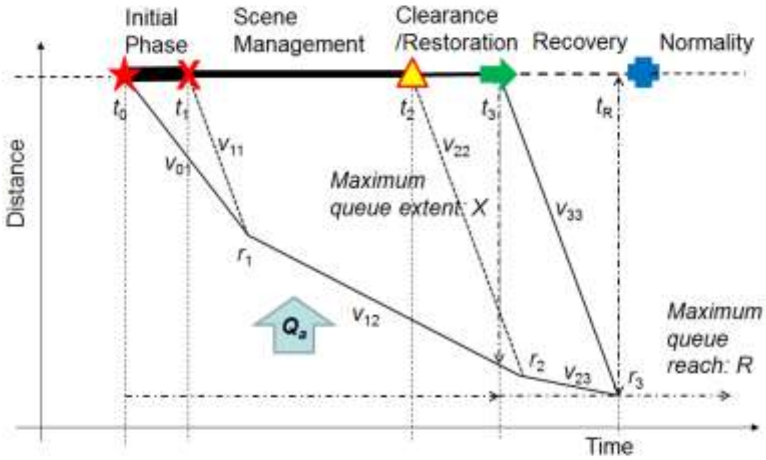


Figure 35: Queue development through four phases

Assuming that flow in queuing phase *i* is at capacity, then the flow is equal to

$$q_i = \chi m_i \mu \,. \tag{37}$$

Speed and density in the queue are obtained as previously (see section 0)

$$v_i = \frac{\lambda q_i}{n_i - \tau q_i} \tag{38}$$

and

$$\rho_i = \frac{q_i}{v_i} \tag{39}$$

The tail wave speed is obtained in the same way as v_{ab} previously (see section 0)

$$v_{i-1,i} = \frac{Q_a - q_i}{\rho_a - \rho_i} \tag{40}$$

Referring to Figure 35, the (virtual) head discharge wave speed is determined by reference to the flow in the *next* phase, where both densities apply to the congested regime:

$$v_{i,i} = \frac{q_{i+1} - q_i}{\rho_{i+1} - \rho_i} \tag{41}$$

It is difficult to calculate the head wave speed according to equation (42) in practice since it depend on the flow and density of the next coming time period which depend on the queue build up in the current time period. However, in most practice cases the head wave speed is equal to the 'shock' wave speed, i.e.

$$w = -\frac{\lambda}{\tau} \,. \tag{42}$$

This applies within the queue because both sides of the boundary are governed by the same congested speed/flow/density relationship. It also applies between the queue and discharging flow because the flows are the same, there being no source of additional traffic, whereas at the tail of the queue of course the flows are different.

The point r_i at which head and tail waves meet, measured from the head of the queue, is obtained by geometry, bearing in mind that the distance and speed values are *negative*, e.g:

$$r_1 = \frac{t_1 - t_0}{v_{01}^{-1} - v_{11}^{-1}} \tag{43}$$

Moving to the next quadrilateral wedge, and so forth:

$$r_2 = \frac{(t_2 - t_1) - r_1\left(v_{11}^{-1} - v_{12}^{-1}\right)}{v_{12}^{-1} - v_{22}^{-1}} \tag{44}$$

The expression for r_1 can be generalised to the same form as that for r_2 by defining $r_0 = 0$, and the maximum reach of the queue

$$R = \max(r_i). \tag{45}$$

With P is the number of phases, the total queued space-time area becomes

$$S = \sum_{i=1}^{i=P} S_i = \sum_{i=1}^{i=P} \tfrac{1}{2}(r_{i-1} + r_i)(t_{i-1} - t_i) \tag{46}$$

The number of vehicles affected by each phase depends on the density in that wedge of traffic, which in turn depends on the flow assumed to be at capacity in the phase. Although the free speed that the traffic would have achieved is the same in each phase, the effect differs so it is likely to be easier to evaluate the delay in each phase separately:

$$D = \sum_{i=1}^{i=N} S_i k_{bi}\left(1 - \frac{v_{bi}}{v_a}\right) \tag{47}$$

It may be assumed that some traffic is diverted either spontaneously or by management or as a result of information received upstream. This reduces the approaching flow and hence the queues and delays at the incident, say by a factor (1-δ_i). However, the usual assumption is that equilibrium obtains between the incident and the diversion route, so total delay and number of vehicles affected should be increased by the factor 1/(1-δ_i).

Calibration and implementation

The parameters in the speed-density-flow relationships used in the queue model, i.e. τ and λ, have been calibrated to fit the relationships used in the CTM model (see section 5.2.1). For the two lane motorway with speed limit 120 km/h the calibration resulted in $\tau = 1.45$ s and $\lambda = 7.434$ m, comparison with the CTM relationships is displayed in Figure 36. For the three lane motorway with speed limit 80 km/h the calibration resulted in $\tau = 1.49$ and $\lambda = 7.434$.

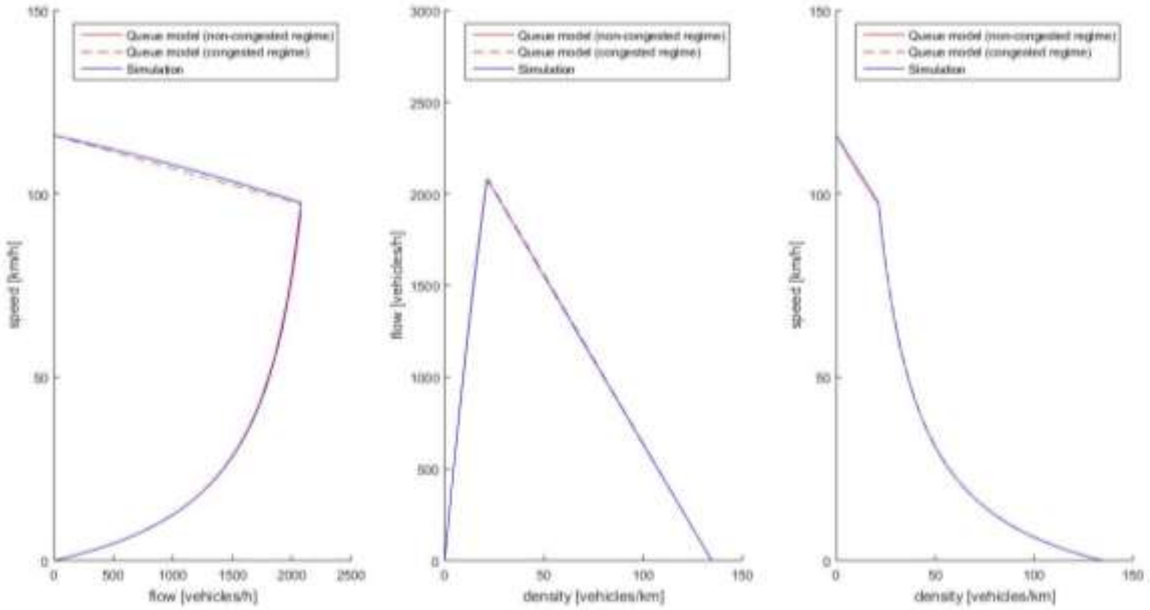
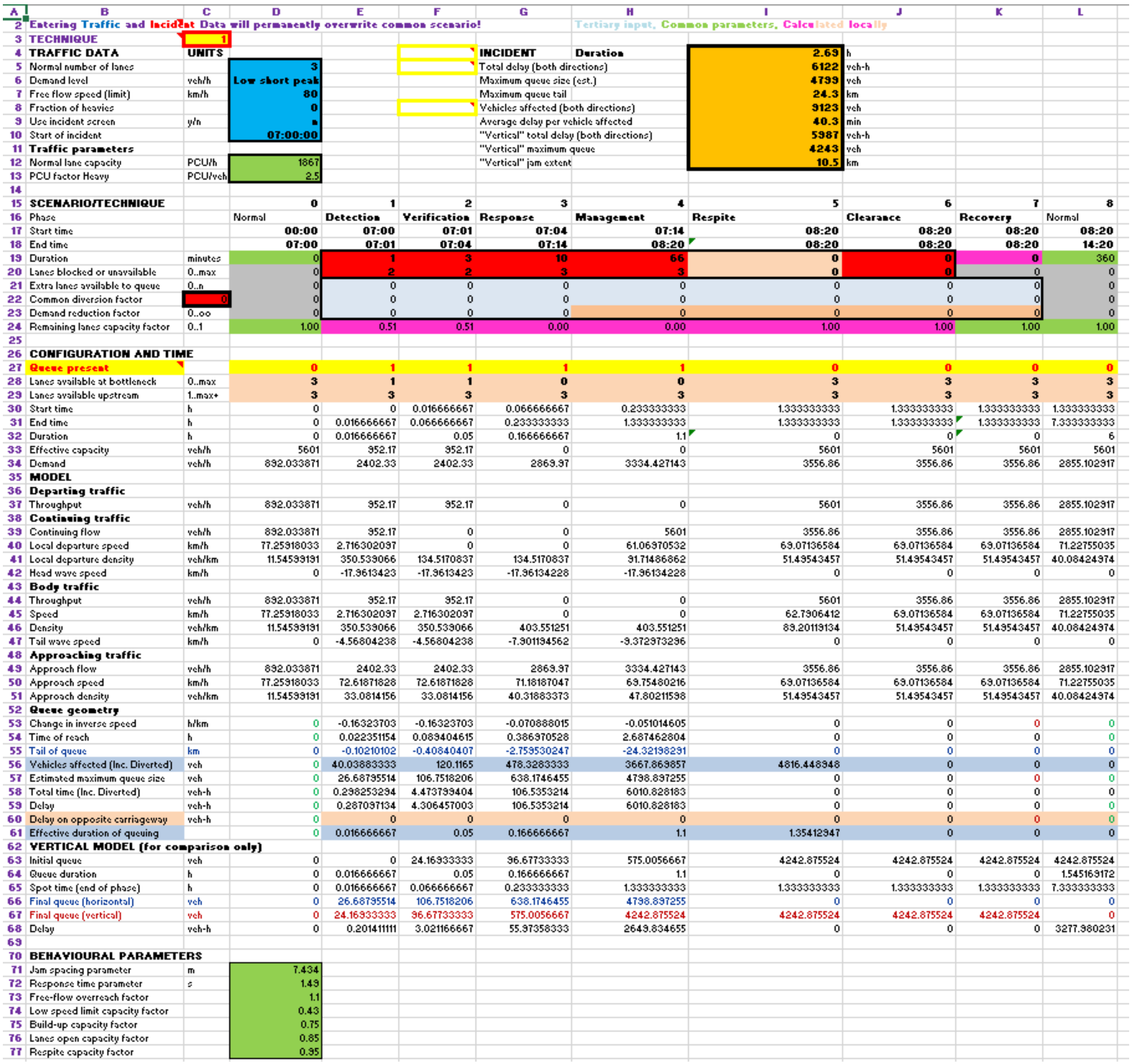


Figure 36: Speed-Density-Flow relationships used in the queue model and the simulations.

The model assumes a constant arriving flow but since the time is divided into different phases for which the capacity may change it is also possible to use different constant flows for the different phases. That means that if the arriving flow varies over time (e.g. as in scenario 1, see Figure 6) it is possible to calculate the average arriving flow during each phase. However, one problem is that the calculation considers the arriving flow to be constant not only during the phase duration but also until the tail wave and the discharge wave meet (see e.g. the point r_1 for phase 1 in Figure 35). Since the time and position at which these two waves meets depends on the arriving flow an iterative approach is needed to find the equilibrium of arriving flow and the meeting point of the two waves.

The queue model was implemented in a spreadsheet model (see screenshot example in Figure 37). A script was developed to allow automation of the calculation of all combinations of incident scenarios, scene management techniques and time savings due to novel technologies. A script for iteration of calculating the average demand during the relevant time period for each TIM phase was also developed.



A	B	C	D	E	F	G	H	I	J	K	L
2	Entering Traffic and Incident Data will permanently overwrite common scenario!						Tertiary input, Common parameters, Calculated locally				
3	TECHNIQUE	1									
4	TRAFFIC DATA	UNITS				INCIDENT	Duration	2.69	h		
5	Normal number of lanes		3			Total delay (both directions)		6122	veh-h		
6	Demand level	veh/h	Low short peak			Maximum queue size (est.)		4799	veh		
7	Free flow speed (limit)	km/h	80			Maximum queue tail		24.3	km		
8	Fraction of heavies		0			Vehicles affected (both directions)		9123	veh		
9	Use incident screen	y/n	n			Average delay per vehicle affected		40.3	min		
10	Start of incident		07:00:00			"Vertical" total delay (both directions)		5987	veh-h		
11	Traffic parameters					"Vertical" maximum queue		4243	veh		
12	Normal lane capacity	PCU/h	1867			"Vertical" jam extent		10.5	km		
13	PCU factor Heavy	PCU/veh	2.5								
14											
15	SCENARIO/TECHNIQUE		0	1	2	3	4	5	6	7	8
16	Phase		Normal	Detection	Verification	Response	Management	Respite	Clearance	Recovery	Normal
17	Start time		00:00	07:00	07:01	07:04	07:14	08:20	08:20	08:20	08:20
18	End time		07:00	07:01	07:04	07:14	08:20	08:20	08:20	08:20	14:20
19	Duration	minutes	0	1	3	10	66	0	0	0	360
20	Lanes blocked or unavailable	0..max	0	2	2	3	3	0	0	0	0
21	Extra lanes available to queue	0..n	0	0	0	0	0	0	0	0	0
22	Common diversion factor	0	0	0	0	0	0	0	0	0	0
23	Demand reduction factor	0..oo	0	0	0	0	0	0	0	0	0
24	Remaining lanes capacity factor	0..1	1.00	0.51	0.51	0.00	0.00	1.00	1.00	1.00	1.00
25											
26	CONFIGURATION AND TIME										
27	Queue present		0	1	1	1	1	0	0	0	0
28	Lanes available at bottleneck	0..max	3	1	1	0	0	3	3	3	3
29	Lanes available upstream	1..max+	3	3	3	3	3	3	3	3	3
30	Start time	h	0	0	0.016666667	0.066666667	0.233333333	1.333333333	1.333333333	1.333333333	1.333333333
31	End time	h	0	0.016666667	0.066666667	0.233333333	1.333333333	1.333333333	1.333333333	1.333333333	7.333333333
32	Duration	h	0	0.016666667	0.05	0.166666667	1.1	0	0	0	6
33	Effective capacity	veh/h	5601	952.17	952.17	0	0	5601	5601	5601	5601
34	Demand	veh/h	892.033871	2402.33	2402.33	2869.97	3334.427143	3556.86	3556.86	3556.86	2855.102917
35	MODEL										
36	Departing traffic										
37	Throughput	veh/h	892.033871	952.17	952.17	0	0	5601	3556.86	3556.86	2855.102917
38	Continuing traffic										
39	Continuing flow	veh/h	892.033871	952.17	0	0	5601	3556.86	3556.86	3556.86	2855.102917
40	Local departure speed	km/h	77.25918033	2.716302097	0	0	61.06970532	69.07136584	69.07136584	69.07136584	71.22755035
41	Local departure density	veh/km	11.54599191	350.539066	134.5170837	134.5170837	91.71486862	51.49543457	51.49543457	51.49543457	40.08424974
42	Head wave speed	km/h	0	-17.9613423	-17.9613423	-17.96134228	-17.96134228	0	0	0	0
43	Body traffic										
44	Throughput	veh/h	892.033871	952.17	952.17	0	0	5601	3556.86	3556.86	2855.102917
45	Speed	km/h	77.25918033	2.716302097	2.716302097	0	0	62.7906412	69.07136584	69.07136584	71.22755035
46	Density	veh/km	11.54599191	350.539066	350.539066	403.551251	403.551251	89.20119134	51.49543457	51.49543457	40.08424974
47	Tail wave speed	km/h	0	-4.56804238	-4.56804238	-7.901194562	-9.372973296	0	0	0	0
48	Approaching traffic										
49	Approach flow	veh/h	892.033871	2402.33	2402.33	2869.97	3334.427143	3556.86	3556.86	3556.86	2855.102917
50	Approach speed	km/h	77.25918033	72.61871828	72.61871828	71.18187047	69.75480216	69.07136584	69.07136584	69.07136584	71.22755035
51	Approach density	veh/km	11.54599191	33.0814156	33.0814156	40.31883373	47.80211598	51.49543457	51.49543457	51.49543457	40.08424974
52	Queue geometry										
53	Change in inverse speed	h/km	0	-0.16323703	-0.16323703	-0.070888015	-0.051014605	0	0	0	0
54	Time of reach	h	0	0.022351154	0.089404615	0.386970528	2.687462804	0	0	0	0
55	Tail of queue	km	0	-0.10210102	-0.40840407	-2.759530247	-24.32198291	0	0	0	0
56	Vehicles affected (Inc. Diverted)	veh	0	40.03883333	120.1165	478.3283333	3667.869857	4816.448948	0	0	0
57	Estimated maximum queue size	veh	0	26.68795514	106.7518206	638.1746455	4798.897255	0	0	0	0
58	Total time (Inc. Diverted)	veh-h	0	0.298253294	4.473799404	106.5353214	6010.828183	0	0	0	0
59	Delay	veh-h	0	0.287097134	4.306457003	106.5353214	6010.828183	0	0	0	0
60	Delay on opposite carriageway	veh-h	0	0	0	0	0	0	0	0	0
61	Effective duration of queuing		0	0.016666667	0.05	0.166666667	1.1	1.35412947	0	0	0
62	VERTICAL MODEL (for comparison only)										
63	Initial queue	veh	0	0	24.16933333	96.67733333	575.0056667	4242.875524	4242.875524	4242.875524	4242.875524
64	Queue duration	h	0	0.016666667	0.05	0.166666667	1.1	0	0	0	1.545169172
65	Spot time (end of phase)	h	0	0.016666667	0.066666667	0.233333333	1.333333333	1.333333333	1.333333333	1.333333333	7.333333333
66	Final queue (horizontal)	veh	0	26.68795514	106.7518206	638.1746455	4798.897255	0	0	0	0
67	Final queue (vertical)	veh	0	24.16933333	96.67733333	575.0056667	4242.875524	4242.875524	4242.875524	4242.875524	0
68	Delay	veh-h	0	0.201411111	3.021166667	55.97358333	2649.834655	0	0	0	3277.980231
69											
70	BEHAVIOURAL PARAMETERS										
71	Jam spacing parameter	m	7.434								
72	Response time parameter	s	1.49								
73	Free-flow overreach factor		1.1								
74	Low speed limit capacity factor		0.43								
75	Build-up capacity factor		0.75								
76	Lanes open capacity factor		0.85								
77	Respite capacity factor		0.95								

Figure 37: Incident spreadsheet model screen example

There are some fundamental differences between the macroscopic traffic simulation model and the queue model. In this chapter these differences are analysed and stated in order to clarify to which extent these differences affects the results.

5.2.4 Modelling differences between the simulation and the queue model

There are some fundamental differences in the underlying assumption for the two model approaches. The most important ones are described below.

Time dynamics

- The queue model considers time slices corresponding to the TIM phases, which allows different capacity and arriving flow for different phases but constant values within each phase
- The CTM considers is a time discrete model and in this application a time step of 60 seconds is used. This do not only allow detailed modelling of the variation in capacity,

demand and arriving flow over time but also detailed modelling of changes in traffic dynamics. However, in this application the demand is time-sliced on a 15 min level.

Space dynamics

- The queue model considers one homogeneous road section, or more precise one incident location. The only spatial modelling is the calculation of the queue extent. The model does not include modelling of off- or on-ramps.
- The simulation model considers a road stretch divided into cells (in this application of 486 m) for which the road characteristics may vary. The model can for example handle exiting and entering traffic on off- and on-ramps, respectively.

Traffic dynamics

- The queue model is based the assumption that vehicle density changes instantly at each wedge boundary and does not predict delay in a free-flowing stream departing from a queue.
- The simulation is based on the assumption that the vehicle density is constant in each cell during each time step but that it can vary between cells and time steps.

5.3 Results

This section presents a comparison of results based on the macroscopic traffic simulations and the queue model calculations. The comparisons are divided into three different parts. The first part (see section 5.3.1) compare the result when considering incidents and techniques that include one scene management period (i.e. no respite period) and a constant traffic demand. The second comparison (section 5.3.2) considers scenarios and techniques that still include one scene management period but for which the traffic demand varies over time. The third comparison (section 5.3.3) is for techniques that imply two scene management periods with a respite period in between. Then a comparison of the results when applying the macroscopic simulation model and the queue model for all scenarios and techniques for one travel demand case is presented (section 5.3.4). At the end results of calculations of all combinations and scenarios and techniques are presented (section 5.3.5). An overview and short names for each scenario and technique is given in Table 20 (detail descriptions are available in chapter 2).

Table 20: Overview of modelled Incident Scenarios and Techniques

Scenario	**Techniques**			
S1: Collision	1.1 Close all lanes	1.2 Incident screen	1.3 Close some lanes	1.4 Tow in off-peak
S2: Bad weather	2.1 Close all lanes	2.2 Contraflow	2.3 VMS and speed limit*	
S3: LGV breakdown	3.1 Close extra lane	3.2 Repair on-site	3.3 Tow in off-peak	
S4: Obstruction	4.1 Close all lanes	4.2 Contraflow	4.3 Close blocked lane	

5.3.1 One scene management period and static demand

This section commences with a comparison for a basic case for which the queue model should be able to give similar predictions as the more detailed macroscopic simulation model. In this case, constant traffic demand is assumed and ramps or diverting traffic is not modelled, i.e. a version of scenario 4 (Obstruction).
Figure 38 represents the results from such simulation using input data from incident scenario 4 (Obstruction).

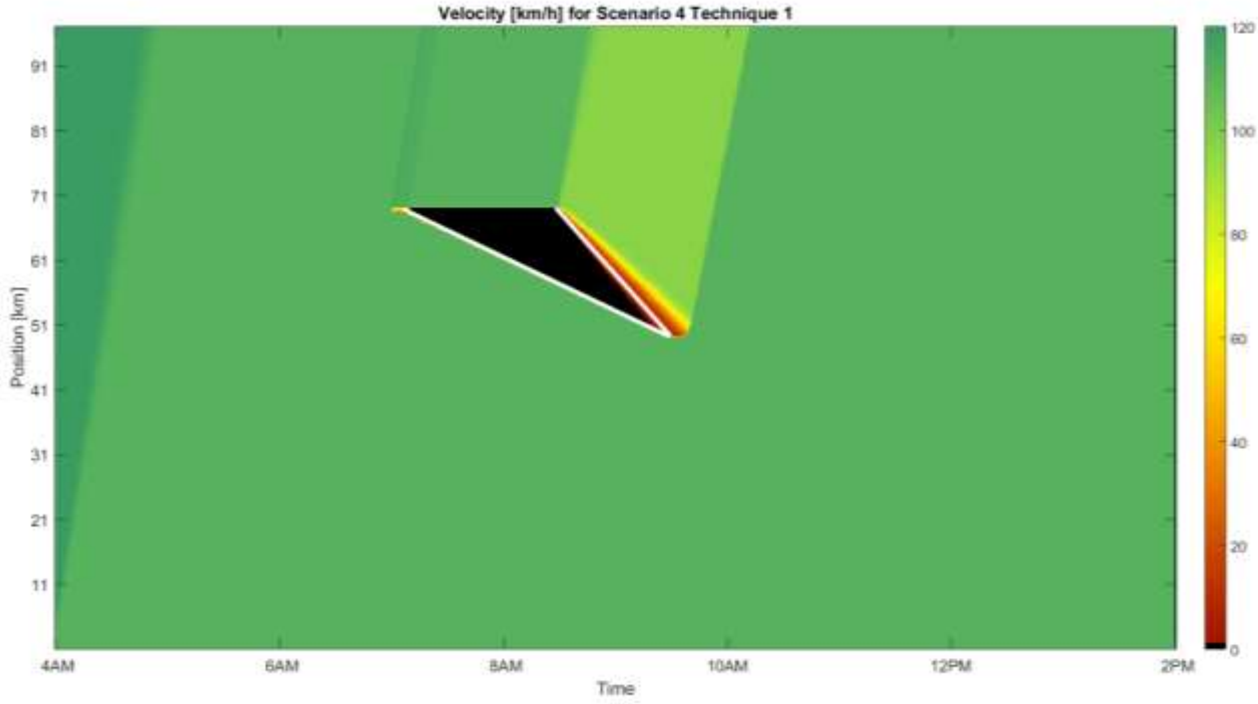


Figure 38: Comparing traffic state estimations using CTM macroscopic traffic simulation and queue modelling for scenario 4 (Obstruction), technique 1 (Close all lanes). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

According to the figure the queue model predicts similar queuing as the simulation. A more comprehensive comparison of scenario 4 is represented in Table 21 containing the total delay, total queue length and duration over all TIM techniques.

Table 21: Comparing incident estimations simulated by CTM and queue model for scenario 4

Simulation tool	TIM technique	Total delay [h]	Max queue length [km]	Total duration [h]
CTM	1 (close all lanes)	4 912	20	2.6
Queue model	1 (close all lanes)	3 764	20	2.6
CTM	2 (contraflow)	2 323	11	2.1
Queue model	2 (contraflow)	1 909	11	2.1
CTM	3 (close blocked lane)	1 070	6	2.0
Queue model	3 (close blocked lane)	1 024	7	2.0

The results in Table 21 confirm that the total queue length and the total duration estimated by the queue model corresponds to the estimation by the CTM. Significant differences are though observed comparing the total delay estimated by each tool. This may be explained by the complexity of the CTM which enables to capture the delay caused downstream of the congested site. Only comparing the heavy congested locations in
Figure 38 (coloured dark red and black in the space time plot) gives the following results according to Table 22.

Table 22: Comparing incident estimations simulated by CTM and queue model for scenario 4. Comparing only congested locations upstream of the incident

Simulation tool	TIM technique	Total delay [h]	Max queue length [km]	Total duration [h]
CTM	1 (close all lanes)	3 764	20	2.6
Queue model	1 (close all lanes)	3 764	20	2.6
CTM	2 (contraflow)	1 974	11	2.1
Queue model	2 (contraflow)	1 908	11	2.1
CTM	3 (close blocked lane)	999	6	2.0
Queue model	3 (close blocked lane)	1 024	7	2.0

According to the results comparing the CTM and the queue model with static characteristics, there is obviously one major difference between these models. Comparing only heavy congested locations gives a good correlation between the two models while the queue model underestimates the total delay from the simulation. The reason is that the simulation considers a whole road stretch which extends both upstream and downstream of the incident location and thereby also include the delay downstream of the incident location caused by the incident. Furthermore the queue model assumes instant changes in density at the wedges while the simulation models a more smooth change of density when the recovery wave propagates upstream. Continuously comparison will be made exclusively for the heavy congested locations, i.e. the main queue upstream of the incident location.

5.3.2 One scene management period and variable demand

Several of the traffic incidents scenarios assume varying traffic demand profiles. The reason is to evaluate TIM techniques which utilizes changes in arrival rate to apply actions causing major capacity reductions at off-peak rather than high peak, e.g. move vehicles to the shoulder and tow during off-peak as in scenario 1 (Collision) and technique 4 (Tow in off-peak). Thereby dynamic traffic demand profiles have been included in both the CTM and the queue model.

The CTM uses a profile aggregated on 15 minute level, and the queue model utilizes the averaged values of this profile for each different TIM phase. An example of a simulation performed with varying traffic demand profile (see scenario 1 and section 2.2.4) is illustrated in
Figure 39.

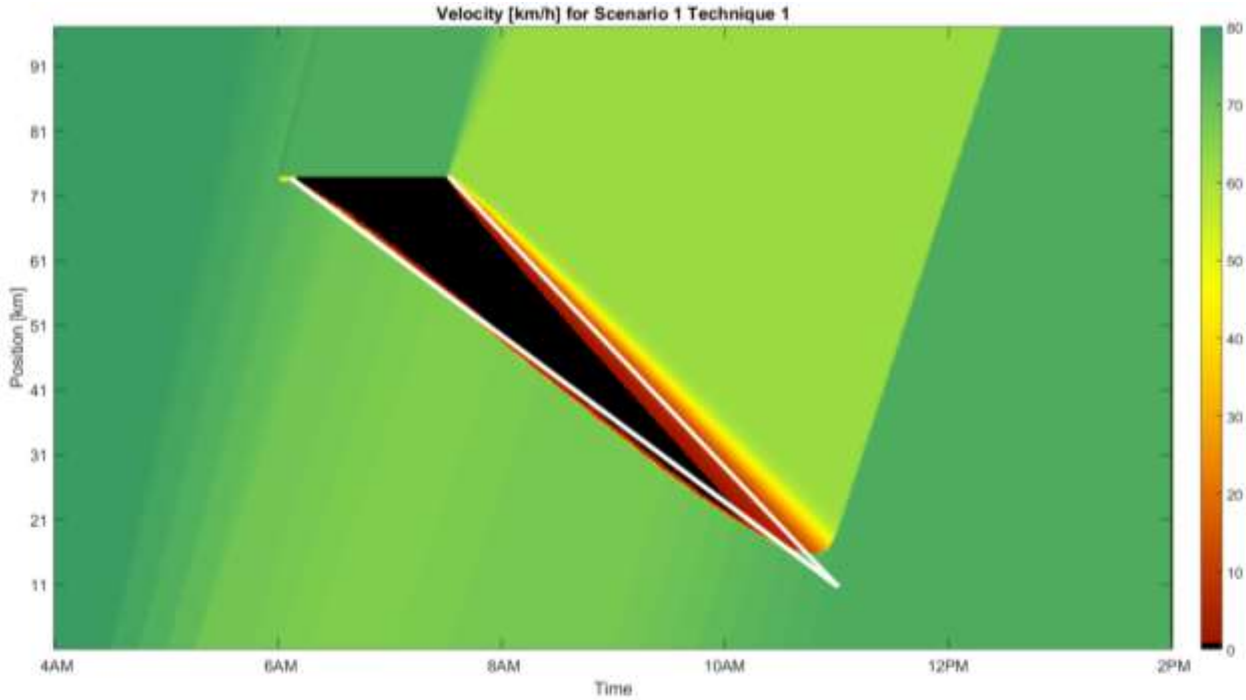


Figure 39: Comparing traffic state estimations using CTM and queue modelling for scenario 1 (Collision), technique 1 (Close all lanes). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

Table 23 includes additional performance indicators covering all of the TIM techniques used in incident scenario 1. As can be observed from Table 23, the queue model clearly overestimates the congestion caused by incident independent of technique.

Table 23: Comparing incident estimations simulated by CTM and queue model for scenario 1. Comparing only congested locations upstream of the incident

Simulation tool	TIM technique	Total delay [h]	Max queue length [km]	Total duration [h]
CTM	1 (close all lanes)	16 612	58	5.0
Queue model	1 (close all lanes)	20 785	63	5.0
CTM	2 (incident screen)	23 878	63	5.6
Queue model	2 (incident screen)	28 503	69	5.7
CTM	3 (close some lanes)	11 018	50	4.5
Queue model	3 (close some lanes)	15 015	55	4.5
CTM	4 (Tow in off-peak)	4 101	33	4.9
Queue model	4 (Tow in off-peak)	7 243	45	5.0

The overestimation is related to the fact that the CTM simulates a road stretch while the queue model assumes a single incident location (see section 5.2.4). This implies that the complexity of the CTM enables the arriving rate to be relative the traffic demand profile depending on the location of the queue tail. The traffic profile fed into the queue model is exactly the same that enters at the start of the road stretch in the CTM simulation. The implication is that the arrival rate at the end of the queue considers the extent of congestion in the simulation but not in the queue model. One way would be to feed the queue model with the exact flow profile at the location of the incident, while no incident is simulated. The outcome of theses simulations is represented in Table 24.

Table 24: Comparing incident estimations simulated by CTM and queue model for scenario 1. Comparing only congested locations upstream of the incident and using traffic demand measured at the location of the scene

Simulation tool	TIM technique	Total delay [h]	Max queue length [km]	Total duration [h]
CTM	1 (close all lanes)	16 612	58	5.0
Queue model	1 (close all lanes)	17 265	67	5.2
CTM	2 (incident screen)	23 878	63	5.6
Queue model	2 (incident screen)	23 941	73	5.7
CTM	3 (close some lanes)	11 018	50	4.5
Queue model	3 (close some lanes)	11 413	55	4.6
CTM	4 (Tow in off-peak)	4 101	33	4.9
Queue model	4 (Tow in off-peak)	4 066	33	5.0

As can be observed from Table 24, using the flow profile at the location of the incident scene would clearly improve the result comparison for technique 4. This behaviour is natural since the extent of the congestion is smallest using this technique, which means that the arrival flow at the end of the queue is fairly well represented by the flow at the location at the scene since the queue is quite short. Techniques for which there is a major queue show less good agreement when comparing the queue model and the CTM results. This since the traffic demand from the scene is not a good representation of the arrival rate at the end of the queue.

Figure 40 illustrates the differences between the demand profiles from the location of the scene compared with the demand at the start of the simulated road stretch.

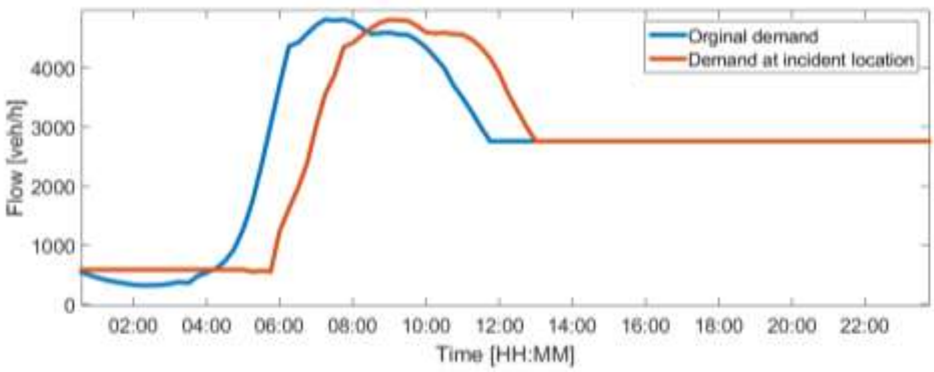


Figure 40: Differences between traffic demand measured at the location of the scene compared with the traffic flow entering the network

The consequence of using the demand profile entering the network as input to the queue model is that the congestion during the initial phases are overestimated compared to the CTM. The offset of the traffic peak in the simulation is related to the characteristics of the network since the entering vehicles needs to travel ~70 km downstream to the location of the incident.

The consequence of using the demand profile at the location of the scene as input to the queue model is that the congestion during the last phases are overestimated. The extent of the error is mainly depending on the length on the queue since longer queues leads to more congestion which do not appear in the CTM.

This implies that both demand profiles overestimates the congestion in the queue model compared with the results in the CTM. One potential way to overcome this problem may be to combine the two profiles depending on the length of current length of the queue in each separate phase of the incident.

If conducting a small sensitivity analysis to this scenario it becomes clear that the differences are not only related to the demand profile in this case. For example, scenario 1 and technique 3 has similar fundamental characteristics compared to scenario 2 and technique 2. Though, there seems to be large deviations between these techniques comparing the results from the simulation and the queue model. For Scenario 1 and technique 3 there is and overestimation of the congestion compared with the results from the CTM, even though the relative change is quite small. See Figure 41.

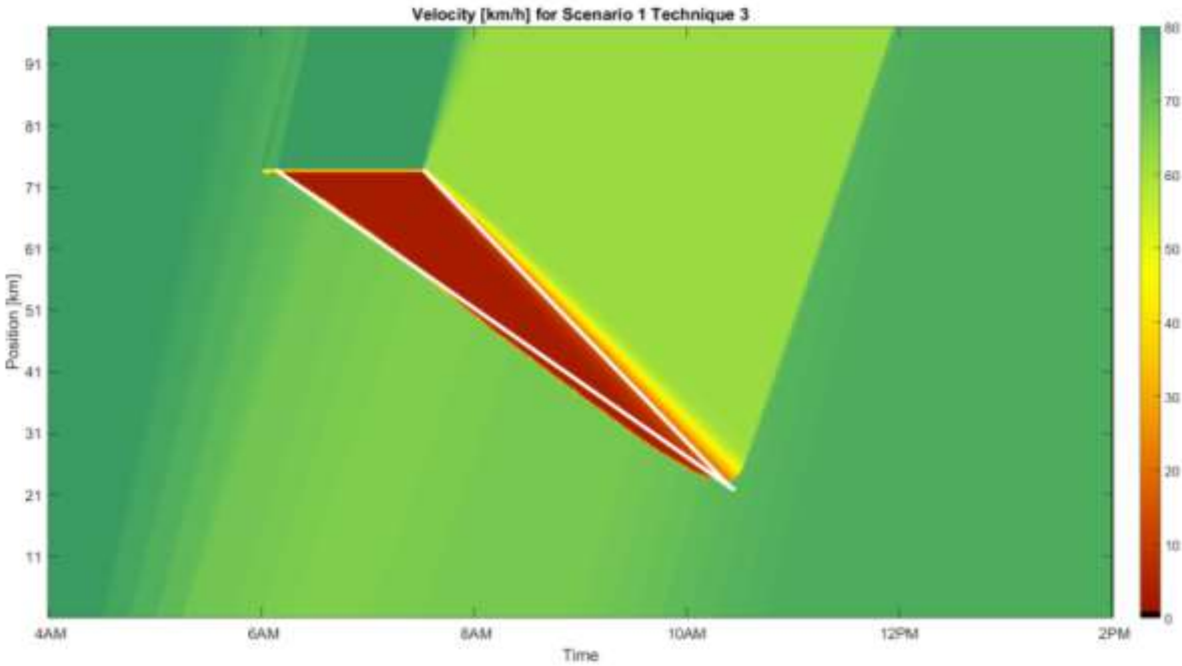


Figure 41: Comparing traffic state estimations using CTM and queue modelling for scenario 1 (Collision), technique 3 (Close some lanes). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

The delay for scenario 2 and technique 2 is overestimated by 17 % by the queue model (see further detailed comparison in Table 24).This overestimation is larger than the overestimation of 10 % for scenario 1 and technique 3, also cf. Figure 41 and Figure 42. This may be explained by the fact that the queue model assumes a static head wave speed only dependent on the response time parameter τ and the jam space parameter λ according to equation (30) (see further discussion in section 5.2.3). This implies that the head wave speed will remain the same for all the wedges in Figure 35. As can be observed in Figure 42, the head wave speed varies in the simulation for the different phases, which causes large deviations in the congestion when comparing the queue model and CTM estimations.

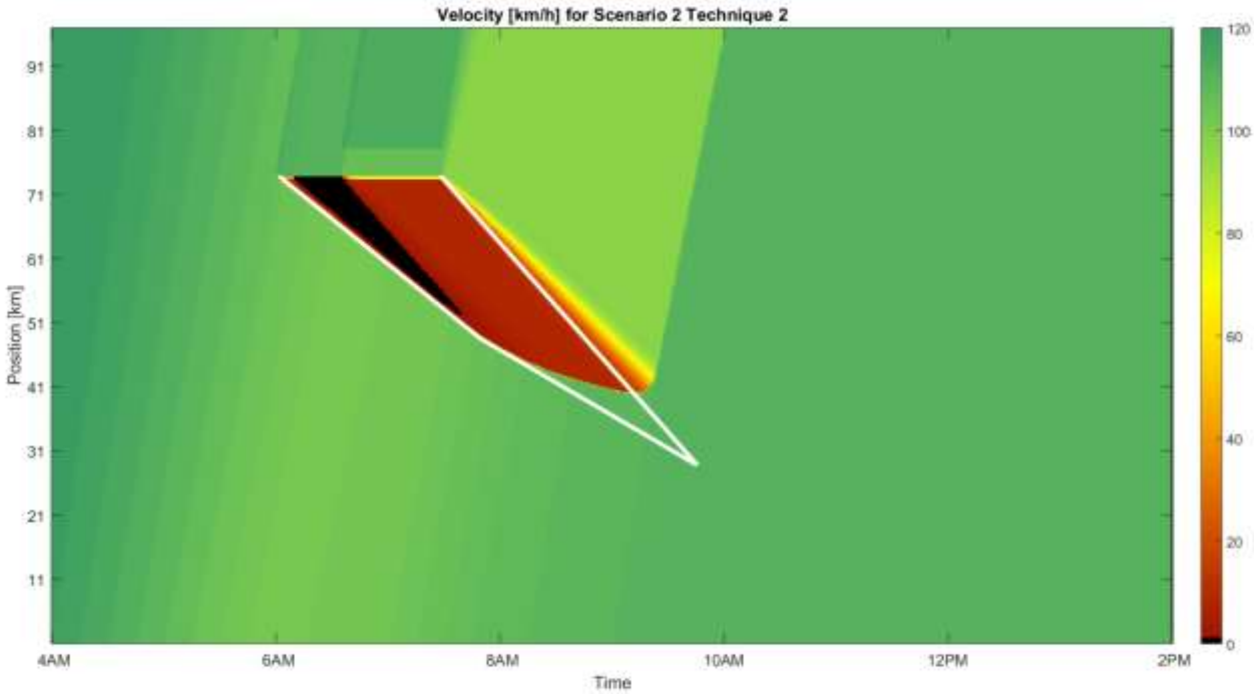


Figure 42: Comparing traffic state estimations using CTM and queue modelling for scenario 2 (Bad weather), technique 2 (Contraflow). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

The current version of the queue model is unable to include a dynamic estimation of the head wave speed since it would require an iterative process. This limitation is only affecting the results when there are several different capacity reductions within the same TIM technique.

5.3.3 Two scene management periods and variable demand

Another potential problem related to the queue model is TIM techniques containing TIM phases with reduced capacity over long time period. This problem is usually related to the respite phase. The purpose of the respite period is to represent delaying of TIM actions causing major capacity reductions until the end of a traffic peak. The available capacity at the scene may still be reduced but clearly less than a comprehensive clearing action would have required.

Since the queue model assumes a constant demand averaged during the whole respite period it becomes highly importance to remain the reliability of the demand profile. This becomes even more important for the respite period compared with the other phases since the duration of the respite phase typically exceeds the other phases.

Minor errors in estimations of the demand during the respite period may have potential huge effects of the results. Figure 43 illustrates technique 1 for scenario 1, which contains quick temporary clearance during the initial phases followed by total clearance during off-peak.

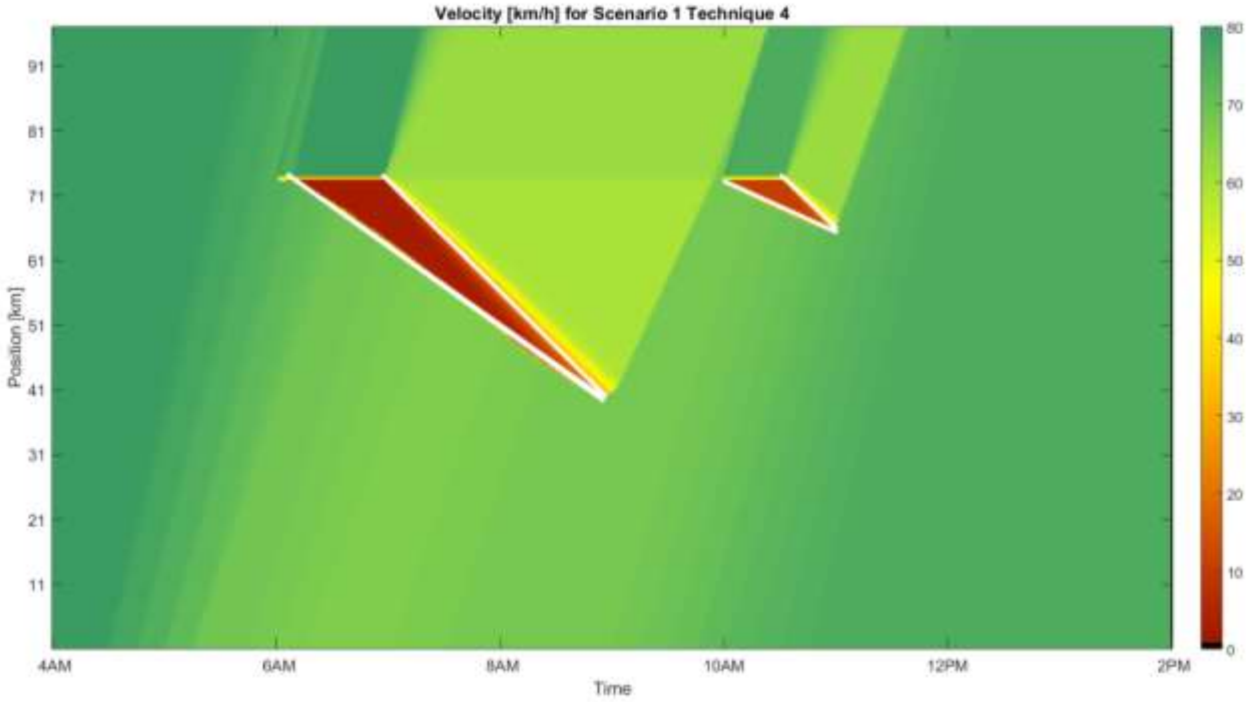


Figure 43: Comparing traffic state estimations using CTM and queue modelling for scenario 1 (Collision), technique 4 (Tow in off-peak). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

There seems to be correlation between the results estimated by the CTM and the queue model in this particular case. It means that the queue model is able to estimate several queue propagations within the same TIM technique.

As mentioned earlier, the availability of the queue model is limited due to the demand during the respite phase.
Figure 44 represents the propagation of scenario 2 technique 3 simulated using a high and short traffic peak. The queue model is overestimating the traffic demand during the respite period causing overestimations of the congestion due to the traffic incident.

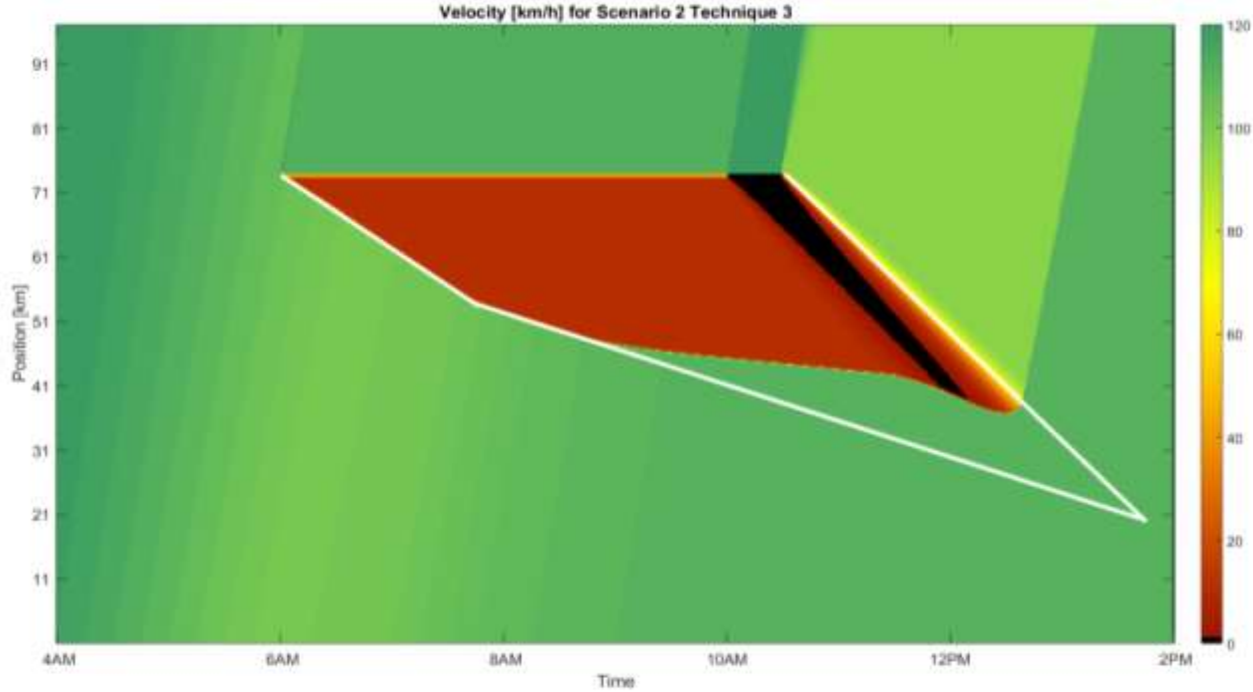


Figure 44: Comparing traffic state estimations using CTM and queue modelling for scenario 2 (Unsafe road conditions), technique 3 (VMS and speed limit). The colour bar illustrates the traffic state estimated by the CTM and the white line represents the queue propagation estimated by the queue model

This example proves obvious limitations of the queue model when having comprehensive durations of TIM phases in combination with varying traffic demand. The CTM is able to capture these changes when estimating the traffic state since the demand profile is using a certain resolution independent of the duration of each TIM phase.

5.3.4 All validation cases

Detailed comparison of the results from simulations with the CTM and calculations using the queue model have been conducted for a sub set of the total amount of combinations of scenarios, techniques, demand profiles, etc. Combinations investigated and the results are presented in Table 25. In general, the queue model overestimates the delay, queue length and the duration around about 0-20 %. An exception is scenario 1 and technique 4 for which there is a small underestimation. Another exception is the large overestimation for scenario 3 (LGV breakdown) and technique 2 (Repair on-site), as discussed in section 5.3.3.

Table 25: Comparing incident estimations simulated by CTM and queue model for scenario 1. Comparing only congested locations upstream of the incident and using traffic demand measured at the location of the scene

Scenario	TIM technique	Demand peak	CTM simulation Total delay [h]	CTM simulation Max queue length [km]	CTM simulation Total duration [h]	Queue model Total delay [h]	Queue model Max queue length [km]	Queue model Total duration [h]
1	1 (close all lanes)	High long	16 612	58	5.0	17 265	67	5.3
1	2 (incident screen)	High long	23 878	63	5.6	23 941	73	5.9
1	3 (Close some lanes)	High long	11 018	50	4.5	11 413	55	4.6
1	4 (tow in off-peak)	High long	4 101	33	4.9	4 066	33	5.0
2	1 (close all lanes)	High	10 109	42	3.9	10 292	51	4.3
2	2 (contraflow)	High	6 409	34	3.4	7 266	42	3.8
2	3 (VMS + speed limit)	High	18 908	37	6.6	23 529	60	7.7
3	1 (close extra lane)	High long	2 469	27	2.7	2 603	27	2.5
3	2 (repair on site)	High long	1 590	16	4.9	1 412	14	4.9
3	3 (tow in off-peak)	High long	29 301	45	7.2	28 014	55	7.6
4	1 (close all lanes)	Constant	3 740	20	2.6	3 764	20	2.6
4	2 (contraflow)	Constant	1 974	11	2.1	1 908	11	2.1
4	3 (close blocked lane)	Constant	999	7	2.0	1 024	7	2.0

5.3.5 Queue model calculations for all scenarios and techniques

This chapter contains all the results from the different calculations performed using the queue model presented in section 5.2.3. There are some small deviations compared with the results in section 5.3.4, since the implementation of the queue model consist of dynamic characteristics enabling suitable time estimations, when post peak actions should be performed depending on the travel demand profile. In the CTM simulations, post peak actions were assumed to be performed at 11.00 independent of traffic demand peak. Deviations may also occur due to that the delay in in this section contains the total delay in both directions in order to capture the total effect of using contraflows and incident screens.

The key performance indicators used in the cost-benefit analysis is the total delay and the duration of the incident. The delay is used to estimate the cost of the congestion, while the duration is used in the estimation of the risks of secondary incidents (the longer the duration the higher the risk for a secondary incident).

Scenario 1 – Car to car collision involving injury, before traffic peak

Figure 45 to Figure 50 present the results for scenario 1 (Collision). For an incident involving a collision at the beginning of the peak the total delay is always shortest for the tow in off-peak technique (technique 4), independently of how long or heavy the peak is. However, to wait until off-peak often implies a longer duration of the incident, which can be contra productive from a balance of cost and risk point of view). To put up incident screens increase the total delay due to that it takes some time to apply the screens and the delay increase in the incident direction is higher than the savings in the opposite direction. For the incident screens the benefit is more probably on the risk side (i.e. lower risk for secondary accidents). There are substantial delay savings for only closing some lanes (if possible from a safety point of view) compared to closing all lanes (technique 1). It must be noted that there are substantial time savings when closing only some lanes or tow later for all combinations independent of traffic peak or number of lanes blocked.

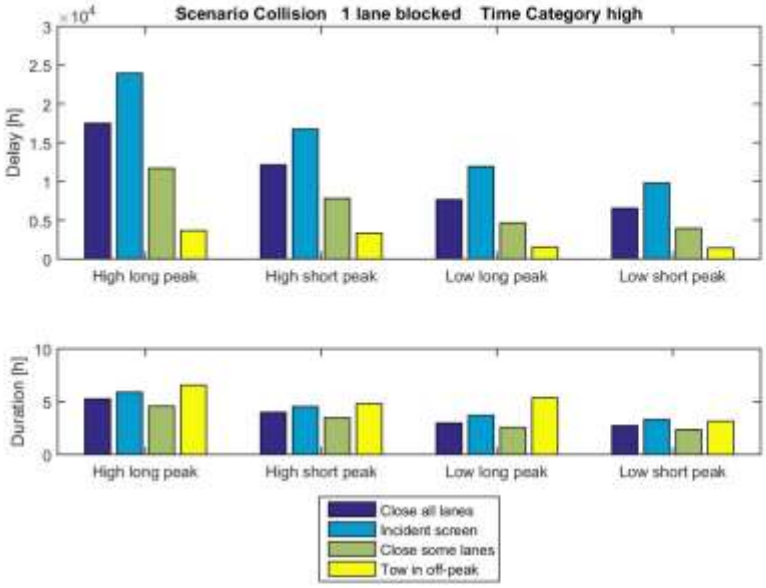


Figure 45: Results from incident scenario 1 (Collision) with one lane blocked and no time savings due to novel technologies

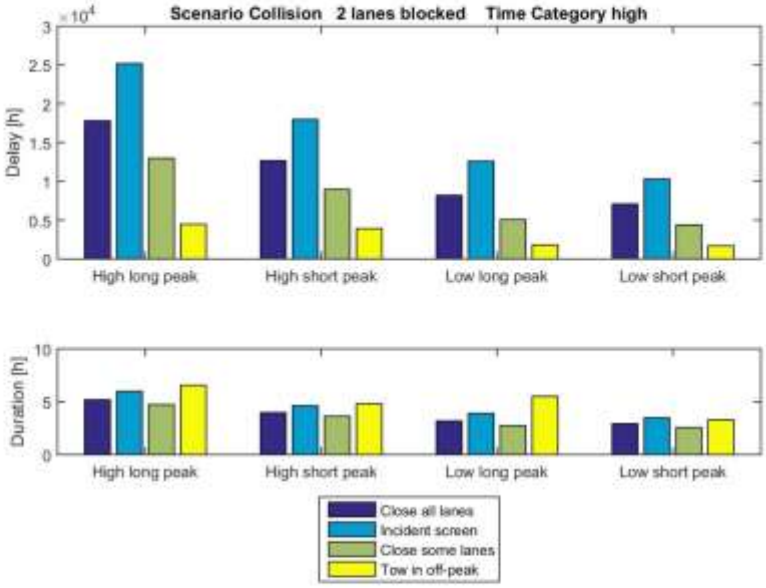


Figure 46: Results from incident scenario 1 (Collision) with two lanes blocked and no time savings due to novel technologies

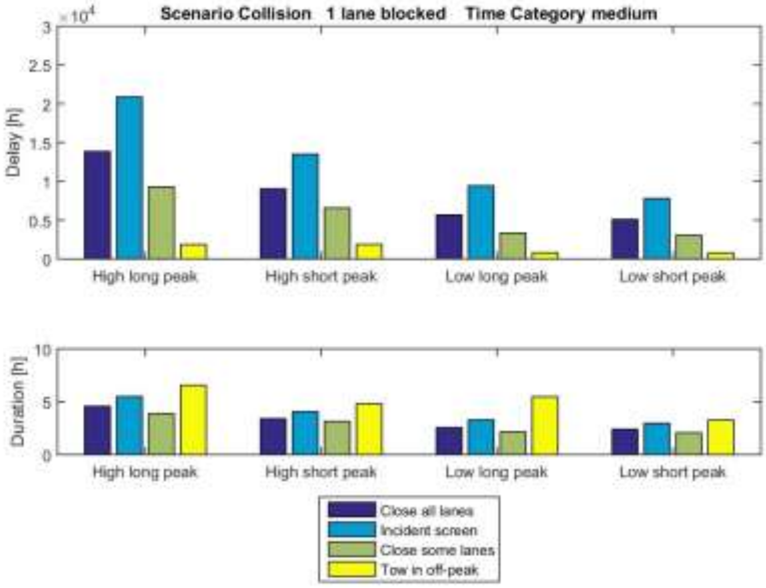


Figure 47: Results from incident scenario 1 (Collision) with one lane blocked and medium time savings due to novel technologies

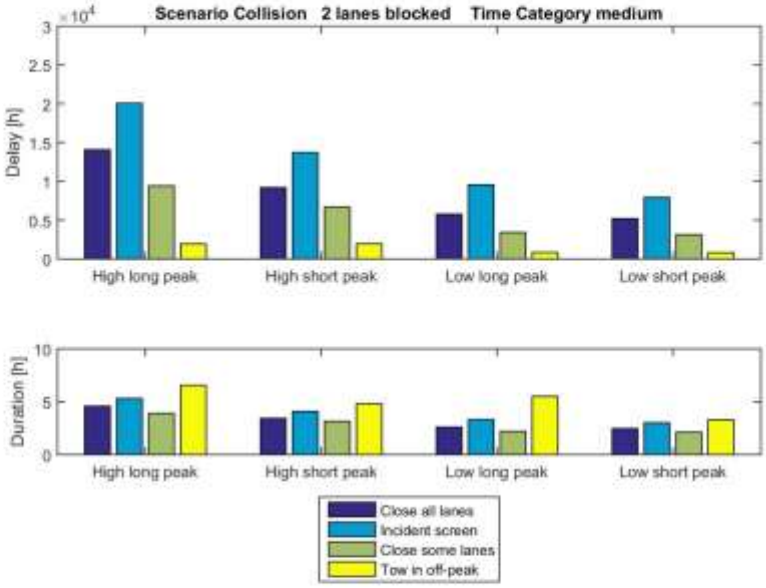


Figure 48: Results from incident scenario 1 (Collision) with two lanes blocked and medium time savings due to novel technologies

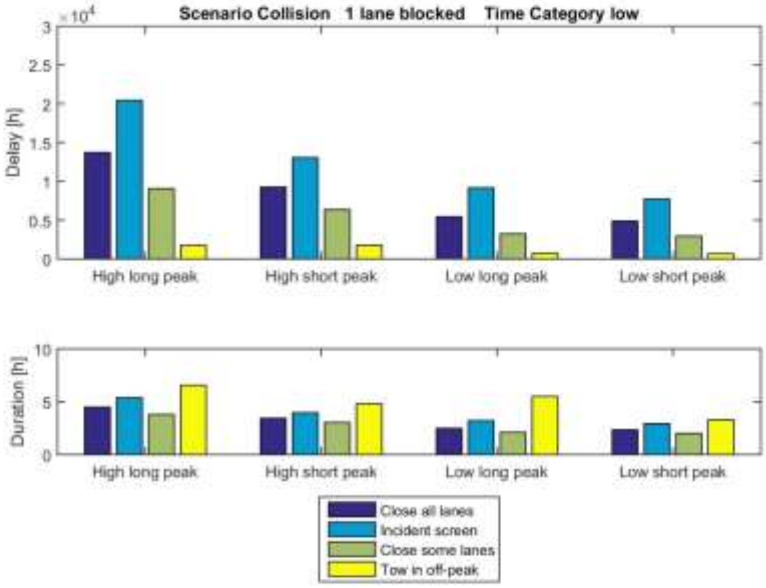


Figure 49: Results from incident scenario 1 (Collision) with one lane blocked and major time savings due to novel technologies

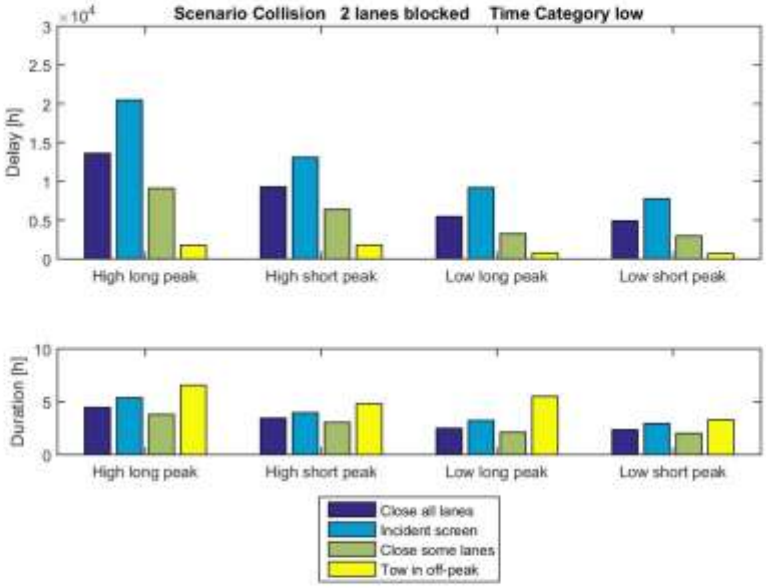


Figure 50: Results from incident scenario 1 (Collision) with two lanes blocked and major time savings due to novel technologies

Scenario 2 – Unsafe road conditions due to adverse weather leading to congestion

Figure 51 to Figure 53 show the delay and the duration calculated for scenario 2 (Bad weather). The alternative technique 2 (Contraflow) only decrease the delay when the duration of the incident is long enough. The option of just warning the drivers via a variable speed limit sign and wait until off-peak to clear the scene do not seem to be a desirable option for the specification of a scenario with unsafe road conditions due to adverse weather used in PRIMA. The unsafe conditions are in this scenario assumed to have a large effect on the safe operating speed when passing the incident site. Furthermore the unsafe conditions are also assumed to affect the time headways between the vehicles leading to a large capacity decrease. This option are more likely to be attractive if the incident occur at the end of the peak rather than in the beginning.

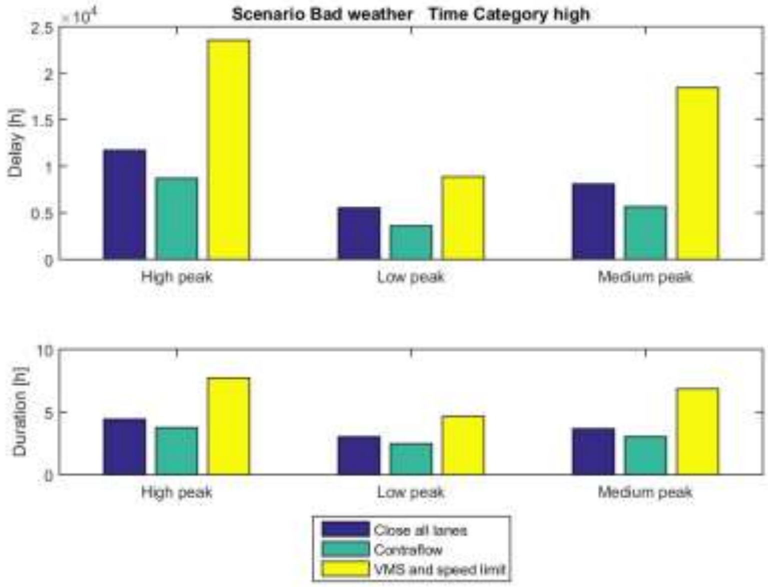


Figure 51: Results from incident scenario 2 (Bad weather) with no time savings due to novel technologies

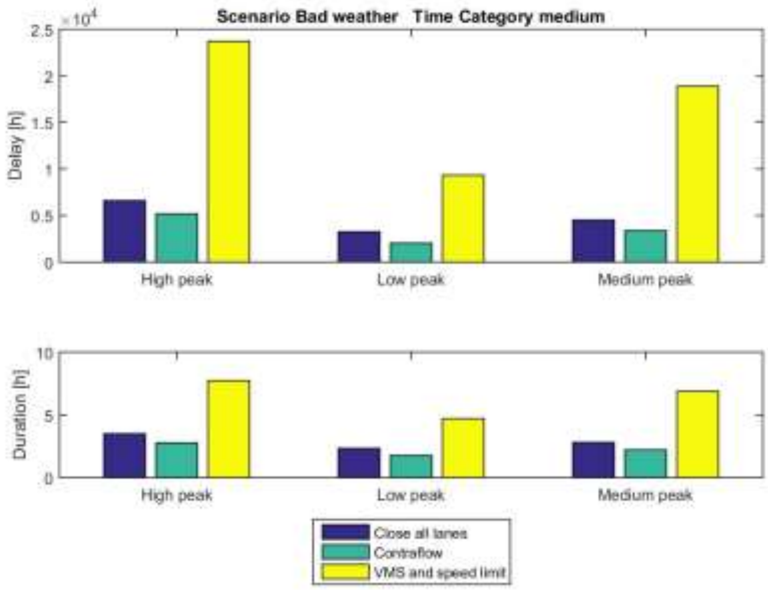


Figure 52: Results from incident scenario 2 (Bad weather) with medium time savings due to novel technologies

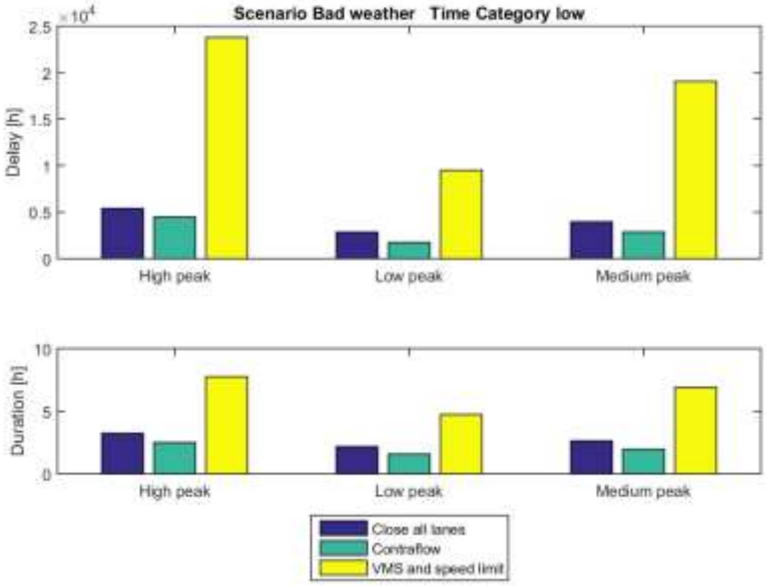


Figure 53: Results from incident scenario 2 (Bad weather) with major time savings due to novel technologies

Scenario 3 – Large Goods Vehicle stranded on a motorway

Figure 54 to Figure 56 presents the total delay and the duration for scenario 3 (HGV breakdown). For an incident occurring at the start of the peak quick repairing on site to allow moving the truck off the motorway shortens the delay but increase the duration. The option to make a secure lane close using a TMA and wait until off-peak with the tow activities is not desirable since the capacity reduction lasts for a too long time. It might be a more attractive option if the incident would occur at the end of the peak.

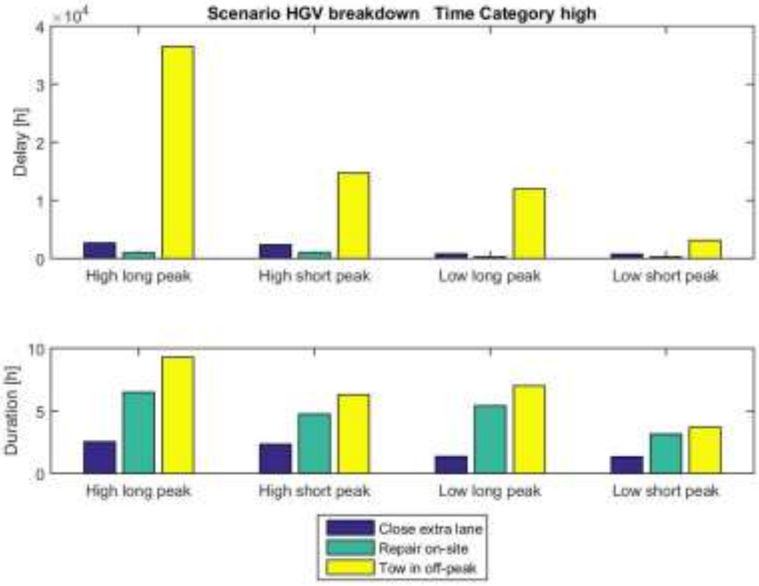


Figure 54: Results from incident scenario 3 (HGV breakdown) with no time savings due to novel technologies

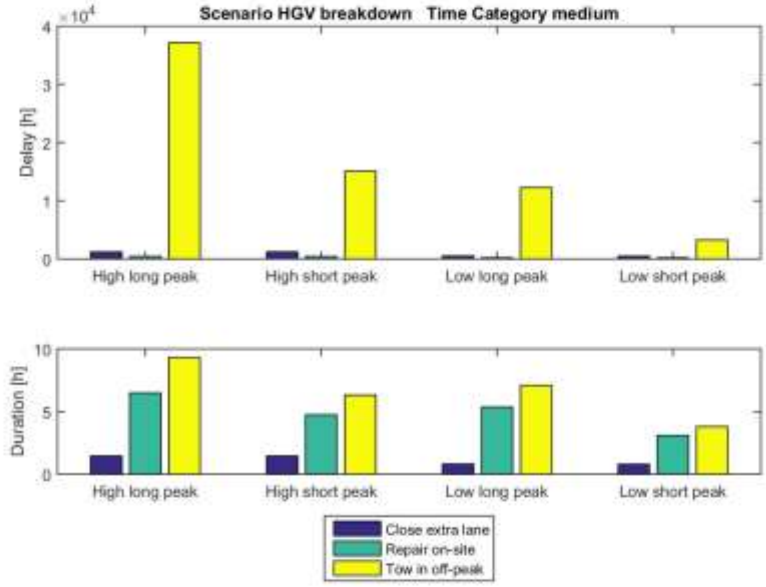


Figure 55: Results from incident scenario 3 (HGV breakdown) with medium time savings due to novel technologies

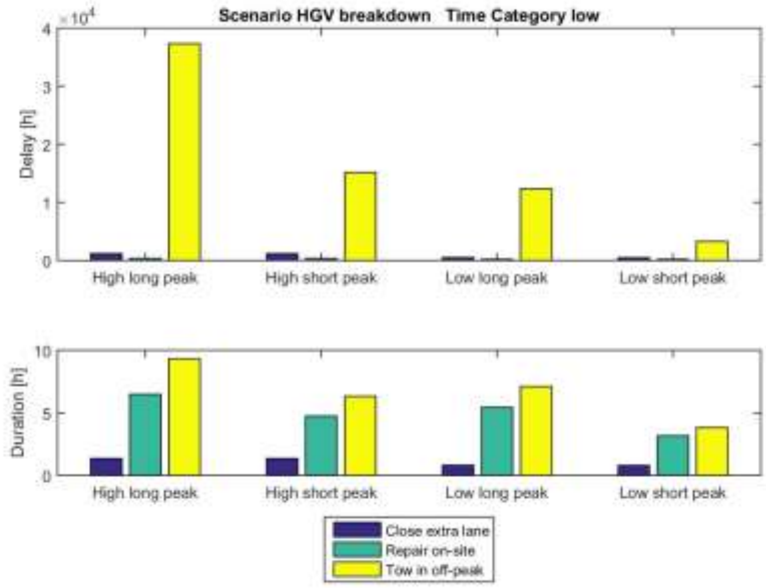


Figure 56: Results from incident scenario 3 (HGV breakdown) with major time savings due to novel technologies

Scenario 4 – Unpredictable congestion due to obstructions on a motorway

Figure 57 to Figure 59 show the calculated delay and duration for scenario 4 (Obstruction). Closing only the blocked lane is preferable both from a delay and duration point of view. However, this depends to a large extent on if it is possible to remove the obstruction in a safe way with only one lane closed. Using a contraflow is more or less always the second best option from a delay point of view but on the other hand it often gives the shortest duration.

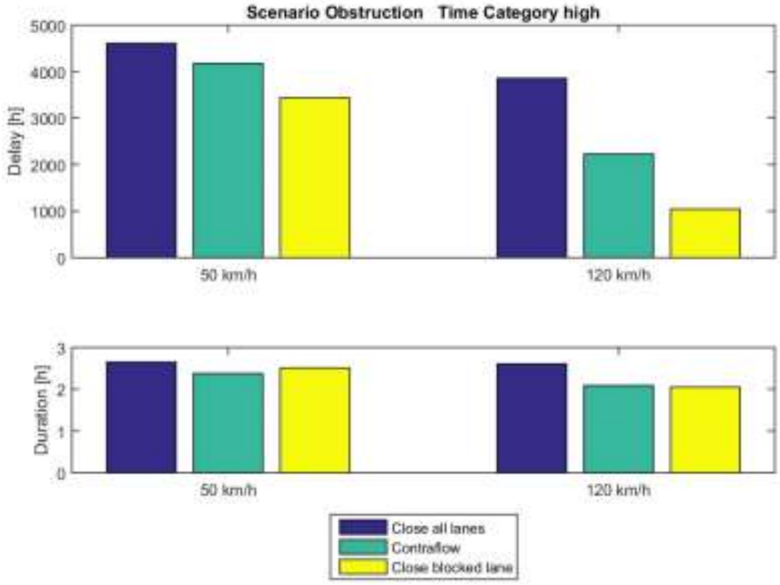


Figure 57: Results from incident scenario 4 (Obstruction) with no time savings due to novel technologies

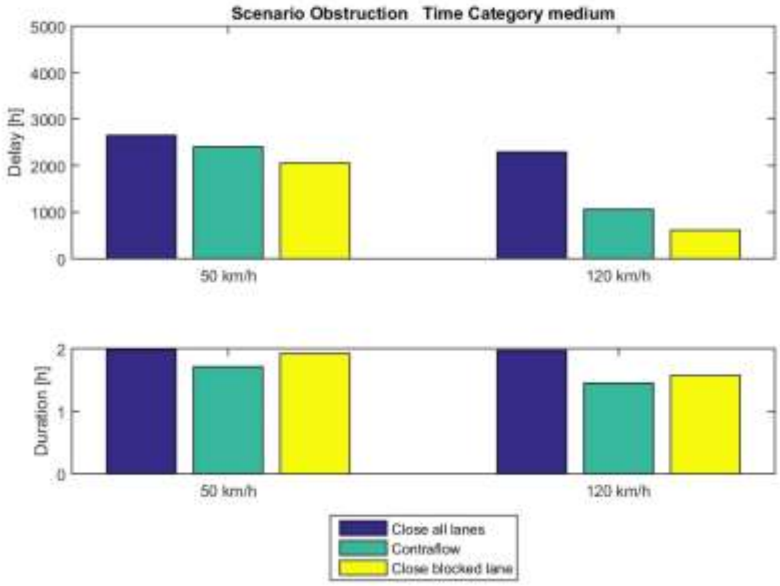


Figure 58: Results from incident scenario 4 (Obstruction) with medium time savings due to novel technologies

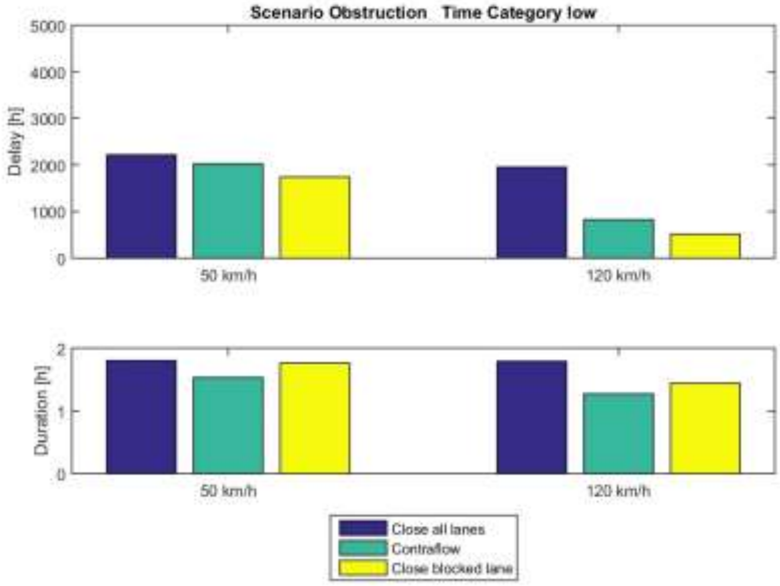


Figure 59: Results from incident scenario 4 (Obstruction) with major time savings due to novel technologies

6 Conclusions and Implications for PRIMA

Assuming the relevant requirements, such as available communication networks and appropriate penetration rates, vehicle-based systems provide good capability for the detection of incidents, whereas video-based systems provide good capability for the verification of incidents. Potential time savings due to overlapping of phases may result from direct communication links with involved or reporting. The actual time savings depend on the baseline conditions, which vary between countries, regions and road types. Urban motorways are in general more densely equipped with detectors and video monitoring compared to rural motorways and general roads. For the two urban motorways scenarios investigated in PRIMA, the time savings are estimated to be around 4-5 minutes (80-97%), while for the interurban motorway scenarios, the savings were estimated to be around 10-15 minutes (67-93%). These estimates are based on expert judgements using data from a Dutch incident database, which indicated large variations in the durations of the discovery, verification and initial response. There is a need for further investigations using more data sources, but the problem is that the incident databases commonly only include total incident durations and rarely include information on the duration of the different phases. The actual length of the discovery, verification and initial response phases also depend on the type, quality and correctness of the information that these novel technologies provide. To this end, quality indicators were also investigated. The assessment of the quality-related indicators shows best capability of vehicle and video based systems for incident discovery. Full and reliable verification of incidents can be expected by professional reports on the scene or via video. The assessment has also shown that good response performance is enabled by high quality in verification.

An extension of eCall to advanced eCall including injury severity estimation using models as the Human State Estimator seems promising. However, to prove its suitability, an extended investigation towards more cases (to account for the variation in human variability), other body regions (not only thorax) and different impact scenarios (not only frontal impacts) is needed. It should also be investigated how the injury risk information can be used in practice, for example to adjust the (emergency) response actions accordingly (is it needed to send and ambulance, or will only a police officer suffice; is specialized medical help required, or maybe even a helicopter), or to estimate the impact of the incident on the traffic, which can in turn be used to take appropriate actions (how long is it expected for the road to be blocked, is redirecting of traffic needed, etc.).

The traffic performance assessment of different scene management techniques show that alternative scene management techniques as quick clearance involving towing in off-peak, contraflow, and closing limited number of lanes can decrease delay and incident durations. However, the rank order of techniques depends on the start time of the incident in relation to the traffic peak, the assumptions for the duration of the different phases, the travel demand profiles etc. The results show that there can be substantial differences between the total delay and the incident duration depending on which technique is applied for a given incident scenario. The queue model developed is proven to be useful to conduct quick comparisons for different techniques given the start time of the incident, the travel demand profile, speed limit, number of lanes, etc. The 'GUI' and the implementation needs to be enhanced if the model is to be used in operational incident management, but its simplicity for quick and rough estimates for scene management techniques makes it an interesting candidate as a supportive tool for incident managements centres. In addition the macroscopic cell transmission simulation model was applied to investigate the effect of different scene management techniques in more detail. The cell transmission model has longer execution times but gives a more detailed description of changes in the traffic state due to an incident and different incident management techniques. The simulation model takes on- and off ramps into consideration and can capture variations in the travel demand at a higher level of detail. So, for more complex motorway sites with recurrent incidents, a local calibrated macroscopic traffic simulation model would be a more preferable decision support tool for scene management. The work on modelling incidents and scene management techniques in the cell transmission model presented in this report are for example planned to be incorporated in the Mobile Millennium Stockholm platform for estimations and prediction of traffic states on the Stockholm motorway network. Partly in order to enhance the traffic state estimation and prediction in case of incidents, but also as a help for the traffic control centre to predict the traffic state depending on the incident management technique they apply.

The assessment results with respect to novel technologies and more traditional scene management techniques have been fed into a cost-benefit analysis, which is described in the separate PRIMA deliverable D3.2 (Taylor et al., 2015b). The results presented in this report, together with the cost benefit analysis, will constitute an important input to the development of the PRIMA incident management guidelines.

7 Acknowledgement

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9 List of figures

10 List of tables