CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME

SAFEPATH: SAFE caPAciTy Highways

WP2000: Problem and Systems Analysis

Deliverable: D2.1, D2.2, & D2.3 Version 1.10

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SAFEPATH: SAFE caPAciTy Highways

WP2000 Problem and systems analysis

D2.1 Problem definition

D2.2 Specified KPIs and research criteria

D2.3 Specified factors and variables

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Executive summary

SAFEPATH

This report contains final deliverables D2.1, D2.2, and D2.3 from Work Package WP2000 of the SAFEPATH project.

Objective

The main objective is to investigate different measures to *increase highway capacity without compromising traffic safety*. There are many innovative ways to do this with or without extending the road network, since research suggests that building or extending infrastructure does not necessarily relieve traffic congestion problems as new demand is induced with improvements in infrastructure. It is critical to know any safety impacts arising from their implementation.

Approach

The relationship between safety and capacity is complex, with many levels of interactions. So, we chose a "systems analysis" approach to help understand the "system" of how capacity and safety impact each other. Systems analysis provides a way to analyse the effect of different "means and measures" on capacity and safety. This also helps defining our focus for analysis and systematically consider all relevant factors. One key limitation is that systems analysis does not model a complete system. Instead, it focuses on the most important factors that are critical to understanding the system. Thus, our analysis was a multiple step process which included a literature review, brainstorming sessions, expert reviews, feedback sessions and discussions, and was not simply a modelling task. This ensures that we develop a practical model which can be used later by National Road Authorities (NRAs).

Outcomes of systems analysis

Systems analysis involves four different steps: Problem demarcation and determining the level of analysis; Specifying objectives and criteria; Identifying influencing factors and mapping out causal relations; and Creating the systems diagram. The outcomes within each step are:

- *Problem demarcation and determining level of analysis*
  This step helped us understand problems and objectives with more clarity. The outcome was the "means-ends diagram" (Figure 3.3) which gives a broad overview of objectives from strategic to tactical level. From this analysis, we identified "*increasing highway capacity*" as the focal objective. "Means" are ways to achieve objective (increasing highway capacity), e.g., hard shoulder running, dynamic speed limits etc. The "means" to increase capacity were identified as to *Increase infrastructure capacity (*by for example improving traffic management and infrastructure technologies with e.g., digital road infrastructure*); Improve driver behaviour; Improve vehicle technologies, data, and services; and Improve road safety.*

  From the diagram, we identified three "dilemmas" in increasing highway capacity– *Road Safety, Investment costs, and Environmental effects*. These dilemmas are the key factors to balance against the capacity and out of which we identified *Road Safety* as the main dilemma to align with the focal objective.

- *Specifying objectives and criteria*
  The second step involved identifying more specific objectives, and criteria with which to measure them. We narrowed down the objective into three sub-objectives: *increase highway capacity; improve user experience and maintain or enhance road safety*. For these objectives, we identified 6 criteria which can measure change in capacity and safety. This step resulted in the objective tree diagram shown in Figure 3.5 The identified criteria were: congestion severity, collision risk, traffic flow, delays, travel time reliability, and collision severity. These criteria provided reliable Key Performance Indicators (KPIs) to measure the effect of the different "means" on capacity and safety.

- *Identifying influencing factors and mapping out causal relations*
  The third step was to identify factors that influence the criteria (identified in step 2) and map out the "causal relationships" between them – What factors cause which criterion to change? The outcome

was the causal relation diagram (Figure 3.6) which gives us insight into how different factors influence the criteria.

- *Systems diagram*

In the final step, we combined all the findings along with external factors to gain a full overview of the system involving highway capacity and traffic safety. This step resulted in the systems diagram (Figure 3.7), the main product of this report. This is a tool which will help us in the conducted research of the upcoming work packages. The systems diagram is the key to understanding and analysing different means for achieving an increase in highway capacity, and then relating them with measurable criteria for both highway capacity and traffic safety.

Results and implications for NRAs

The systems diagram is the basis for further analysis. It provides an opportunity for the project, and going forward, members of NRAs to consider new ideas with a basic model for the “system” of capacity and safety. It uncovers the fundamental building blocks affecting the complex system and underlying interactions. It also provides a scientific understanding of various influencing factors, means, and criteria within the system of highway capacity and traffic safety.

Examples of some such interactions in the systems diagram are:

- With an increase in the adherence of traffic rules, the collision risk decreases.
- With an increase in traffic demand, the density (in both free flow and congested state) increases.

We also have derived a set of Key Performance Indicators (KPIs) that align well with CEDR’s work related to KPIs and are specifically targeted at measuring the trade-offs between capacity and safety. These KPIs are suitable for practical use by NRAs.

NRAs with capability and experience of systems analysis can now potentially use the systems diagram to start identifying the most influential factors in their highway networks. This can help to further redefine their approach towards implementing a measure, by considering its impact. Additionally, through the identification of negative side effects, other measures to reduce negative impacts could be considered by NRAs. The systems analysis would eventually lead to a more complete, insightful, and useful good practice guide.

The systems diagram is a valuable outcome from the project. For the first time, the complexity of the highway capacity versus the safety “dilemma” for an NRA has been structured and analysed in depth.

The value of this work in next steps

On the way to developing the good practice guide, the systems diagram will help in the initial assessment of different measures identified in WP3000 and in determining their effect on road safety. Through the greater understanding of the system behaviour, that we have acquired through systems analysis, it will be easier to identify factors which might impact safety. Additionally, it will be easier to investigate the influence of a given measure to increase road capacity on other factors, which might have been overlooked.

This work now provides an opportunity to perform a more robust analysis of various effects and side-effects due to each means, which will be carried out in WP3000.

WP4000 aims to develop a safety impact assessment methodology, to analyse safety and capacity criteria defined in WP2000 and WP3000 and compare various solutions. The criteria and KPIs we identified will provide a firm base for further analysis and will help in creation of good practice guide in WP5000.

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List of Acronyms

ACC	Adaptive Cruise Control
ADAS	Advanced Driver-Assistance Systems
AEB	Automated Emergency Braking
CEDR	Conference of European Director of Roads
DoRN	Description of Research Needs (CEDR call for proposal 2019(2))
EPDO	Equivalent Property Damage Only
EU	European Union
GDP	Gross Domestic Product
HGV	Heavy Goods Vehicles
I2V	Infrastructure to Vehicle
ISA	Intelligent Speed Adaptation
KPI	Key Performance Indicator
LKS	Lane Keeping System
MAIS	Maximum Abbreviated Injury Scale
NRA	National Road Authority
PCU	Passenger Car Unit
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

1 Introduction

The transportation network is a fundamental backbone of the economy and it enables economic and social benefits to the society. However, with the increase in affordability of personal vehicles has led to a growing traffic demand due to which the transportation network often becomes saturated. Whenever demand exceeds road capacity, traffic flow breaks down leading to congestion. According to the European commission, congestion leads to a loss of around EUR 250 billion per year to the European Union (EU) [1]. However, traffic demand continues to grow, and it is estimated that road passenger transport will grow by 16% between 2016 and 2030, and 42% by 2050 [2]. Road freight transport is projected to increase by 33% by 2030 and 60% by 2050 [2]. To accommodate increasing traffic demand, there is a pressing requirement to improve road capacity.

In recent years, developments in transport and traffic technologies have led to many innovative solutions which aim to improve traffic flow and efficiency. Using new methods, the existing infrastructure can be utilised in a better and smarter way, thereby increasing the capacity without constructing new roads. However, selection and implementation of innovative technologies depends upon requirements, readiness, available resources, maturity level of technology and infrastructure. These will vary due to differences in external factors such as climate, culture, and existing technology. Because of these variations, the expected benefits of innovative solutions might not be realised. Also, with lack of proper assessment, if innovative solutions are implemented incorrectly, they might pose serious threats in terms of traffic safety and may deteriorate the efficiency of traffic flow. Thus, it is critical to properly assess and understand the requirement and implications of new implementations.

Traffic safety is one of the leading requirements while implementing new technologies. In the EU-27 approximately 25,000 fatalities are reported due to road collisions [3]. In monetary terms, the costs of accidents in the EU are estimated to be around EUR 280 billion, equivalent to 2% of GDP [4]. In order to improve traffic safety, the European commission has set up a Road Safety Policy Framework to achieve “Vision Zero” objectives, which focus on a safe systems approach and shared responsibility [5]. It is, therefore, crucial to pay special attention to Road Safety for the implementation of any new traffic related technology.

If new solutions are implemented without enough research and information, they might pose a risk in terms of deteriorating traffic safety. Conference of European Director of Roads (CEDR) has identified a gap in existing research related to the safety performance of measures to increase Highway Capacity. This gap needs to be addressed within the Call 2019(2) under CEDR Transnational road research program. The participating countries in the call include Austria, Belgium (Wallonia), Finland, Germany, Hungary, Ireland, the Netherlands, Sweden, and the United Kingdom. This research is based on a systems analysis approach, in which the system of highway capacity and road safety is studied with the help of identification of different influencing factors.

This report contains the final deliverables D2.1, D2.2, and D2.3 within the Work Package WP2000. Section **2** provides insights in the purpose and methodology of this research and defines the scope of this research. Section **3** presents the output of the systems analysis and aims to provide insight into its different steps. In Section **4**, the main conclusions are presented.

2 Purpose and methodology

2.1 Purpose and research questions

The main purpose of this research is to gain greater understanding of the existing measures to increase road capacity without physical widening of the highway (i.e additional road space) and without compromising traffic safety. To achieve this objective, a systems analysis approach is used (as explained in Section 2.3) to understand the problem and objectives, identify the correct level of analysis, determine measurable criteria, and identify influencing factors which affect the realisation of objectives. The combination of these steps is illustrated in a systems diagram which helps understanding the system behind increasing the road capacity without compromising traffic safety.

The main research question as defined within Description of Research Needs (DoRN) in this study is:

"How can the road capacity be increased without compromising with traffic safety?"

To answer the main research question, the following sub questions needs to be addressed:

1. What are the various means of increasing road capacity without building new road networks or extending the current ones?
2. How can we measure the changes in Highway capacity and Road safety?
3. What are the different influencing factors for Highway capacity and Road safety?

2.2 Scope

As transportation systems are highly complex, it is important to define the scope of research to achieve the desired results within a practical timeframe and fulfilling the purpose of this research. The scope of the current research can be summarised as follows:

1. This report deals with the aspects that help understanding road capacity and traffic safety as outlined in WP2000. The specific measures improving the road capacity is out of scope of this report and will be addressed in WP3000.
2. The measures being considered are within the influential power of National Road Authorities (NRAs).
3. The measures to be considered are applicable for the Major Highways (Motorways[1]) within the Trans-European Road Network. City streets and connecting highways are out of scope of this research.

2.3 Introduction to systems analysis

This project uses the systems analysis approach to gain an overview of the road transportation system with a focus on factors influencing traffic flow and safety. The systems analysis approach evolved in the 1950s and 1960s from the field of operations research and this method uses scientific, analytical and mathematical approaches to gain an overview of large and complex systems [6]. Systems analysis helps in problem exploration and formulation in early stages of the analysis and provides a firm consistent structure and direction for further analysis [7]. This approach helps in defining focal areas of analysis and analytically considers all relevant factors. One key limitation of systems analysis is that it does not

[1] Motorway is defined as a dual-carriageway road designed for fast-moving traffic (slow moving vehicles are not permitted), with limited access points, several lanes, and restrictions for non-motorised vehicles.

result in a complete system; rather it focuses on the most important factors that are necessary and critical to understand the system [8].

There are many ways to perform systems analysis. In this project, the four-step methodology of systems analysis as proposed by Enserink et. al., (2010) is used [8]. The systems analysis has the following steps:

1. Initial problem demarcation and setting up the level of analysis.
2. Specification of objectives and criteria/KPIs.
3. Identification of potential means, influencing factors, their influence on criteria and mapping out causal relations.
4. Overview of the problem area using the systems diagram.

The process of systems analysis is illustrated in Figure 2.1.

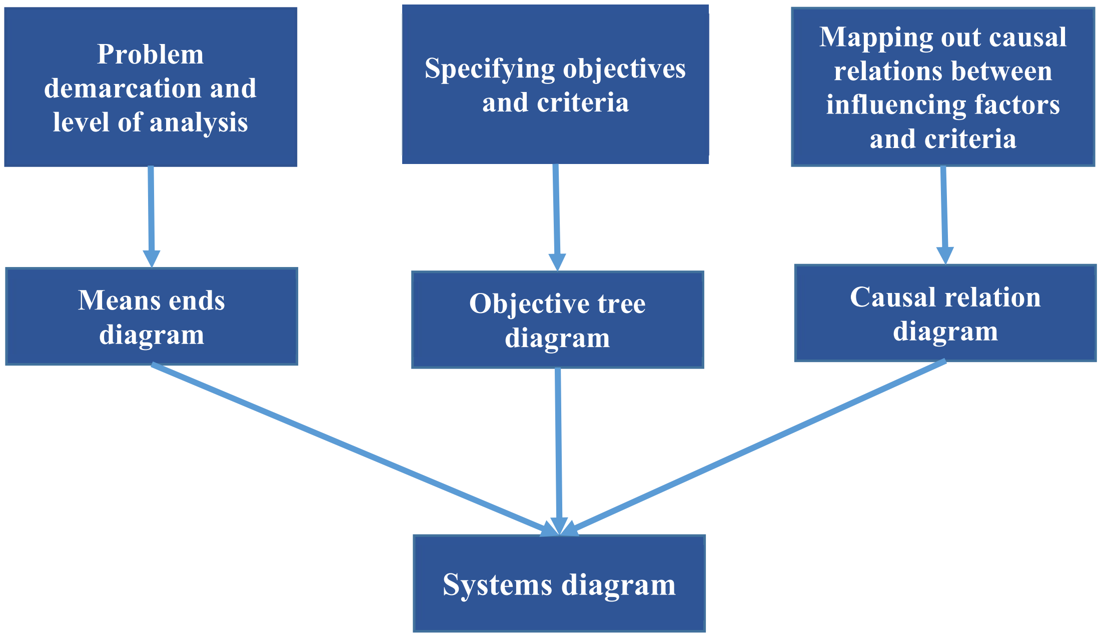


Figure 2-1: Process of systems analysis

2.4 Key terms

The following terms are used frequently in systems analysis in different steps. The definitions of these terms are given below.

System: *A* System is defined as a part of reality which is being studied and whose boundaries are defined by the problem statement. For example, in this project, system refers to the collection and relation between various means, influencing factors, external factors, KPIs and objectives referring to increasing road capacity and highway safety.

Objectives: Objectives refer to the desired situation relevant to the project. The main objective in this project defined within DoRN is to increase highway capacity without compromising with traffic safety.

Means: Means are the instruments or measures through which a system can be affected and through which objectives are achieved. For example, increasing the number of lanes is a means to increase highway capacity.

Ends: Ends are the end goal of the project also referred in place of objectives. For example, increasing highway capacity is the end goal in this project.

External factors: External factors are the elements which cannot be influenced by any means or factors inside the system but play an important role in the outcome. For example, Weather cannot be influenced by any means and thus is an external factor.

Criteria/KPIs: Criteria are the Key performance indicators (KPIs) which can quantify and measure the achievement of objectives. For example, traffic flow can be measured to estimate the highway capacity.

Dilemmas: Dilemmas are the challenges to encounter while realising the main objectives. For example, road safety is a dilemma while implementing new measures, as it should not be negatively affected.

2.5 Methodology

The systems analysis was carried out in a structured approach as shown in Figure 2.2. The core of this research includes an extensive review of literature which was conducted throughout all phases of WP2000. Before each step of the systems analysis, a brainstorming session was conducted with project team members to gain inputs required to perform further steps. From the inputs of brainstorming sessions combined with literature review, the diagrams were created. Further, the diagrams were discussed in a workshop session with project team members for feedback, comments, and relevance. In the end, two expert sessions were conducted with various other experts from related domains to gain expert feedbacks and comments. Throughout the whole process, the diagrams went through continuous fine-tuning. A list of project team members and contributing experts has been provided in Appendix B.

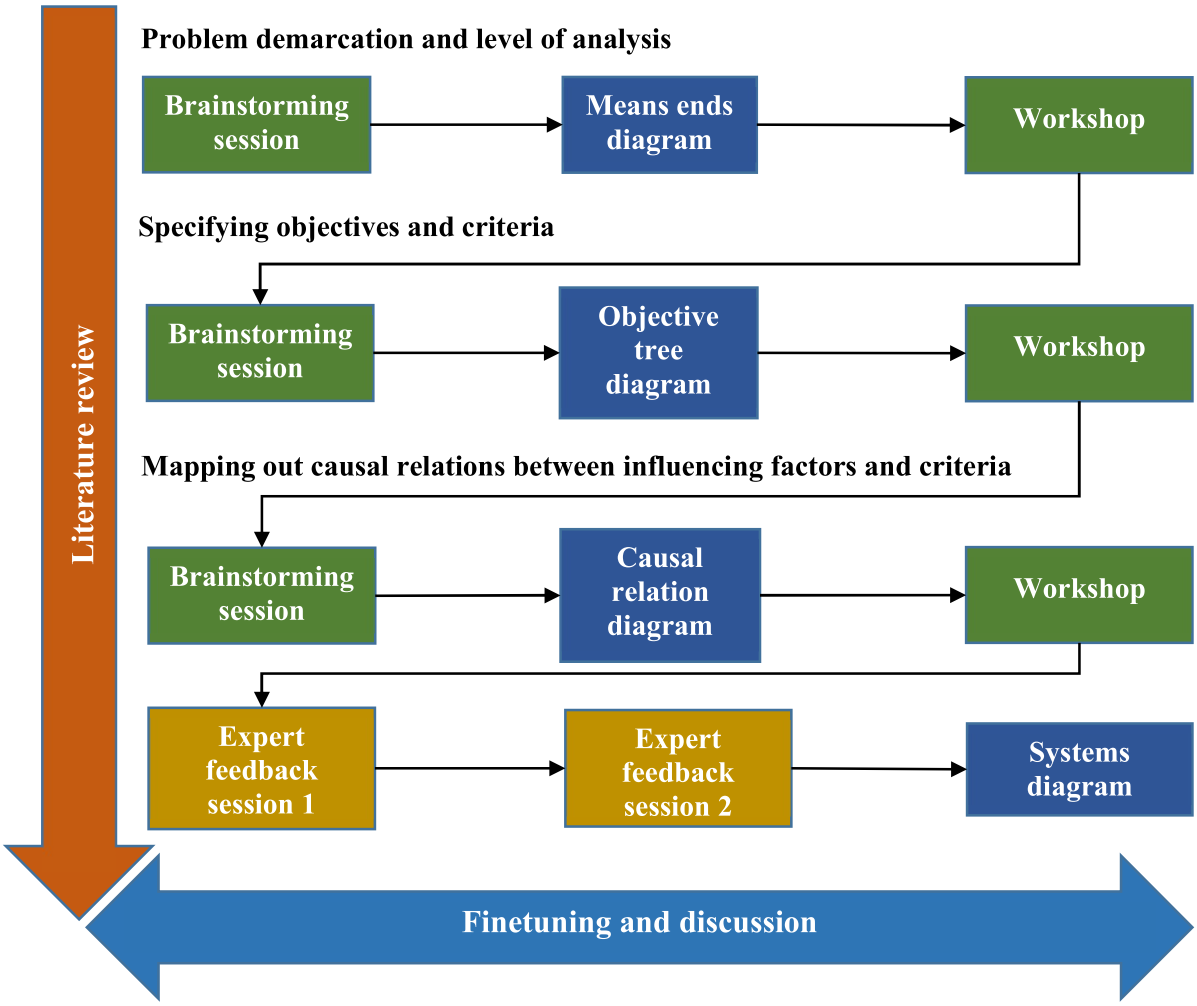


Figure 2-2: Method adopted for systems analysis

3 Systems analysis in SAFEPATH

This section aims to provide the details of systems analysis process and the results which originate from various steps, literature review, brainstorming sessions, expert review, feedback sessions and discussions. The different steps of systems analysis are discussed in detail in the following sub-sections. It consists of 4 steps which are described using the following practical non-technical example and then later on in the report with an example in the Highway capacity management domain. These steps are: 1) Initial problem demarcation; 2) specification of objectives and criteria; 3) Preparation of causal-relation diagram; 4) preparation of the systems diagram.

Practical Example

Practical example of Systems Analysis

Initial problem demarcation and setting up level of analysis
As a non-technical illustration; assume the problem of a tired individual who is in need of a refreshment and therefore needs a cup of coffee to be made. To make coffee one needs to know what exactly should be made, the reason behind the need of coffee, what type of coffee and the starting point of making coffee. The initial problem demarcation and setting up the level of analysis provide answers on these questions by scoping the problem.

The means-ends diagram provides us the initial information and starting point needed of why and how the coffee should be made. For example, the coffee is made is made such that the individual feels less tired during a morning meeting. Next to the objective of making coffee, the means-ends diagram also provides the tools to make coffee (e.g., kettle, electricity, teaspoon etc.). In this phase the objective of making the coffee and means to make the coffee is set.

Specifying objectives and criteria
Once one knows why and how the coffee should be made it is time to set up criteria to assess the coffee once this has been made. The Objective tree provides the criteria (e.g., taste, smell, texture, level of caffeine) of the coffee. The objective tree helps in identifying criteria and Key Performance Indicators (KPIs) which can be used to measure in which degree the objective of making coffee is achieved.

Identification of influencing factors and mapping out causal relations
The Causal Relation Diagram provides the different ingredients of the coffee (e.g., milk, water, sugar, coffee beans) which are needed to make the coffee. Besides this the Causal Relation Diagram also shows the interdependencies between these ingredients. The interdependencies between the ingredients show how the ingredients reacts upon each other. What will for example happen to the taste of the coffee is one adds more sugar to the milk and water mix.

Overview of the system (systems diagram)
Once one knows the why and the how behind the making of the coffee, the needed ingredients and how the ingredients react upon each other; these different steps can be put together to make the recipe for the coffee. This recipe can be seen as the systems diagram, where input, formula and output are brought together. Recall that systems analysis will end with the recipe for a good coffee to achieve a higher objective (make the individual feel less tired during the morning meeting). The process making the coffee itself is not the under the authority of the analysist but must be performed by the individual him/herself. The individual will eventually make the coffee.

3.1 *Initial problem demarcation and setting up level of analysis*

Theory

Problem demarcation and setting up level of analysis

A problem can be formulated at many levels. It is, however, very important to choose the right level of analysis as the means of achieving objectives greatly depend on it. Thus, the first step in systems analysis is to demarcate the problem and identify the focal level of analysis. The problem formulation and demarcation result to a means ends diagram which provides an overarching view of the main objective and means which can be implemented to achieve the objective. The means ends diagram provides an opportunity to view the problem from a broad spectrum, identify the focal level of analysis, and define the scope of the project.

The problem demarcation is carried out by asking "Why" and "How" questions. The "Why" questions help to achieve a more strategic level of analysis. This helps in revealing more fundamental objectives by asking the question "Why this objective is worth striving for?" On the other hand, "How" questions help in achieving more operational level of analysis and provide an overview of the options available to achieve the objectives: "How this objective can be achieved?". These two steps provide a complete spectrum of problem analysis from abstract to more concrete levels and result into the means-ends diagram. Figure 3.1 provides a representation of a means ends diagram, the final product of problem demarcation stage.

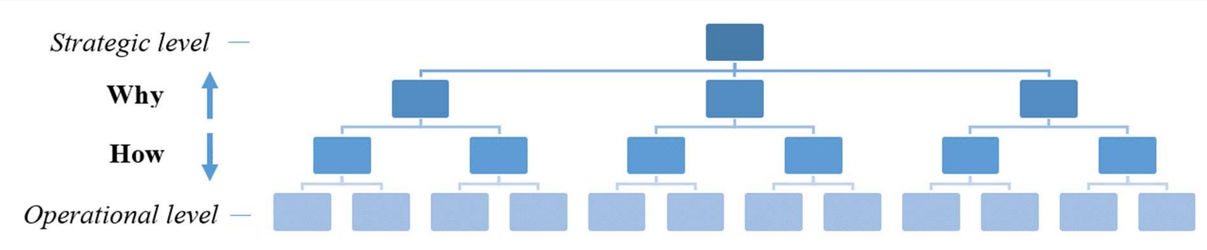


Figure 3-1: A representation of means ends diagram

The purpose of the means ends diagram is to identify the focal objective and correct level of analysis. The means ends diagram can be read in both directions: top to bottom and bottom to top. Note that the means-ends diagram is not supposed to encompass a detailed list of all the means to achieve the objective. Instead, it provides a tool with sufficient broad categories into which the measures can be placed. Additionally, the means ends diagram aims to provide an overview of dilemmas that will be encountered in the realisation of the focal objectives of the SAFEPATH project.

As mentioned in text above, the initial problem demarcation is carried out to define the scope and direction of the research.

The process of problem demarcation was carried out in three phases as shown in Figure 3.2. In the *first phase*, the main problem statement from DoRN was carefully examined to identify the starting objective. From the identified objective, the question "Why this objective is worth striving for?" was asked to move on to higher level of objectives within the means ends diagram and identify more strategic objectives. In the *second phase* of the problem demarcation, the question "How can this objective be achieved?" was asked to move on to lower operational levels of objectives and find means of achieving the objectives. Furthermore, in the *third phase* of the analysis, the focal objective was defined and dilemmas in achieving focal objective were investigated. At this stage, the means to achieve the focal objective were selected for core level of analysis.

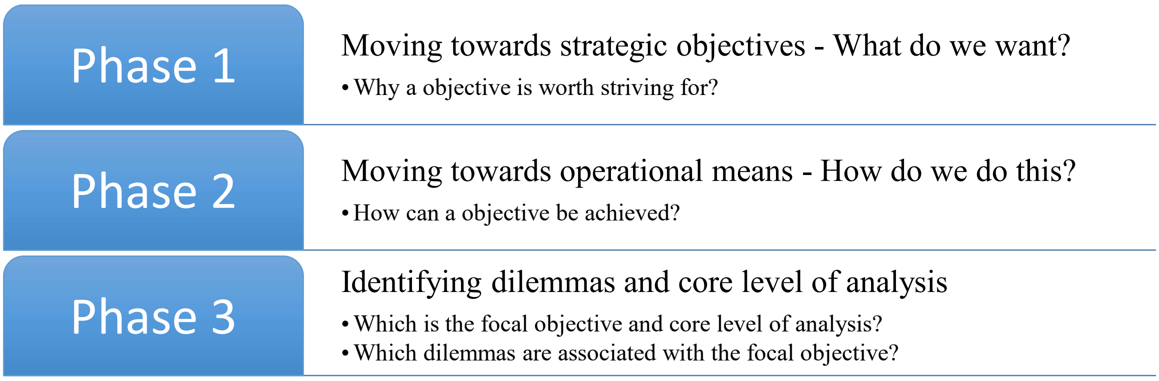


Figure 3-2: Three phases of problem demarcation and determining level of analysis

The following sub-sections provide details about the different phases of the problem demarcation and setting up level of analysis. The result of problem demarcation is the means ends diagram which is shown in Figure 3.3.

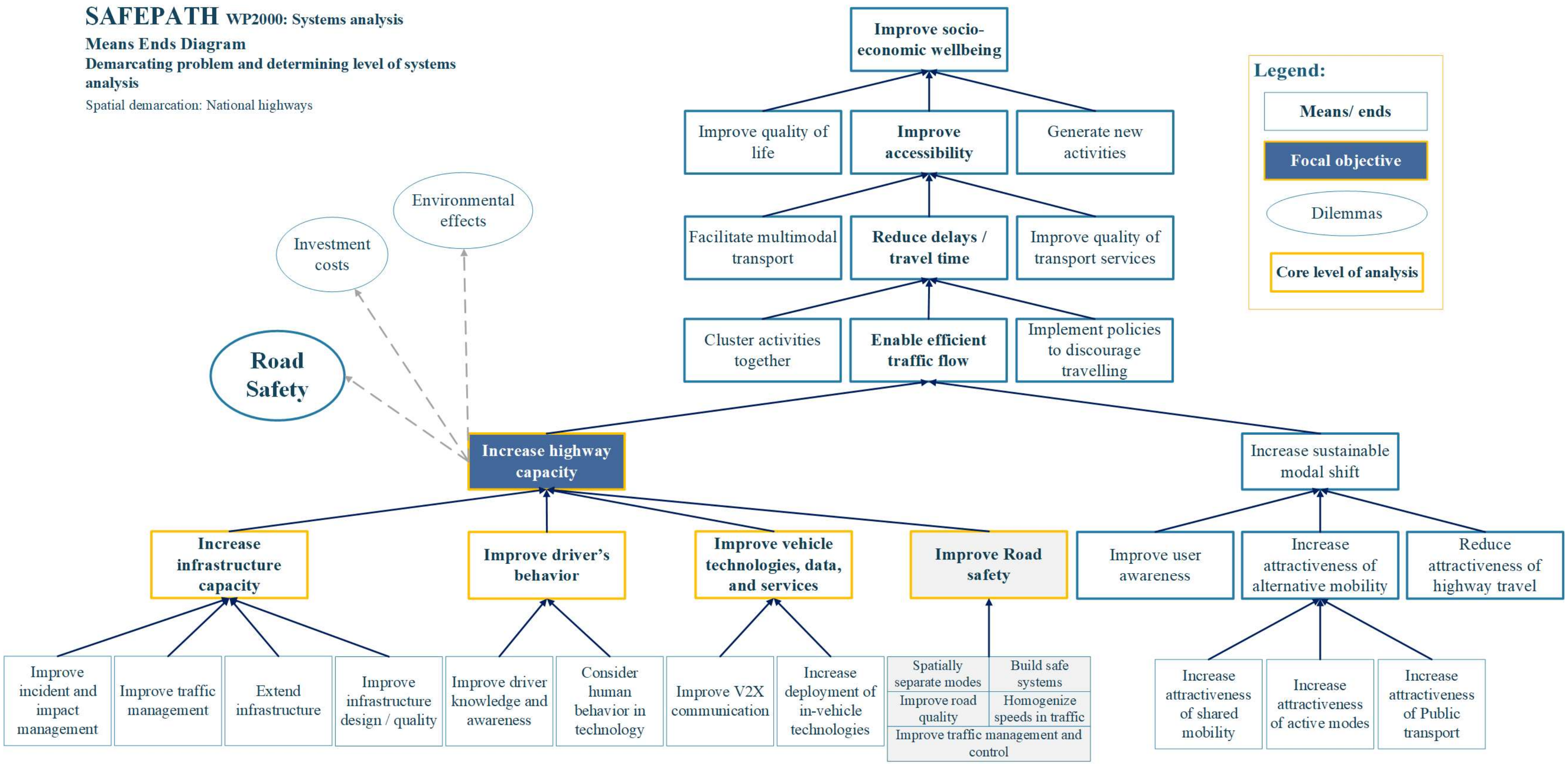


Figure 3-3: Means-ends diagram determining the level of systems analysis

3.1.1 Phase 1: Moving towards strategic objectives – what do we want?

The DoRN for Call 2019(2) specifies the focal objective of SAFEPATH project as “Increasing capacity of highways without compromising with road safety”. This provided us with a starting point for the means ends diagram as an objective to *increase Highway capacity*. More strategic levels of analysis can be achieved by answering “Why highway capacity needs to be increased?”. It was found that one of the most common reasons behind increasing highway capacity is to *improve the efficiency of traffic flow* [9],[10]. The core reason behind improving efficiency in traffic flow is to *reduce congestion and delays* [11]. Whenever the traffic demand exceeds the capacity of the highway, the traffic breaks down leading to congestion and delays to the road users. This in turn results to an increased travel time [12]. Since traffic congestion leads to a loss of around 250 billion euros to EUs economy, increasing capacity and *improving traffic flow efficiency* are two of the main means to reduce congestion and delays.

Furthermore, congestion and delays lead to reduced accessibility and have a greater impact on the lives of people [13]. Traffic congestion and delays lead to increased travel costs, fuel consumption, air and noise pollution, deterioration of human health and reduced *accessibility*. A reduction in congestion leads to increased accessibility to different places and services, which in turn brings more economic opportunities and access to healthcare facilities, bringing overall improvement in human socio-economic wellbeing [14]. Thus, *improving socio-economic wellbeing* was identified as the fundamental objective in the means ends analysis.

3.1.2 Phase 2: Moving towards operational means – how do we do this?

After identification of the fundamental objective, the means of achieving the objective were investigated by asking “How” questions. The investigation started with “How can the socio-economic wellbeing be improved?”

Improve socio-economic wellbeing

There are many different factors which collectively account for the improvement of *socio-economic wellbeing*. Along with accessibility, employment opportunities are one of the main driving factors of economic growth as it brings financial stability in the lives of people, allows them to satisfy their needs, improve social wellbeing (life expectancy, education, quality of life etc.) and pursue important life goals [15]. *Generating new activities* provides more employment opportunities and thus improving the overall social wellbeing of the people [16]. Also, social wellbeing depends greatly on many other factors such as education, health, safety and security, housing, childcare, environmental quality, work and life balance, governance and connectivity [16]. Most of these factors are associated with the *quality of life* and *accessibility*. Thus, improvement of quality of life and accessibility contributes to improving the socio-economic wellbeing.

Accessibility

Accessibility is a widely used term in transportation and is mostly defined in terms of travel time to access different opportunities [13]. A reduction *in journey travel time* improves the overall accessibility of the transport network. Additionally, accessibility does not only encompass travel time to reach different locations but also includes access to different modes of transportation and access by different groups of society [17]. Overall *improvement in quality of transport services* and facilitating *multimodal transport* contribute to improving accessibility. Improvement of the quality of transport services may translate to maintaining high quality infrastructure, provisions for pedestrians and cyclists and quality infrastructure for physically disabled people [17].

Delays and travel time

Whenever traffic demand exceeds the highway capacity, the traffic flow breaks down leading to congestion compromising with the efficiency of transport infrastructure [12]. As congestion and delays are leading problems in transportation systems, efficient utilisation of road capacity is one of the main ways to reduce congestions to further reduce delays and travel time [18]. Congestion is caused by traffic demand exceeding the capacity. A reduction in traffic demand is, therefore, an effective means to reduce congestion and resulting delays [12]. Traffic demand can also be reduced either by *clustering multiple activities together* leading to a smaller number of trips or by implementing *policies which discourage travel* such as policy to work from home, road pricing, parking costs, licence plate restrictions, etc. [19].

Modal shift

Modal shift is an effective way to improve the efficiency of traffic flow on highways by shifting the road users from highways to alternative (and more sustainable) modes of transportation [20]. Modal shift occurs when alternative modes of transportation become more attractive (better quality of service, higher capacity and availability), and people aim to improve their travel experience by choosing the alternative transportation mode instead driving. Some alternative modes of transportation involve (but are not limited to) shared mobility, active modes of transportation and public transport [21]. Another approach towards modal shift is to reduce the attractiveness of highways by various means such as reducing capacity or imposing policies to discourage people to travel [22]. This approach also works in the same direction as increasing quality of service of alternative mode of transportation. Furthermore, increasing and improving the awareness of people towards alternative modes of transport also help in promoting a shift from road transportation [21].

Increase highway capacity

Increasing the capacity of highways is another way to enable efficient traffic flow. Increase in highway capacity not only refers to achieving higher traffic flows but also refers to better utilisation of existing capacity by decreasing congestions, delays, improving resilience of network and improving traffic safety.

Highway capacity depends on the three core aspects of transportation: infrastructure (e.g., available space, road design, quality, clarity of road environment, traffic management systems etc.), human (driving behaviour, culture, adherence to traffic rules, driver education etc.) and vehicle (in-vehicle technologies, Advanced Driver Assistance Systems (ADAS), route and speed advisory, V2X communication etc.) as these aspects define the utilisation of transport systems [23]. Improvements within these core aspects help in realising higher capacity in highways.

Figure 3-4 An overview of measures to increase highway capacity

Additionally, traffic incidents are one of the main reasons behind congestions as the capacity of highway temporarily decreases due to incidents. A reduction in the number of incidents can greatly contribute towards the traffic flow efficiency as it would lead to reduction in incident induced congestions. Thus, improvement of road safety can be considered as one of the major requirements to increase highway capacity.

In the rest of this sub-section the four means of increasing highway capacity are discussed in detail. The three means of increasing sustainable modal shift are not described further in this report. Increasing sustainable modal shift and increase highway capacity are twin goals (on the same sub-level) of the ultimate goal "Improve socio-economic wellbeing". Furthermore, increasing highway capacity – assuming the main users of the highway are private vehicles – will make "increase sustainable modal shift" more difficult, because it is expected to attract more users to the highways. For these reasons, "Increase highway capacity" has been identified as the focal objective, in line with the DoRN.

The four means of increasing highway capacity are:

A. Increase infrastructure capacity

Increasing infrastructure capacity is one of the most straightforward ways of increasing highway capacity. Increase in infrastructure capacity can not only be realised by physically increasing infrastructure capacity but also by ***better utilisation of existing highway capacity*** by means of influencing driver behaviour, redesigning existing infrastructure and vehicle technologies. Some of the means of increasing infrastructure capacity are as follows:

- A direct way to increase infrastructure capacity is to build new infrastructure or *extend the existing infrastructure* in terms of constructing new lanes. However, research suggests that building or extending infrastructure in terms of additional road space does not necessarily relieve traffic congestion problems as new demand is induced with improvements in infrastructure [24], [25]. Instead of adding additional road space, there are other (smarter) ways to increase infrastructure capacity, like for example optimization of signs (see sections below).
- *Improving incident and impact management* can effectively improve the response time of emergency services leading to faster mitigation of temporary lane drops and eventually recovering capacity. Road incidents are a major cause of a decrease in capacity as lanes become temporarily unavailable. Incidents also attract other drivers' attention leading to 'rubbernecking' in highways which itself leads to further decrease in road capacity and increases the likelihood of further incidents [58]. The impact of incidents can be reduced by various measures such as using a safe systems approach to build forgiving infrastructure or improving the emergency response services.
- With *improvements in traffic management*, the road capacity can be fully utilised, leading to reduction in congestion, emissions, incidents, and a resulting increase in traffic flow efficiency. Traffic management plays a major role in preserving the capacity of the infrastructure as well as in improving the safety, security, and reliability of road transportation. Various traffic management strategies such as signal control, route, incident and travel time information, ramp metering, speed control, weather management, rush hour lane, priorities and right of way etc, not only help safely control traffic but also manage the supply and traffic demand. Traffic management strategies can be broadly implemented on the policy as well as technological side.
- *Improvements in infrastructure design and quality* contribute to increased road capacity as it can have a major impact on traffic flow efficiency and safety. The capacity of highways can be influenced by road quality features such as horizontal and vertical alignment, sight distances, lane markings, visibility, smoothness, and comfort, merging and weaving section design etc. These factors influence the driver's capability to maintain the recommended speed and thus influence the capacity.

B. Improve driver's behaviour

On the side of human factors, driver behaviour plays a major role in overall traffic safety, efficiency, sustainability, and capacity. Humans have limited capabilities of processing information and rely on three fallible mental functions: perception, memory, and attention [26]. Whenever the task demand exceeds the capabilities of the human driver, the situation goes out of control of the human driver and leads to an unsafe situation [27]. While collisions significantly contribute to temporary decreases in highway capacity, it is known that around 95% of collisions are caused by human error [28]. Thus, improving driver behaviour is one of the most effective means of improving highway capacity. Some means of improving driver behaviour are presented below:

- Driver knowledge and awareness play an important role in the driving task and relevant improvements in their content and structure can lead to overall improvement in driver behaviour. Driver knowledge and awareness can be enhanced through improvements in training in which drivers can be trained on the functioning of traffic control systems and various in-vehicle technologies. Additionally, driver training can focus on other important aspects like distraction during driving, rubbernecking, tailgating, speeding, and state of mind. Training on higher order skills (like risk perception and socioemotional skills) are also crucial in adopting safe driving behaviour. As a result of changes in the content and/or structure of driver training, similar changes are relevant for the driver licencing processes, the content and/or structure of which would have to be aligned with training.
- Human behaviour should be taken into consideration while designing and implementing new technology. With the availability of various systems that assist or take over the driving task, drivers adapt their behaviour to use the technology in a way which suits their driving purpose, motivation, driving style and physical process [29]. This unintended change in behaviour of the users against intended designed operation may jeopardise the expected benefits of the systems [30]. Thus, while designing and implementing technology, a careful consideration of driver behaviour can eliminate any unexpected behaviour adaptations.

C. Improve vehicle technologies, data, and services

For more than 20 years, Cooperative Intelligent Transport Systems (C-ITS) have been developing [31]. The cellular network technology allows various road users and transportation management personnel to communicate with each other, forming a connected transportation infrastructure. With improvement and optimisation of connectivity between vehicles and infrastructure as well as wider deployment of in-vehicle technologies, the demand and road capacity can be more effectively managed. Some means of improving vehicle technologies are presented below:

- Vehicular communication systems enable different forms of exchange of information from Vehicle-to-vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Infrastructure-to-vehicle (I2V).
  - V2V communication enables exchange of information between different vehicles which can be used to enhance the functionality of collision detection systems. Other vehicles in the network can be made aware of an unsafe situation ahead and prepare accordingly. Additionally, with the help of V2V communication, vehicles can drive in platoons and drive with smaller headways, leading to an increase in traffic efficiency.
  - V2I communication enables vehicles to communicate with infrastructure and provide details about different traffic situations. This form of communication has various applications, such as identification of congestion state and location, providing traffic light priority to approaching emergency vehicles, optimisation of traffic signal cycles, regulation, identification of speed limit violators, etc. One example of V2I communication is floating car data which is utilised by Rijkswaterstraat in the Netherlands to improve traffic flow and safety [32]. Additionally, this enables efficient operation of the smart traffic management system and helps in improving traffic flow.
  - I2V communication can be used to broadcast and provide information to road users and vehicles for efficient operation. Some examples of I2V communication are speed advisory, speed limits, route and travel time information, warnings regarding road works, traffic jams, incidents, closed lanes etc. I2V communication provides information about the road condition and assists drivers and vehicles in making well-informed decisions. Improvement in these communication systems helps in better utilisation of road capacity, improving overall traffic safety, and helps in achieving efficient traffic flow [59].
- There are several *in-vehicle technologies* which assist the driver in or take over the driving task and help to achieve consistent safe driving behaviour. There are various in-vehicle systems, such as Intelligent Speed Adaptation (ISA), Lane Keep Assist (LKA), Adaptive Cruise Control (ACC), Automated Emergency Braking (AEB), Forward Collision Warning (FCW), Lane-Departure Warning (LDW), etc. These systems have proved to reduce human driving errors,

while assisting in compliance with traffic rules [60] [61] [62] [63]. They have, therefore, potential in accident reduction and improvement of road safety and traffic flow.

D. Improve road safety

Incidents are a major cause of congestion and decrease in highway capacity. Improving road safety is not only a major requirement but also a large contributor to the improvement of highway capacity. Using a safe systems approach to build forgiving infrastructure, spatially separating modes and directions, homogenising speeds, improving road quality and improving traffic management and control are all means of improving traffic safety. Most of the means described in the previous paragraphs have a twofold impact, both on road safety and traffic flow. For example, adequate driver training helps in improving the road safety through an improvement in driver behaviour such as adherence to traffic rules. As a result, application of those both fulfil road safety requirements and enable road safety to enhance traffic flow efficiency.

Since the means-ends diagram of Figure 3.3 is not complete, various lower level means also encompass different other more specific means as provided in Table 3.1.

Table 3.1 List of some more specific means as a part of greater objective.

Increase and utilise existing infrastructure capacity	Improve incident and impact management	• Access for emergency services* • Incident detection • HGV policies • Separation of slow and fast lanes
	Improve traffic management	• Speed management* • Driving regulations and bans* • Extreme weather events* • Routine maintenance work management* • Road work management* • Hard shoulder running* • Ramp metering* • High occupancy vehicle lanes* • Variable speed limits* • Road zippers: Moving road barriers*
	Extend infrastructure	• Constructing new lanes • Constructing safety barriers • Extend digital infrastructure
	Improve infrastructure design/quality	• Lane widths • Clarity of environment (road lighting, lane marking, sign boards, priority markings etc.)
Improve driver's behaviour	Improve driver knowledge and awareness	• Adherence to traffic rules and regulations • Driver training and education
	Consider human behaviour in technology	• Nudging infrastructure • Rule enforcement techniques e.g., speed cameras • Take over requests by Automated Vehicles
Improve vehicle technologies, data, and services	Improve V2X communication	• C-ITS* • Emergency communication devices* • Automated vehicle platooning • Speed advisory • Traffic and route information
	Increase deployment of in-vehicle technologies	• Advanced driver-assistance systems • Lane keeping systems • Emergency braking systems • Intelligent speed adaptation • Adaptive cruise control

* As mentioned in DoRN call 2019(2)

3.1.3 Phase 3: Identifying dilemmas and core level of analysis

Following the research requirements from DoRN, "Increase highway capacity" was identified as the focal objective for this research. The following means of increasing highway capacity were chosen as core level of analysis: Increase infrastructure capacity, increase efficiency in driver behaviour, and improve deployment of vehicle C-ITS.

Dilemmas are the challenges encountered while realising the focal objectives. In the absence of a dilemma, the objective can be very easily achieved. Dilemmas pose a restriction on the available solutions due to which new solutions need to be considered. The dilemmas (illustrated as ellipses in Figure 3.3) identified through literature review, discussion, DoRN and workshops, were as follows:

- *Road safety:* As different measures for increasing highway capacity influence the road transport system, the associated road safety can improve or deteriorate. With new measures, it is important to not compromise road safety if the road safety cannot be improved. Zero negative impact of road capacity measures on Road Safety is, therefore, the main challenge to address.
- *Investment cost:* Investment cost is another factor due to which implementation of certain measures to increase highway capacity might not be feasible. Due to differences in economic situations within different countries, the available budget for infrastructure development varies. Depending upon the current maturity of transport infrastructure technology within a country, the investment cost to implement measures also varies. Additionally, the priorities of development are different within different countries, policies, and time frames.
- *Environmental effects:* The selection of measures should ensure that those with zero or minor negative environmental impact are preferred, so as to avoid damaging the environment.

It can be seen that the means of improving road safety also fall under the means of increasing infrastructure capacity. Thus, for the sake of reducing double counting, road safety will be seen as a focal dilemma instead of as a means to increase highway capacity.

3.2 Specifying objectives and criteria

Theory

Specifying objectives and criteria/Key Performance Indicators

The means-ends diagram helps identify the focal objective and the dilemmas associated with it. Having identified the focal objective and relevant dilemmas, the next step in systems analysis is to identify more specific "lower level" objectives. The lower-level objectives help in identifying criteria and Key Performance Indicators (KPIs) through which the degree of the focal objective can be measured.

To identify lower-level criteria and KPIs, an objective tree is constructed. An objective tree can only be read from top to bottom. The topmost block provides the focal objective and dilemma, as identified from the means-ends diagram. Going down the objective tree breaks down the focal objective into more specific objectives which can be measured with some specific KPIs. The lowest layer of the objective tree contains the units for the criteria which can be used to compare the effect of different means upon the focal objective.

As seen from the means-ends diagram and following the DoRN requirements, the focal objective of this project is to "increase highway capacity" with "no compromise on road safety" as the main dilemma. Since the influence of both capacity and safety is critical for the road users, the main objective in this project is phrased as "Safe increase of highway capacity (for road users)".

The main objective was further scoped with the help of literature review, discussion, and expert feedback sessions to identify more specific objectives and criteria. The process of objectives and criteria specification resulted into the objective tree shown in Figure 3.5.

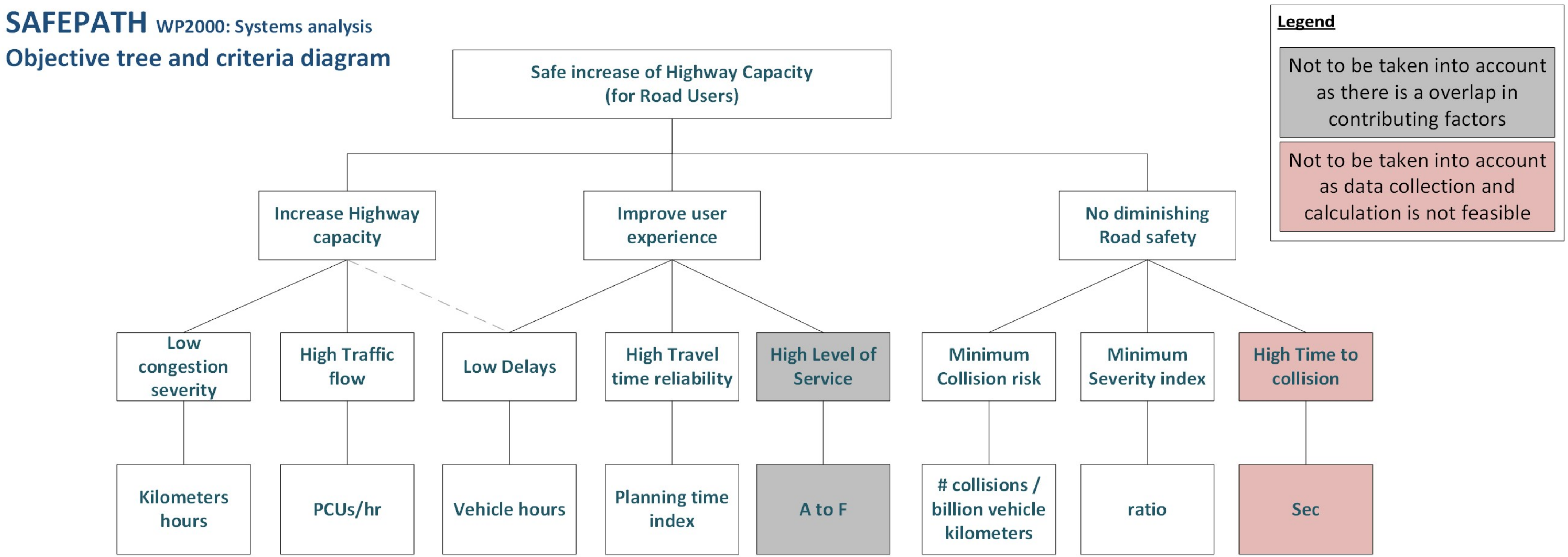


Figure 3-5: Objective tree diagram indicating main objectives and measurable KPIs

Focal objective was narrowed down further into more specific sub-objectives: Increase Highway Capacity, Improve user experience and no diminishing road safety. These sub-objectives were further made more specific by defining criteria and KPIs whose detailed explanation is given below.

A. Increase highway capacity

Increase highway capacity is the main objective of this project. However, this term also refers to efficient and better utilisation of capacity. Highway capacity is defined as the "maximum sustainable hourly flow rate at which vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions" [33]. As discussed earlier in this report, traffic flow breaks down when traffic demand exceeds capacity. This leads to congestion and delays, which are indicators of insufficient highway capacity. To increase highway capacity, following criteria can be used:

- *Low Congestion Severity* – Congestion severity (originating from the Dutch term "Filezwaarte") is a factor that defines the weight or gravity of the traffic congestion [34]. On a highway with sufficient capacity, low congestion severity is expected. Decrease in congestion severity over time indicates increase or better utilisation of highway capacity. Congestion severity (kilometre-hours) is calculated by multiplying the length of congestion (in kilometres) with the duration of congestion (in hours).
- *High Traffic Flow* – Traffic flow is defined as "the total number of vehicles (or passenger car units (PCU)) that cross a given point or section of a lane or roadway during a given time interval" [33]. Highway capacity is expressed as the maximum possible traffic flow before breakdown occurs. Traffic flow is, therefore, a direct indicator of highway capacity and is expressed in unit PCUs/hour.

B. Improve user experience

Since road users directly or indirectly experience the various traffic situations, it is important to focus on measuring the most important for the road users' experience criteria. Some of them are:

- *Low Delays* – A delay is defined as "The increased travel time experienced by a person or vehicle due to circumstances that impede the desirable movement of traffic" [35]. Delays are calculated as the time difference between actual travel time and free-flow travel time. Delays detract from road users' experience. The total delay – measured as the cumulative delays over a fixed duration caused by all the traffic on a road segment and expressed in terms of vehicle-hours – is also an indicator of highway capacity. A reduction of the total delay indicates better utilisation of highway capacity.
- *High Travel time reliability* – Travel time is defined as the time elapsed while travelling from point A to point B, including the stops and delays [35]. Travel time varies as delays vary. Travel time reliability is an indicator of quality of service, and is a measure of how travel times vary over time (e.g., hour-to-hour, day-to-day) [36]. It is important to transport users because of the need to plan their time, without arriving at their destinations too late or too early.
  A standard measure of travel time reliability is the *Planning Time Index*. It is an indicator of how much total time a road user should take to ensure arrival on time. The Planning Time Index is the ratio of the 95th percentile travel time over the free flow travel time [36].
- *High level of service* – The Level of Service (LOS) translates the performance of the road network into an A to F level system that represents the road users' perception of quality of service [33]. Although widely adopted the LOS, because it reduces complex mathematical performance metrics to six simple levels, is insufficiently sensitive when small changes in performance need to be monitored.

C. No diminishing road safety

It is vital to measure road safety indicators to keep track of the impact of different measures upon road safety. The most relevant criteria for road safety applicable to this project are:

- *Minimum collision risk* – Collision risk (or Accident risk) is defined as the probability of being involved in a collision or accident while driving [37]. It does not specify the severity of the collision or resulting injury – this must be specified in addition. Collision risk can, among others, be influenced by for example the amount of lane changes and speed differences. For this project, the measure *number of collisions per billion vehicle kilometres travelled* was chosen as an appropriate unit.
- *Minimum collision severity* – Collision severity is the quantification of health and material damage once a collision has taken place. Collisions can be categorised into multiple levels of seriousness: fatalities, severe injuries, minor injuries, and material damage. In the EU, the Maximum Abbreviated Injury Scale (MAIS) is used to classify the seriousness of injuries [38]. Injury scores range from 1 to 6, where 6 represents fatality, 3+ indicates serious injury, 1+ indicates minor injury and 1 indicates material damage only. The severity index can be calculated by converting the different types of severity of accidents into an equivalent property damage only (EPDO) index. The number of accidents of different severity are multiplied by a factor representing equivalent property damage and are added together to identify the total equivalent of property damage. This equivalent property damage is divided by the number of million vehicle kilometres travelled to obtain the severity index.
- *High Time to Collision* – The time to collision is a surrogate safety measure which refers to the remaining time before the rear end collision, given the speed and trajectory of the vehicles are kept constant [39]. The time to collision indicator is superior than traditional methods of quantifying traffic safety as it does not rely on collision statistics. However, the data collection for estimating time to collision is very complex and currently mostly used for the safety analysis of intersections using video cameras. This method is, thus, not very suitable for safety analysis of highways. The time to collision is calculated in seconds.

After performing the analysis of different objectives and identifying the criteria and KPIs, several criteria were selected to measure different objectives as shown in Figure 3.5. Some factors, although considered important, will be excluded from further analysis for the following reasons:

- *Level of service* – Since this criterion is not sensitive to small changes in performance, it is not effective to use this as a KPI. Furthermore, the LOS depends on other criteria such as traffic flow. Inclusion of the LOS would lead to double counting because of overlapping.
- *Time to collision* – Due to limitations in data collection, and the calculation processes required to estimate the time to collision, it is not a feasible metric in this study.

3.3 Identification of influencing factors and mapping out causal relations

Theory

Causal relation diagrams

As discussed earlier, the means-ends diagram specifies the focal objective, dilemmas, and appropriate level of analysis. Further, from the identified focal objective and dilemmas, the objective tree was constructed to identify the different criteria used to measure the focal objective. For a complete view of the system, one must identify different factors which affect the measurable criteria, and their effect on each other. This is done by plotting a causal relation diagram, depicting the causal relations between the relevant factors.

The causal relation diagram depicts factors as nodes and causal relationships between them as connecting arcs. The relevant factors are identified by conducting an extensive literature review and conducting interviews and workshops with experts. Since it is important to keep the causal relation diagram comprehensible, only the most relevant factors are plotted. These factors are identified by asking: "Which factor can cause X to change?".

The causal relation diagram provides an overview of the factors to be considered in the problem analysis. The relationships between factors are indicated in the causal relation diagram as positive (change in one factor will cause a change of the same direction in another factor) or negative (change in one factor causes a change in the opposite direction in another factor).

In the objective tree analysis, six criteria were identified:

1. Congestion severity
2. Traffic flow
3. Delays
4. Travel time reliability
5. Collision risk
6. Collision severity

As a next step in the systems analysis, the factors influencing the criteria and the relationships between them were identified with the help of literature review and expert discussions. To identify the different factors, two assumptions were made:

1. The relationship between two factors is only valid if all the other factors are assumed to be constant.
2. The direction of relationship (positive or negative) should be definite i.e., valid in all cases within specific situation (e.g., congestion state).

Following these assumptions, different factors were identified and were put together with their relations to form the causal relation diagram as shown in Figure 3.6. Some factors were only valid for congestion state; these are marked with an asterisk (*).

Section 3.3.2 provides the description of the relationships within causal relation diagram, with relevant literature references.

As described earlier, the causal relation diagram is not complete as only the most relevant factors are plotted, to maintain comprehensibility. Several other factors which are also relevant but have not been included are itemised in Appendix A.

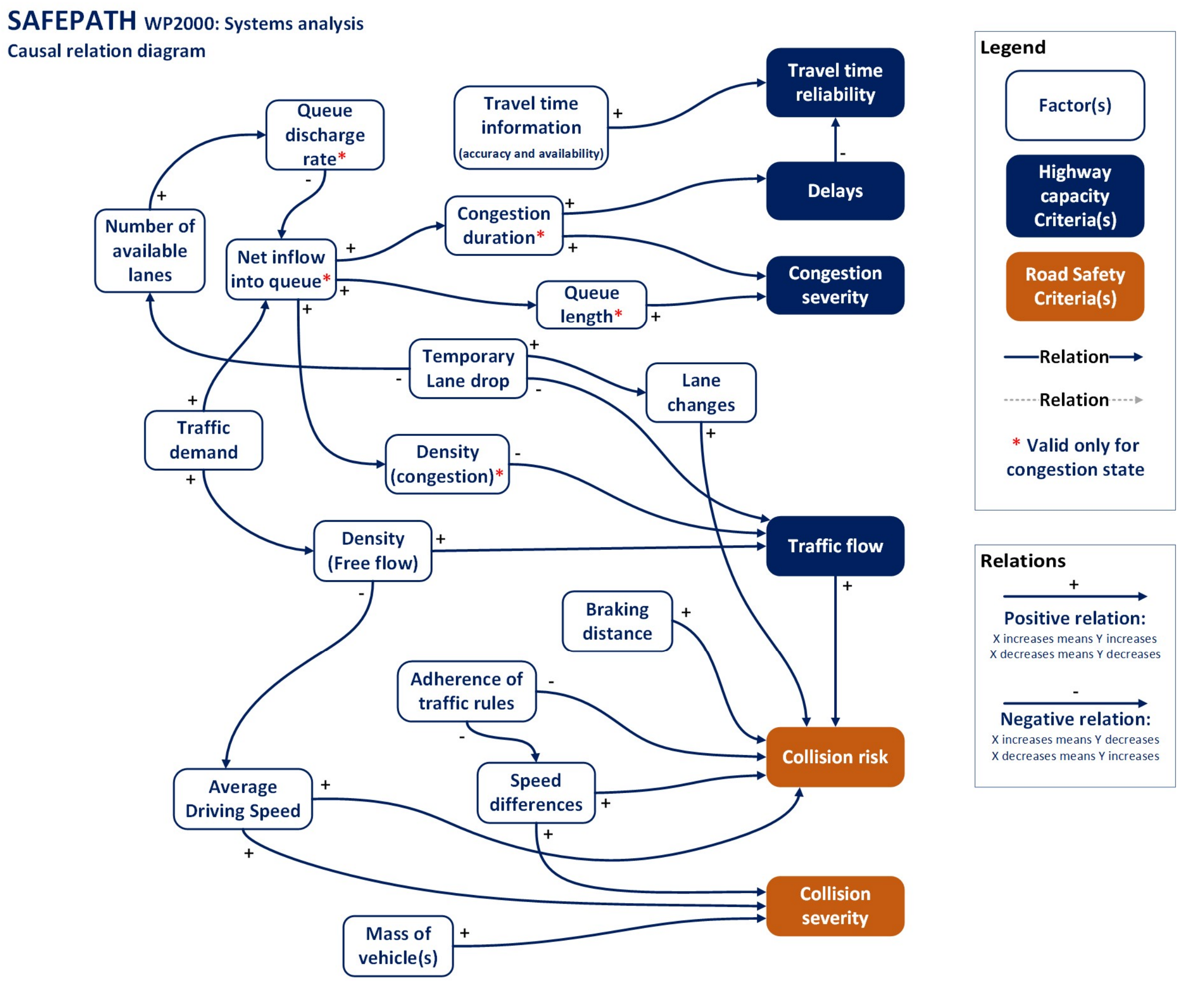


Figure 3-6: Causal relation diagram for SAFEPATH project

3.3.1 Definitions and key terminology

The various influencing factors discussed in the causal relation diagram are defined as follows:

- *Travel time information* – The available information to the road users regarding the travel time in a particular route from their origin to destination.
- *Congestion duration* – Time period in hours for which traffic in a particular location stays in a congested state.
- *Queue length* – Distance between head and tail of the congestion in kilometres.
- *Net inflow into queue* – Effective traffic flow into the congestion. This is equal to inflow into the queue minus outflow from the queue. Positive net inflow refers to a growing number of vehicles in congestions whereas negative net inflow refers to congestion dissolution.
  - *Net inflow into queue = Inflow – Outflow (queue discharge rate)*
- *Queue discharge rate* – The traffic flow downstream of congestion i.e., outflow from the congestion expressed in PCUs/hour.
- *Number of available lanes* – Total number of lanes available/allowed for the vehicles to drive.
- *Traffic demand* – Set of all the vehicles in the transportation system with their associated routes [40].
- *Temporary lane drop* – A temporary decrease in the number of lanes available for driving. Reasons for temporary lane drop include incidents, road works, weather conditions, road blockage etc.

- *Lane change(s)* –Movement of a vehicle from one lane to another, where both lanes have the same direction of travel. Here, lane changes are seen in macroscopic sense where the frequency of lane changes by all road users over a particular location is being considered.
- *Density (congestion)* – The number of vehicles per kilometre of road when the traffic is at a congested state.
- *Density (Free flow)* - The number of vehicles per kilometre of road when the traffic is at free flow state.
- *Braking distance* – The distance required for the vehicle to stop completely after the occurrence of hazard. The braking distance takes into account 'thinking time' – time taken to perceive the hazard and react [41].
- *Adherence to traffic rules* – User behaviour regarding compliance and adherence to the rules of traffic.
- *Speed differences* – Differences in speed between different road users in a particular road segment. This variable is used in macroscopic terms, to depict homogeneity of speeds in traffic. Thus, speed differences refer to the standard deviation of speed differences between different road users.
- *Average driving speed* – The average driving speed of different road users in a particular road segment.
- *Mass of vehicle(s)* – The mass of vehicle(s) getting involved in a collision.

3.3.2 Influencing factors and their relationships

The causal relation diagram provides details of direct influences between factors. From these, various indirect relationships between factors can be identified.

As an example, to identify the relationship between traffic demand and collision risk, we can think as follows. With increase in traffic demand, the density in free flow state increases as more vehicles use the network. With higher density in the free flow state, more vehicles drive per kilometre at the free flow speed, which results in an increase in traffic flow. With the increase in traffic flow, more interaction between vehicles takes place, thus the exposure of vehicles driving near each other increases. As a result, the collision risk also increases. Thus, it can be said that the with increase in traffic demand, the collision risk increases.

In a similar manner, various other indirect relationships can be explored by the reader.

Table 3.2 provides the description of various relationships within the causal relation diagram, with relevant literature references. As previously, with the causal relation diagram itself, factors which are relevant but have not been included in the table are itemised in Appendix A.

Table 3.2 Relationships between different factors in causal relation diagram.

Primary factor	Influenced by	Relation	Explanation	Literature reference
Traffic flow	Density (congestion)*	Negative	From the fundamental diagram of traffic flow, at congestion state, with increase in the density of traffic, the traffic flow decreases as the speed of traffic decreases due to congestion.	[42]
	Density (Free flow)	Positive	From the fundamental diagram of traffic flow, at free flow state, with increase in the density of the traffic, the traffic flow increases as more vehicles can cross.	
	Temporary lane drop	Negative	With an increase in number of lane drops, fewer lanes are available for the traffic to cross and thus the traffic flow decreases.	[43]
Congestion severity	Congestion duration*	Positive	Since congestion severity depends on the congestion duration, increase in congestion duration increases the congestion severity.	[34]
	Queue length*	Positive	With increase in the length of the queue in congestion, the congestion severity also increases.	
Delays	Congestion duration*	Positive	Delays are mainly caused due to congestion. With an increase in duration of congestion, the total cumulative delays of traffic participants facing congestion also increases.	
Travel time reliability	Travel time information (accuracy and availability)	Positive	With increase in availability and accuracy of the travel time information, travel time can be predicted more accurately, thus contributing towards improvement in reliability of travel time.	[36]
	Delays	Negative	Delays can be of two types: Expected and unexpected. Expected delays are caused by various traffic interventions such as new speed limits, traffic signals, road works etc. However, uncertain events such as traffic incidents, signal failure, weather etc may cause unexpected delays. With increase in delays, the travel time varies leading to an overall decrease in travel time reliability.	[44]
Collision risk	Braking distance	Positive	When the braking distance of the vehicle increases, the probability of stopping within the safe distance decreases and the probability of getting into a collision increases.	[45]
	Traffic flow	Positive	Higher amount of traffic flow leads to more exposure of traffic. Since collision risk increases with increase in exposure, high traffic flow	[46]

			can lead to high collision risk.	
	Adherence to traffic rules	Negative	With more adherence to traffic rules, road users are expected to drive and behave in a safe manner leading to a decrease in collision risk.	[47]
	Speed differences	Positive	An increase in speed differences between road users is proven to lead to higher collision risk.	[48]–[50]
	Average driving speed	Positive	Speed has direct influence on collision risk. The higher the driven speed, the more likely it is for a collision to occur.	
	Lane changes	Positive	Studies have identified lane changes as one of the leading causes of traffic incidents. With a higher occurrence of lane changes, the collision risk also increases.	[51]
Collision severity	Speed differences	Positive	With increase in speed differences between road users, the relative speed of the collision is higher, leading to a more severe collision.	[49]
	Average driving speed	Positive	Driving speed has a direct influence on severity of collision. With an increase in driving speed, the impact on the collision also increases.	[48]
	Mass of vehicle(s)	Positive	Vehicles with higher mass store high potential energy. Upon collision, due to large mass, more energy is released leading to higher damage and severity of collision.	[52], [53]
Congestion duration*	Net inflow into queue*	Positive	With an increase in net inflow into the queue, the number of vehicles in the queue increases (or starts decreasing slowly if net inflow was negative) which in turn leads to increase in duration of congestion.	
Queue length *	Net inflow into queue*	Positive	With an increase in net inflow into the queue, the number of vehicles in the queue increases thereby increasing the queue length.	
Net inflow into queue*	Queue discharge rate*	Negative	An increase in the queue discharge rate leads to an increase in the rate of vehicles leaving the queue (outflow). Since, the net inflow in the queue = inflow – outflow, with increase in outflow, the net inflow decreases.	
	Traffic demand	Positive	An increase in traffic demand positively relates to the inflow into the queue, as the latter increases. Assuming fixed queue discharge rate, the net inflow into the queue also increases.	
Queue discharge rate*	Number of available lanes	Positive	Queue discharge rate is the traffic flow out of the congestion. With an increase in the number of lanes, the traffic flow out of the congestion also increases as a result of increased capacity.	[43]

Number of available lanes	Temporary lane drop	Negative	With a lane drop, one or more lanes become unavailable, resulting into decrease in number of lanes available for driving.	
Lane changes	Temporary lane drop	Positive	With a temporary lane drop, one or more lanes become unavailable for driving. The vehicles driving in dropped lane need to switch lane to continue driving. With an increase in the number of lane drops, the number of lane changes also increases.	[43]
Density (congestion)*	Net inflow into queue*	Positive	According to the fundamental diagram of traffic flow, with an increase in net inflow into the queue, the number of vehicles in the queue increases, leading to an increase in density of congestion state.	
Density (Free flow)	Traffic demand	Positive	An increase in the traffic demand at free flow state, means that the traffic flow also increases. This results into more vehicles per unit distance. This leads to an increase in density of traffic flow at free flow state.	
Average driving speed	Density (Free Flow)	Negative	According to fundamental diagram, an increase in density at the free flow state results to more traffic interaction and subsequently to a decrease in average driving speed.	[42], [47]
Speed differences	Adherence of traffic rules	Negative	With an increase in adherence to traffic rules, more vehicles drive closer to the speed limit. This results to less speed differences between traffic participants.	[47]

3.3.3 Secondary influencing factors

There are numerous other factors which influence the system of highway capacity and road safety criteria. However, not all factors can be included in the causal relation diagram for the sake of simplicity and to maintain comprehensibility of the diagram. Various other factors which are very relevant to the system, but are not present in the causal relation diagram are provided in Appendix A.

Theory

3.4 *Overview of the system (systems diagram)*

Theory of the systems diagram

The main purpose of the systems diagram is to summarise the findings from different analyses conducted earlier: means ends, objective tree, and causal relations analysis. There are four main elements in the systems diagram.

Means (presented on the left side) are the actions which can influence the system to achieve objectives.

Criteria (presented on the right side) are the factors whose values indicate the degree of influence and quantified the achievement of objective.

External factors (presented on the top) are the factors which cannot be influenced by any means.

Internal factors (presented in the centre) are the factors affected by means and which affect the criteria.

Means, external factors, and criteria forms the system boundaries and demarcate the system.

The systems diagram provides a firm structure for further problem analysis. From the systems diagram, conclusions can be made on how different means affect different criteria. This is done with the help of causal chains. Furthermore, the factors which need to be influenced to achieve an objective can be determined with the help of systems diagram.

In the analyses conducted earlier, the means-ends diagram, objective tree diagram and causal relation diagram were constructed as described in Sections 3.1, 3.2, and 3.3. The findings from these three diagrams were combined to construct the systems diagram shown in Figure 3.7. This systems diagram provides an overview of the system related to achieving the focal objective of increasing highway capacity without compromising road safety.

3.4.1 Elements of the systems diagram

As the systems diagram combines the elements from the different diagrams, various elements from different diagrams were selected:

Means

In the problem demarcation and means-ends analysis (Section 3.1), several means for increasing the highway capacity were identified as the core level of analysis. The means in this core level of analysis were included as the means on the left side in the systems diagram.

Criteria

In the analysis of objectives and criteria (Section 3.2), six criteria were identified for quantifying the highway capacity and road safety related objectives. These criteria were placed on the right side of the systems diagram.

External factors

These are factors that influence the system but cannot be influenced by any means. Several external factors that were identified through literature review, discussions, and workshops:

- *Weather* – Weather is an external factor that cannot be influenced, although it affects various factors that eventually affect highway capacity and road safety. Some examples are closed lanes due to snow/water, fluctuations in traffic demand, reduced visibility because of fog, rain, and/or snow, longer braking distance e.g., due to decrease in road friction, etc.
- *Ambient light* – Lighting conditions on the road such as reflection on the surface, shadows etc. Ambient light can affect factors such as road quality (clarity of infrastructure), driver distraction, etc.

- *Time of day* – The time of day can influence various factors such as traffic demand during morning and evening peak hours, number of available lanes (due to policy), etc.
- *Culture* – Culture is a factor which is difficult to influence. It affects, however, various factors such as differences in road user behaviour, adherence to traffic rules, traffic demand (due to festivals and events), etc.

Internal factors

Various factors that were identified in the causal relations analysis (Section 3.3) were included in the systems diagram as internal factors.

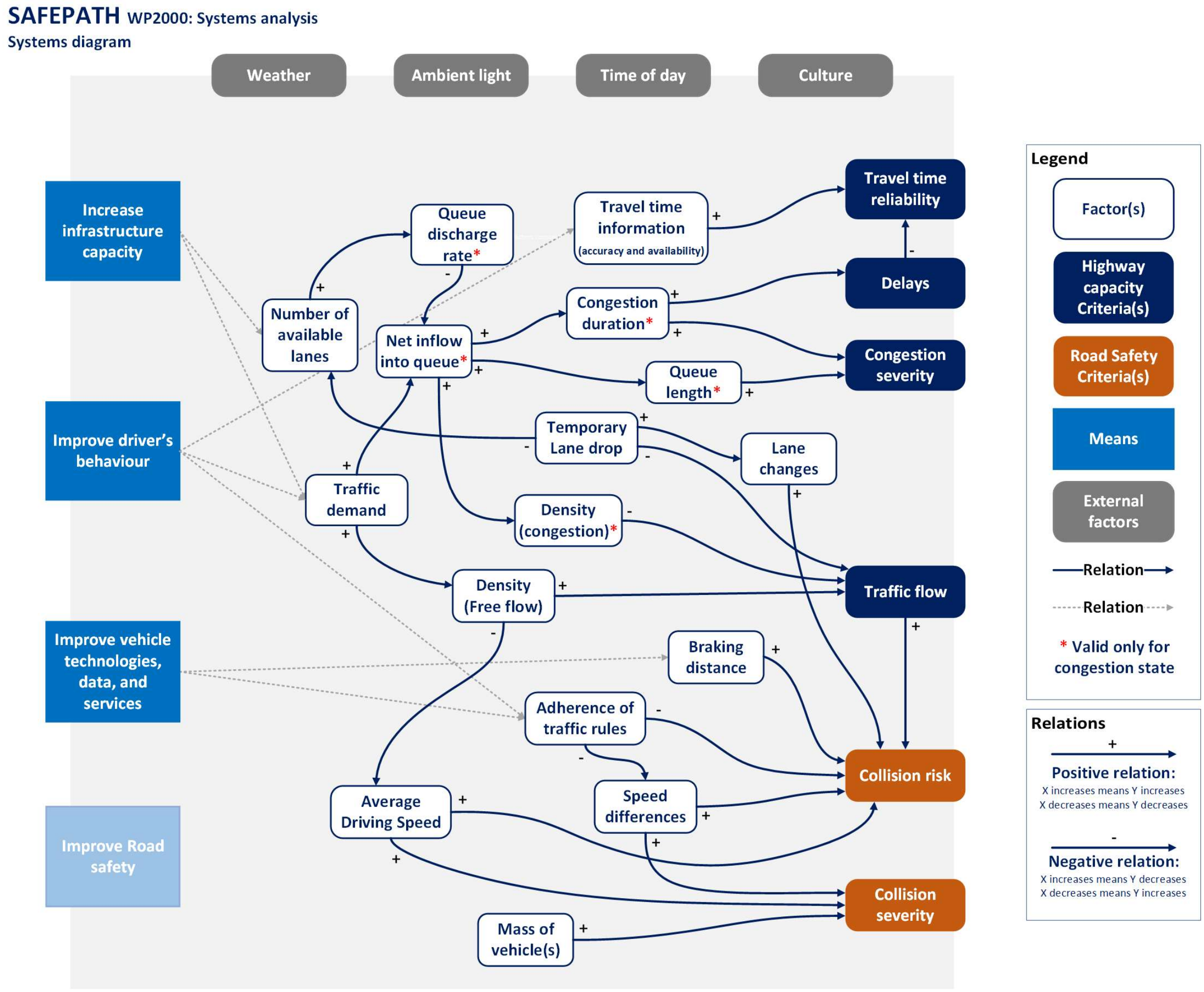


Figure 3-7: Completed systems diagram for SAFEPATH project

The means on the left side of the diagram were linked to the factors that can be influenced by different measures. The relationships between different means and factors were established with the following reasoning:

- Several means to improve infrastructure capacity can influence a variety of factors. A direct way to increase infrastructure capacity is to increase the number of lanes that influences the factor "Number of available lanes". However, other means may include better utilisation of infrastructure capacity. Additionally, research has found that increase in infrastructure capacity increases the attractiveness of highways and further leads to increase in traffic demand due to "Induced demand" [25].

- Several means to increase efficiency in user behaviour may influence factors like availability and accuracy of travel time information, traffic demand and adherence to traffic rules.
- Similarly, improving the deployment of vehicle C-ITS technologies can affect braking distance and adherence to traffic rules.
- Since the means "Improve road safety" covers all previously mentioned means (related to infrastructure, road users and vehicle), no specific connections were made to the factors.

3.4.2 Interpretation of the systems diagram

The systems diagram presented in Figure 3.7, provides an overview of the aspects and factors related to the focal objective of increasing highway capacity without compromising road safety. This diagram provides a clear structure through which one can understand the system and the various relationships between different factors. This information is used to identify how different means for increasing capacity would influence the system.

The systems diagram shows the means for increasing highway capacity being connected to the factors by dashed arrows. The dashed arrows indicate that a means directly influences a particular factor in specific conditions. Dashed arrows can take any direction (positive or negative) depending upon situation. However, it is to be noted that the relationship between different means and other unlinked factors is also valid along the chain of causal relation. For example, a means to increase infrastructure capacity can also influence Collision risk which is indirectly connected via the link:

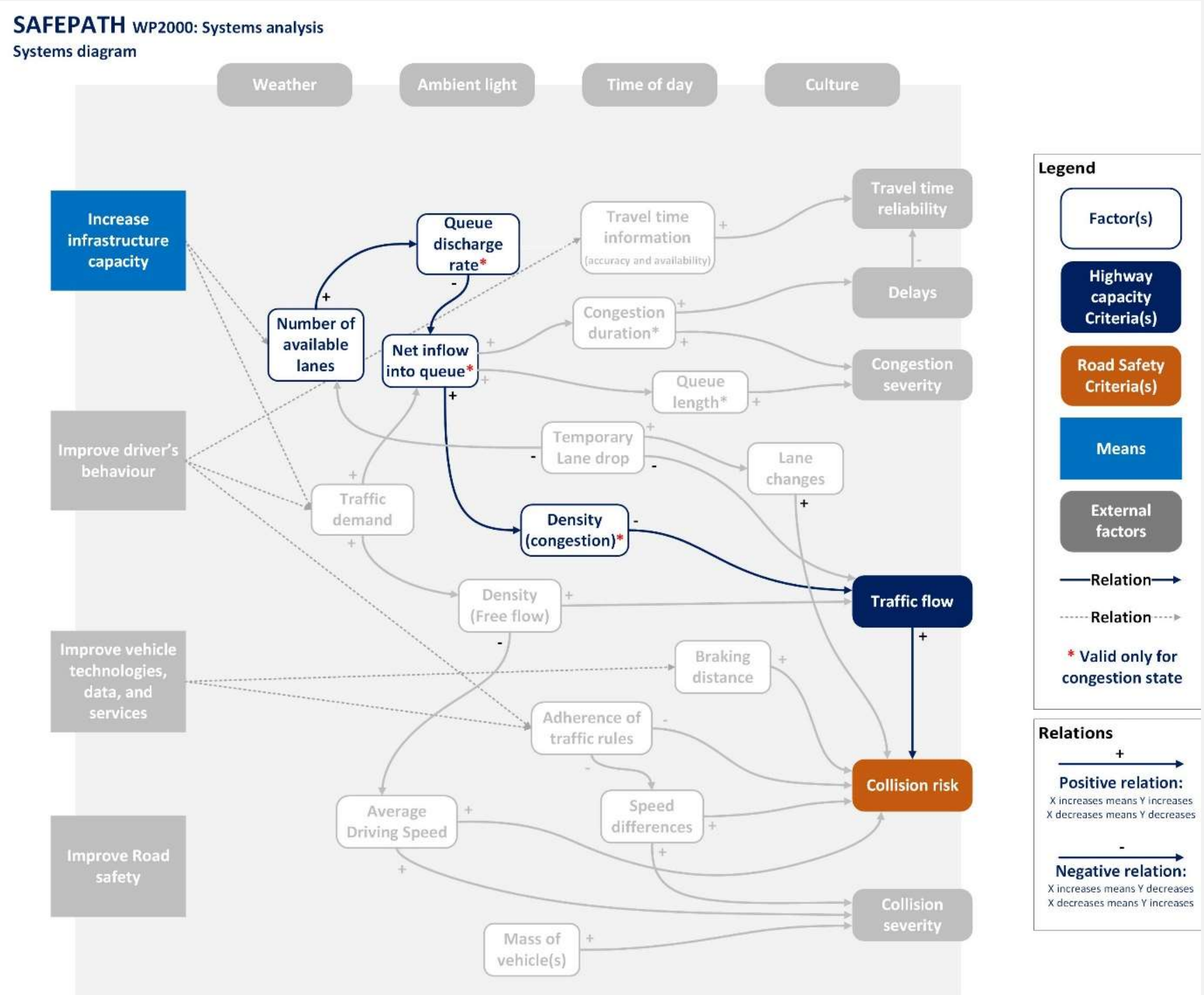
Increase infrastructure capacity -> Number of available lanes -> Queue discharge rate -> Net inflow into queue -> Density in congestion -> Traffic flow -> Collision risk

The systems diagram can be read in many ways. It is, however, recommended to study the system by starting from the means. The following practical example shows how one can read a small part of the systems diagram. The rest of the diagram follows the same principle.

Practical Example

Practical Example of the Systems Diagram

Consider a measure to ***increase infrastructure capacity*** known as **“rush hour lane”** to resolve congestion during peak hours. See 8 for example. In this measure, the hard shoulder is made available to the traffic during the peak hours to accommodate the increased demand. This measure influences the factor ***number of available lanes*** for driving. Looking at the systems diagram, a greater number of available lanes increases the ***queue discharge rate***. As a result, more vehicles can exit congestion. This in turn leads to low ***net inflow into queue*** as the traffic demand is considered as constant in this example. Fewer vehicles at congested state mean that the ***density in congestion*** is reduced. With reduction in density, there will be more space for the vehicles to drive and thus ***traffic flow*** will increase. Furthermore, once traffic flow increases to free flow and thus high speeds, the ***collision risk*** will also increase.



Infrastructure Capacity **Opening Rush Hour lane**	Number of available lanes ↑	Queue discharge rate ↑	Net inflow into queue ↓	Density (congestion) ↓	Traffic Flow ↑	Collision risk ↑

Figure 3-8: Interpretation of the systems diagram example infrastructure capacity, rush hour lane

Understanding the systems diagram is an exploratory process and the causal paths can vary depending on the starting point. The reader is encouraged to explore its connections with different starting points.

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4 Summary of findings and next steps

4.1 Summary

The main objective of this project as indicated in DoRN call 2019(2) is to investigate different measures to increase highway capacity without compromising traffic safety. There are many innovative solutions for increasing capacity without physical widening of the highway (i.e additional road space). It is, however, vital to be informed about any safety concerns arising from the implementation of these measures.

To conduct this research, a systems analysis approach was chosen which helps understanding the system and provides a systematic way to analyse the effect of different means and measures on highway capacity and traffic safety. The process of systems analysis involved 4 different steps: Problem demarcation and determining level of analysis; Specifying objectives and criteria; Identifying influencing factors and mapping out causal relations; and Creating the systems diagram. This report has presented the aim of each step, the methodology in theory and practice as well as the results of each step.

In the first step of systems analysis, problem demarcation was carried out to understand the problem and objective of this research. The outcome of this step was the means-ends diagram which provided a broad spectrum of the objectives and means from strategic to tactical level. From the means-ends diagram, "*increasing highway capacity*" was identified as the focal objective of this research. The means to increase highway capacity, being *Increase infrastructure capacity; Improve driver behaviour; Improve vehicle technologies, data, and services; and Improve road safety* were identified as means for the core level of analysis. From the means ends diagram, three dilemmas were identified in increasing highway capacity. These are Road safety; Investment costs and Environmental effects out of which Road safety was considered as the main dilemma and has been dealt with in the rest of the analysis.

The second step of systems analysis, which involved identifying more specific objectives and criteria to measure objectives, has built upon the outcomes of the first step. The main objective was narrowed down into three sub-objectives: increase highway capacity; improve user experience, and do not diminish road safety. For these sub-objectives, a total of six criteria were identified which can quantify and measure the change due to different means in terms of highway capacity and road safety. The identified criteria were: congestion severity, collision risk, traffic flow, delays, travel time reliability, and collision severity. These criteria provided a set of reliable KPIs to measure the effect of different means and to continue with further steps of systems analysis.

The third step of the systems analysis was to identify the factors that influence the criteria identified in step two and map the causal relationships between them. The outcome of this step was the causal relation diagram which provided insight into how different factors influence the criteria and other factors.

In the last step of systems analysis, all the findings from the first three steps were combined along with findings on external factors to gain a full overview of the complete system. This step resulted in the systems diagram, the main product of this report, which is a tool to understand and analyse the different means for achieving an increase in highway capacity and to relate them with measurable criteria.

The systems diagram is the main product of work package WP2000 for the SAFEPATH project and forms the basis for further analysis within this and other work packages. The systems diagram provides a basic conceptual model for the system of Highway capacity and Traffic safety which shows various aspects and fundamental building blocks affecting the system. In addition to expressing the description of research needs into a systematic model, the systems diagram also provides a scientific understanding of the influencing factors, means, and criteria.

NRAs can use the systems diagram as a tool to identify most influential factors in their transport systems which can help to further redefine the approach towards implementing a means in a country considering its impact. Additionally, with the identification of the side effects due to implementation of a means to increase highway capacity, other measures to reduce the negative impact can be investigated. This will in turn lead to a more complete, insightful, and useful good practice guide.

Furthermore, the systems diagram created in this work package can be used for investigation of highway capacity and road safety systems in future projects.

4.2 Next steps

The outcomes of this work package WP2000 are critical in upcoming phases of the project. WP3000 aims to build a database of a wide variety of projects and measures, with an assessment of their impact on highway capacity, safety, and other relevant environmental, financial, and societal factors. The process will involve conducting interviews, workshops, and literature reviews to gain deeper insights into the different measures in place to increase highway capacity and its implications. The systems diagram, the basis of the SAFEPATH project, is meant to assist in the initial assessment and analysis of different measures identified in WP3000 to increase highway capacity and determine their effect on road safety.

With a greater scientific understanding of the system, it will be easier to identify the factors which might impact the key dilemma of maintaining road safety while using different means to increase highway capacity. Additionally, it will be easier to investigate the influence of a means (to increase road capacity) into other factors, which might have been overlooked.

This provides an opportunity to perform a more robust and thorough analysis of different effects and side-effects due to means in WP3000.

WP4000 aims to develop safety impact assessment methodology, to analyse the safety and capacity criteria defined in WP2000 and WP3000, and to compare various solutions. The criteria and KPIs identified in this work package will provide a firm base for further analysis.

Furthermore, the outcomes from WP2000, WP3000 and WP4000 taken together will feed into the creation of good practice guide in WP5000.

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Appendix A Secondary influencing factors

Various factors not included in the causal relation diagram, but are relevant to the analysis of Highway capacity and Traffic safety system are as follows:

i. Lane width – The width of the carriageway marked by lane markings or edge of the road.
ii. Speed limit – The maximum legal driving speed for vehicles in a stretch of road.
iii. Driver distraction – "Diversion of attention away from activities required for safe driving due to some event, activity, object, or person, within or outside the vehicle" [54]. Some examples include use of mobile phone while driving, rubbernecking, daydreaming, eating, talking etc.
iv. Road quality – Various factors indicating the quality and clarity of infrastructure such as variations in road alignments, road surface quality, sight distances, lane marking clarity, roads infrastructure design etc.
v. Difference in road user behaviour – Differences in personal characteristics and driving behaviour of different road users.
vi. Density difference between lanes – The difference in the density of vehicles between adjacent lanes.
vii. Percentage of Heavy goods vehicles (HGVs) – The composition of HGVs in the traffic involving vehicles of different types.

The relationship between various secondary influencing factors is provided in Table A.

Table A: Relationship between relevant factors not included in causal relation diagram

Primary factor	**Influencing factor**	**Relation**	**Explanation**	**Literature reference**
Average driving speed	**Lane width**	Positive	Research has shown that with increase in the lane width, the average driving speed of the traffic also increases.	[55]
Average driving speed	**Speed limit**	Positive	With increase in the speed limit of the highway, the average driving speed increases as the road users can driver faster	
Braking distance	**Driver distraction**	Positive	With increase in driver distraction, the reaction of drivers towards hazards on road gets slower which leads to an increase in braking distance	[56]
Traffic flow	**Road quality**	Positive	With improvements in road quality factors, the traffic can with less disruptions and thus traffic flow increases.	

Collision risk	**Road quality**	Negative	With improvement in road quality, various safety related factors such as sight distance, clarity of environment, forgiveness of infrastructure improves. Due to these factors, the collision risk decreases.	
Collision severity	**Road quality**	Negative	With improvements in road quality factors such as forgiveness of infrastructure, hilliness and bendiness etc., for the vehicles involved in an accident, the collision severity decreases.	
Speed differences	**Difference in road user behaviour**	Positive	With increase in difference between road user behaviour, the traffic gets more heterogeneous with many interactions and thus speed difference between road users decreases.	
Lane changes	**Density difference between lanes**	Positive	The studies indicate that one of the main reasons behind lane changes is the difference in density between different lanes. When a road user observes lower density in the adjacent lane, it provides an incentive for the road user to change lane and driver more freely. Thus, more is the density difference between lanes, more road users may end up changing lanes.	[57]
Mass of vehicle(s)	**Percentage of HGVs**	Positive	With increase in proportion of heavy goods vehicles on road, the average mass of vehicles in traffic increases.	

Appendix B Contributing project team members and experts

The various project team members and experts who have been involved in the process are mentioned in Table below.

Name	Organisation	Role	Specialisation
Anastasia Tsapi	Royal HaskoningDHV	Project team	Road safety, Sustainable mobility, Smart mobility, Human factors
Evert Klem	Royal HaskoningDHV	Expert	Road safety, Traffic management, Smart mobility, ADAS
Jan van Liere	Royal HaskoningDHV	Expert	Infrastructure planning and design, Traffic engineering, construction
Marson Jesus	Royal HaskoningDHV	Project team	Systems engineering and analysis, Smart and sustainable mobility
Peter Vlugt	Royal HaskoningDHV	Expert	Infrastructure quality and design, Asset and road management
Sacco Barendrecht	Royal HaskoningDHV	Project team	Traffic management, Traffic flow and control engineering
Shubham Bhusari	Royal HaskoningDHV	Project team	Asset management, Automated vehicles, Traffic flow and safety
Shubham Soni	Royal HaskoningDHV	Project team	Traffic flow and management, Road safety, Smart mobility
Dave Cowell	AECOM	Project team	Intelligent transport systems (ITS), Smart mobility
Edward Bingham	AECOM	Expert	Smart Motorways, Highways, Road infrastructure
Keith Gilmour	AECOM	Expert	Smart highways and motorways, Road infrastructure
Lee Street	AECOM	Expert	ITS & C-ITS, Smart Motorways, National Highways
Scott Stephenson	AECOM	Project team	Traffic management, Traffic behaviour, Road safety
Stephen Heathcote	AECOM	Expert	ITS and communication systems, In-vehicle systems
Andy Graham	White Willow Consulting Ltd	Project team	Connected vehicle and data, ITS, road charging and tolling systems
Priyanka Karkhanis	Eindhoven University of Technology	Project team	C-ITS, Mobility innovation, Traffic safety and efficiency
Yanja Dajsuren	Eindhoven University of Technology	Project team	C-ITS, Computer science, Traffic safety and efficiency