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ITS EDU LAB

An Assessment Framework for the Speed Policy on Dutch Motorways

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August 2012

Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

TU Delft

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Date	2012 August 1
Status	Final

ITS Edulab is a cooperation between Rijkswaterstaat Centre for Transport and Navigation and Delft University of Technology

Preface

This report is written in the context of my graduation research, which I have performed for the master Transport & Planning at the Delft University of Technology. The research is carried out in the ITS Edulab, a cooperation between Rijkswaterstaat and the Delft University of Technology. Due to this cooperation students can research relevant and actual topics for Rijkswaterstaat.

Graduating at the ITS Edulab was a very interesting experience. Therefore, I would like to thank Marko Ludeking for providing the information for this opportunity. I would also like to thank the other colleagues at Rijkswaterstaat for providing relevant information about the topic. And I say thanks to the other ITS Edulab students for the very enjoyable time. The discussions were very amusing, especially during the coffee breaks.

Furthermore, I would like to thank Serge Hoogendoorn, Henk Taale, Marko Ludeking, Jan Anne Annema and Paul Wiggenraad for reviewing my work. I have learnt a lot of the feedback. In particular, I would like to thank Thomas Schreiter, my daily supervisor. The feedback and the advices have certainly contributed to the completion of my graduation research.

Finally, many thanks go to Robbert Winkel for helping me to finish the report correctly. And I want to thank my parents for all the support during my study (even from the United States where they live), and José, for listening to all my graduation problems, which are all resolved ultimately.

Jurgen Kuijvenhoven
Delft, August 2012

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Summary

Currently, the Dutch government aims to raise the speed limit to 130 km/h on as many motorways as possible. The reason for this is that current speed limits do not correspond with the wishes and expectations of the road user any more. In this speed limit increase the local conditions and targets need to be taken into account. To deal with the location and time dependent circumstances (for instance air quality or traffic safety due to the traffic flow), a dynamic speed limit is an appropriate solution.

At this moment, an integral approach which considers the significant factors (factors dependent of the chosen viewpoint in the speed limit determination) is not available in the Netherlands. Therefore, the *goal* of this research is to develop an assessment framework, regardless of the chosen perspective, for determining the optimal speed limit for a road section on Dutch motorways, taking the local conditions and targets into account.

A literature review on the state of the art developments concerning speed limits provides two different approaches for the assessment framework. These approaches are the engineering philosophy and the economic optimization philosophy. In the engineering philosophy a speed limit is determined by the highest possible speed that the roadway characteristics allow (called the upper bound). In the economic optimization philosophy an optimal speed limit is determined as the speed limit with the lowest cost for society, considering the significant factors. Fort this research the significant factors are the cost of travel time, the vehicle operating cost, the road accidents cost, the cost of traffic noise and the cost of air pollution.

The developed assessment framework distinguishes three steps:

- Step 1 describes the engineering philosophy, where the upper bound is determined.
- Step 2 contains the economic optimization philosophy. In this step an optimal speed limit is determined, with respect to the upper bound.
- Step 3 provides the comparison. The current speed limit is compared to the determined optimal speed limit, which leads to an advice. This advice consists of a permanent result (during all hours of the day) and a dynamic result (dependent of the traffic flow).

In order to test the developed assessment framework in practice, a case study is performed. In the case study road sections located in the Dutch motorway network are applied in the developed assessment framework.

This case study is evaluated. With this evaluation the usefulness of the assessment framework in practice is determined. In the evaluation is found that the developed assessment framework provides a good working methodology for determining an optimal speed limit for a road section. In step 1 the road layout characteristics are considered. For a road section, it is investigated what critical road design elements are present and what upper bound is applied. In step 2 the optimal speed limit is determined. Here, the optimal speed limit should be below the upper bound. When the optimal speed limit exceeds the upper bound, a possible measure is for instance lowering the speed limit on the normative critical road design element.

Concluding, one can state that due to the unavailability of an integral approach in the setting of a speed limit, the economic optimization philosophy (with respect to the upper bound) is a proper way to deal with this. In this way, significant factors can be taken into account by determining the optimal speed limit.

The comparison between the determined optimal speed limits and the current speed limits shows that in general the current speed limit should be changed. Either decreased or increased depends of the perspective: the road authority aims to decrease the current speed limit and the road user aims to increase the current speed limit.

For the dynamic result, further research is needed whether or not the critical region on the fundamental diagram is reached in case of a speed limit decrease or a speed limit increase. Also, further research is needed to the implementation of the optimal speed limit. When the current speed limits needs to be changed (either permanent or dynamic), it is important to investigate how this new speed limit can be implemented and to make known the optimal speed limit (either permanent or dynamic) towards the road user.

Samenvatting

De Nederlandse regering is voornemens om de snelheidslimiet op de Nederlandse snelwegen te verhogen naar 130 km/h. Zij streeft ernaar dit op zoveel mogelijk wegen te doen. De reden hiervoor is dat huidige snelheidslimieten niet meer overeen komen met de wensen en verwachtingen van weggebruikers. Bij deze snelheidsverhoging naar 130 km/h is het belangrijk om de lokale randvoorwaarden en doelen in ogenschouw te nemen. Om met deze plaats- en tijds afhankelijke omstandigheden om te gaan (bijvoorbeeld de luchtkwaliteit of de verkeersveiligheid als gevolg van de hoeveelheid verkeer), zouden dynamische snelheden een geschikt middel kunnen zijn.

Er ontbreekt nu juist een integrale aanpak in Nederland die de significante factoren (factoren afhankelijk van het gekozen standpunt bij het bepalen van een snelheidslimiet) in ogenschouw neemt. Daarom is het *doel* van dit onderzoek om een afwegingskader, ongeacht het gekozen perspectief, te ontwikkelen, waarmee een optimale snelheidslimiet bepaald kan worden voor een wegvak op de Nederlandse snelwegen, rekening houdend met lokale randvoorwaarden en doelen.

Een literatuurstudie over de huidige stand van zaken betreffende snelheidslimieten levert twee verschillende benaderingen op die als basis dienen voor het afwegingskader. Deze benaderingen zijn de wegontwerp filosofie en de economische optimalisatie filosofie. Bij de wegontwerp filosofie wordt een snelheidslimiet bepaald die mogelijk is bij de geldende wegkenmerken (de bovengrens genoemd). Bij de economische optimalisatie filosofie wordt een optimale snelheidslimiet bepaald, die overeen komt met de snelheidslimiet waar de laagste kosten voor de maatschappij bij horen. Hier worden de volgende significante factoren in ogenschouw genomen: de kosten van reistijd, de kosten van het gebruik van een voertuig, de ongevalkosten, de kosten van verkeerslawaai en de kosten van luchtvervuiling.

Het ontwikkelde afwegingskader bestaat uit drie stappen:

- Stap 1 beschrijft de wegontwerp filosofie. Hier wordt de bovengrens bepaald.
- Stap 2 bevat de economische optimalisatie filosofie. In deze stap wordt de optimale snelheidslimiet bepaald, rekening houden met de bovengrens.
- In stap 3 wordt de vergelijking uitgevoerd. De huidige snelheid wordt vergeleken met de bepaalde optimale snelheidslimiet. Deze vergelijking leidt tot een advies. Dit advies bestaat uit een permanent resultaat (gedurende de gehele dag) en een dynamisch resultaat (afhankelijk van de verkeersstroom).

Om het ontwikkelde afwegingskader nu te testen in de praktijk, is een case studie uitgevoerd. In deze case studie zijn een aantal wegvakken gelegen in het Nederlandse snelwegen netwerk ingevoerd in het ontwikkelde afwegingskader.

Deze case studie is vervolgens geëvalueerd. Met deze evaluatie kan de bruikbaarheid van het afwegingskader in de praktijk vastgesteld worden. De evaluatie laat zien dat het ontwikkelde afwegingskader als een goed werkende methodologie functioneert, waarmee de optimale snelheidslimiet voor een wegvak bepaald kan worden. In stap 1 zijn de wegkenmerken in ogenschouw genomen. Er wordt voor een wegvak onderzocht welke kritische ontwerpelementen van toepassing zijn in het wegvak en welke bovengrens dat dan oplevert. In stap 2 is de optimale snelheidslimiet bepaald. Deze optimale snelheidslimiet zou onder de bovengrens moeten zijn. Als de optimale snelheidslimiet toch de bovengrens overschrijdt, is een mogelijke maatregel het verlagen van de snelheidslimiet ter plaatste van het maatgevende kritische ontwerpelement.

Concluderend kan nu gesteld worden dat omdat een integrale aanpak voor het bepalen van een snelheidslimiet niet beschikbaar is, de economische optimalisatie filosofie (rekening houdend met de bovengrens) een geschikte manier is om als integrale aanpak te fungeren. In deze filosofie worden immers de significante factoren in ogenschouw genomen bij het bepalen van de optimale snelheidslimiet.

De vergelijking tussen de bepaalde optimale snelheidslimiet en de huidige snelheidslimiet laat zien dat de huidige snelheid aangepast zou moeten worden. Of de huidige snelheidslimiet dan verlaagd of verhoogd zou moeten worden, hangt van het perspectief af: de wegbeheerder die tot doel heeft de huidige snelheidslimiet te verlagen en de weggebruiker die tot doel heeft de snelheidslimiet te verhogen.

Voor de dynamische snelheden wordt aanbevolen om te onderzoeken in hoeverre het kritische gebied in het fundamentele diagram bereikt wordt wanneer de snelheidslimiet wordt aangepast. Ook is er verder onderzoek nodig naar de implementatie van de optimale snelheidslimiet. Als de huidige snelheidslimiet aangepast zou moeten worden (permanent of dynamisch), is het belangrijk om te weten hoe deze nieuwe snelheidslimiet ingevoerd zou moeten worden en hoe de optimale snelheidslimiet (permanent of dynamisch) kenbaar naar de weggebruiker zou moeten worden gemaakt.

1 Introduction

Currently, the maximum speed limit (from here on referred to as *speed limit*) on Dutch motorways is 120 km/h, as set in the 'Traffic Rules and Signs Code' ('Reglement Verkeersregels en Verkeerstekens, RVV). On several road sections the speed limit is reduced to 100 km/h because of flow conditions, traffic safety issues or environmental targets. On a selective set of bottleneck locations, the speed limit is reduced even further to 80 km/h because of local air quality (Burgmeijer et al., 2010).

The current Dutch government aims to raise the speed limit on motorways to 130 km/h on as many sections as possible. In the letter 'Rollout of the nation-wide speed increase' ('Landelijke uitrol snelheidsverhoging') sent to the Dutch parliament on November 28th, 2011, the minister of Infrastructure and Environment mrs. drs. M.H. Schultz van Haegen formulated the motto for this operation as follows: *faster if possible, slower when necessary*. This letter is shown in appendix A.

The words *if possible* and *when necessary* indicate the time- and location dependency of the speed limit on a road section. This means that, dependent of the time of the day and thus the number of vehicles on a particular road section (the traffic demand), the speed limit should be increased or decreased, called a dynamic speed limit. Because of social issues (for instance travel time, traffic safety, traffic noise and air quality) a dynamic speed limit is an appropriate solution.

The reason for implementing a speed limit of 130 km/h is that current speed limits do not correspond with the wishes and expectations of the road user. In practice it turns out that the local conditions might invite road users to drive faster than allowed. For example, on the A2 between Amsterdam and Utrecht, with a speed limit of 100 km/h and five lanes per direction, road users do not understand why they have to drive 100 km/h (Nijman, 2010). Especially during evening and night hours, when the three left lanes are completely empty for most of the time, resulting in 20% of the motorists exceeding the speed limit of 100 km/h (Nijman, 2010). The reason for the speed limit of 100 km/h is that the residents along the A2 suffer from increased pollution at a higher speed limit of, for instance, 120 km/h. This example shows the tension between different perspectives in the assessment of the speed limit.

1.1 Problem definition

The consequences of the motto formulated in the introduction of this chapter, call for an integral approach for the setting of speed limits on Dutch motorways. This integral approach should consider all significant factors in the speed limit determination, which are dependent on the chosen perspective. However, such an integral approach for setting the speed limit is not yet available in the Netherlands.

Further investigation is desired to find the optimal speed limit for a road section. This optimal speed limit should be based on an integral approach, but at the same time dependent on both traffic conditions and the chosen perspective. A higher speed limit will result in a shorter travel time, but also in lower air quality (higher emissions) and in a lower traffic safety level (severe consequences when an accident occurs). This means that in some cases a lower speed limit seems to be better when looking at the overall effects of the significant factors on a speed limit, for example when the traffic demand is high during peak hours. Consequently, dynamic speed limits must be applied to deal with these issues. A possible solution is applying a higher speed limit at low intensities (vehicles per hour) and a lower speed limit in peak hours (high intensities). Besides that dynamic speed limits will function properly in case of dense traffic (near the capacity of a road section), that means that in dense traffic a lower speed limit will result in better flow conditions (Hegyi et al., 2005).

The optimal speed limit (either permanent or dynamic) for a road section can be determined by an assessment framework. An assessment framework must deal with significant factors affecting the speed limit and must take the individual assessment of the current speed limit on a road section into account. In an assessment framework one or more philosophies must be chosen. A philosophy is an approach that is used to determine and set the speed limit, for instance setting the speed limit after conducting an engineering study of the traffic environment (road geometry) (Fildes et al., 2005).

The *problem definition* is formulated as follows:

> At this moment an integral approach for setting the speed limit on Dutch motorways — which takes for example travel time, environmental targets, traffic safety issues and flow conditions into account — is not available. It is therefore desired to develop an assessment framework, regardless of the chosen perspective, for determining the optimal speed limit (either permanent or dynamic) for a road section on Dutch motorways.

1.2 Research goal and research questions

The *goal* of this research is to develop an assessment framework, regardless of the chosen perspective, for determining the optimal speed limit for a road section on Dutch motorways, taking the local conditions and targets into account. This assessment framework will show the preferred speed limits for all stakeholders of a motorway (road authority, road users and the residents along the motorway). To deal with the local conditions (physical limits of the road) and targets (goals that need to be met), and in relation to this the time dependent traffic demand, a dynamic speed limit may be a possible solution.

To achieve this goal the following *main research question* needs to be answered:

> How does an assessment framework, regardless of the chosen perspective, look like, for determining the optimal speed limit (either permanent or dynamic) for a motorway section in the Netherlands, taking into account local conditions and targets?

In order to answer the main research question, the following sub-questions are used:

1. What philosophies are available for an assessment framework and what are the differences between them? What perspectives are available in such a philosophy?
2. What are the significant factors that influence the speed limit and do these factors affect the speed limit?
3. How can dynamic speed limits improve traffic flow conditions, traffic safety issues and air quality?
4. What structure is appropriate for an assessment framework and how does it work?
5. Which criteria are needed to select a relevant road section for testing the assessment framework in a case study and how are these criteria applied in the assessment framework?
6. How useful is an assessment framework for determining the optimal speed limit for the Dutch motorway network?

1.3 Scope of the research

This research focuses on the determination of the optimal speed limit on Dutch motorways. In this determination only the maximum speed limits are taken into account; mean speeds are not considered. Furthermore, the minimum speed limit is left out of scope. For all road users it is assumed that the maximum speed limit for a road class (trucks have a lower speed limit than passenger cars) is desired to be used.

The assessment framework leads to an advice. The implementing of the (new) optimal speed limit (either permanent or dynamic) is left out of the scope. Furthermore, enforcement, political influence and the cost of implementing the (new) optimal speed limit are not discussed either.

Finally, it must be stated that the developed assessment framework distinguishes permanent and dynamic results. Permanent results are the results that are applied during all hours of the day. Dynamic results are time and location dependent (dependent of the traffic flow). However, it is beyond the scope of this research how dynamic speed limits works in detail. The assessment framework only describes in what situations dynamic speed limits are necessary and what measures are available for these situations. Further research is needed to determine for instance during what times of the day dynamic speed limits are needed or what value the dynamic speed limits should have.

1.4 Relevance of the research

This section describes respectively the scientific relevance (section 1.4.1) and the practical relevance of this research (section 1.4.2).

1.4.1 Scientific relevance

In the Netherlands an integral approach that considers all significant factors in the determination of the speed limit is not available. There are only some general rules applied to determine a safe speed limit.

In this research an assessment framework is developed which takes the significant factors into account. These are the factors dependent of the chosen perspective, which means that the optimal speed limit is determined considering the impact of the speed limit on the significant factors. The relation between the speed limit and the significant factors are used to determine the optimal speed limit with the lowest cost for society. In this context, Pareto optimal solutions are derived. Wismans et al. (2011) explain that there is not one solution (speed limit) at which each significant factor is served in its best way. According to this study a shorter travel time (driving at a higher speed) will result in worse air quality. To summarize, the developed assessment framework determines the optimal speed limit for a road section at certain conditions (i.e. number of crash statistics or number of vehicles), either permanent or dynamic.

1.4.2 Practical relevance

The goal of the assessment framework is determining the optimal speed limit for a road section in the Dutch motorway network, which meets the wishes and expectations of the road user more closely than is currently the case. For this determination an integral approach is used, considering all significant factors. Rijkswaterstaat can apply the developed assessment framework in order to determine the optimal speed limits for the Dutch motorway network, either permanent or dynamic.

1.5 Structure of the report

In figure 1.1 the outline of this report is shown. It shows the relations between the different chapters in this report, but also clarifies how the sub-questions presented in section 1.2 function as a basis for the structure of the report. Finally, the answers on the sub-questions will lead to an answer on the main research question of this thesis.

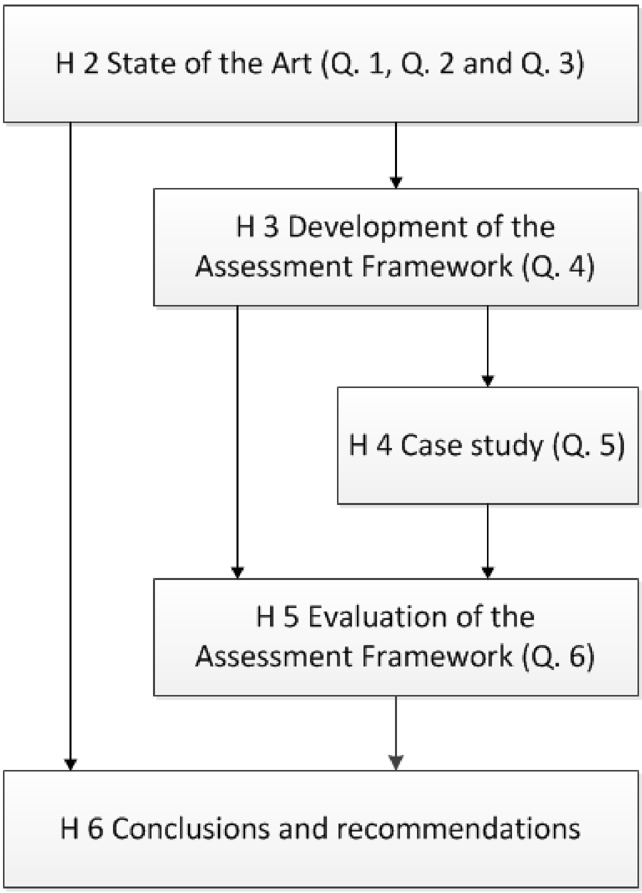


Figure 1.1: Outline of the report and the relation between the chapters and the sub-questions

Chapter 2 starts with an overview of the state of the art developments in speed limits. It clarifies what philosophies are available for setting a speed limit. The perspectives which can be used in a philosophy are explained as well. Furthermore, the significant factors used in this thesis are described in this chapter, including the influence on the speed limit. Finally, dynamic speed limits are described. The focus of this topic lies on the effects that dynamic speed limits have on road capacity.

Chapter 3 develops the assessment framework. The assessment framework consists of three steps. In step 1, the engineering philosophy is considered. Here, the maximum possible speed limit due to the road layout is determined. In step 2, the economic philosophy is considered. The optimal speed limit is determined, which is the speed limit with the lowest cost for society. In step 3, the determined optimal speed limit is compared to the current speed limit, which leads to an advice about the permanent result (speed limit during all hours of the day) and the dynamic result (speed limit dependent of time and location) for a road section. Each step is explained in detail in this chapter.

In chapter 4, the case study for this research is described. In this case study, the developed assessment framework is applied to a set of six road sections situated in the Dutch motorway network. In this way, the steps in the assessment framework are tested in a real-life situation. It turns out that the steps in the assessment framework works properly and that an advice can be given about the current speed limit.

Chapter 5 evaluates the assessment framework. In this evaluation, the usefulness of the assessment in practice becomes clear. It turns out that depending of the perspective the current speed limits in the Netherlands should be changed in general.

In chapter 6, the conclusions from this thesis are described. Both recommendations for practice and for further research are given as well.

2 State of the Art concerning Speed Limits

In this chapter the state of the art developments concerning speed limits are reviewed. The state of the art is used in order to reach the goal formulated in section 1.2. For developing an assessment framework, first the actual way of setting a speed limit (the applied philosophy) needs to be researched.

Since the first implementation of a speed limit of 100 km/h on the Dutch motorway network in 1974, the speed limits have been adapted several times during the years. This was done because of traffic safety issues and growing concerns for the environment (Rijkswaterstaat, 2012c). Nowadays, the Dutch government aims to implement a higher speed limit of 130 km/h, as mentioned in the introduction of this report. To achieve this speed limit increase, dynamic speed limits might be a proper measure (DVS, 2011). However, an integral approach, that takes care of both the significant factors influencing the speed limit and dynamic speed limits, is not available.

Related reports and articles will provide an answer to the issues described above. These issues are converted into sub-questions 1, 2 and 3, formulated in section 1.2:

1. What philosophies are available for an assessment framework and what are the differences between them? What perspectives are available in such a philosophy?
2. What are the significant factors that influence the speed limit and do these factors affect the speed limit?
3. How can dynamic speed limits improve traffic flow conditions, traffic safety issues and air quality?

The first section starts with an overview of existing philosophies. A philosophy is an approach that is used to determine and set a speed limit. The available perspectives for determining a speed limit are also described. Each perspective has its own viewpoint in the setting of a speed limit. Therefore the objectives belonging to the perspectives are different.

Section 2.2 makes clear how the current speed policy in the Netherlands is set-up, leading to a better understanding of the philosophy applied in the Netherlands. Furthermore, the way speed policies are applied in other countries — both in Europe and on other continents — are described. These speed policies are compared to the policy applied in the Netherlands in order to learn lessons from speed policies applied abroad.

In section 2.3 an overview is given of the significant factors that affect the speed limit. The significant factors are the factors dependent of the chosen perspective. Those factors belong to the viewpoint of the perspective and are considered in the assessment of the speed limit. Furthermore, the relation between the significant factors and the speed limit is described as well.

Section 2.4 shows what dynamic speed limits are and how they work. It becomes clear how stop-and-go waves are dissolved by varying the speed limit and consequently enlarging the capacity of the road section. The conclusions of a measure dealing with dissolving stop-and-go waves – the 'speed blanket' – are explained. Furthermore, the main conclusions of Dynamax, which aims to improve the traffic flow, traffic safety and air quality by means of the implementation of dynamic speed limits on Dutch motorways, are described in this section as well.

Finally, in section 2.5 the conclusions of this chapter are given.

2.1 Different philosophies and perspectives

Five major philosophies exist for setting a speed limit. These philosophies are described in section 2.1.1. In a philosophy a perspective is chosen. Possible perspectives are described in section 2.1.2, including the associated objectives.

2.1.1 Major philosophies for setting speed limits

Fildes et al. (2005) stated that, in general, an appropriate balance between a safe speed limit and the risk of crashing under favourable road conditions is the main principle in speed management. Except for this main principle there are more trade-offs present to deal with, such as travel time, societal attitudes, environment concerns and political considerations. As a consequence Fildes et al. (2005) formulated five major philosophies for setting a speed limit. A philosophy is an approach for determining and setting the speed limit. The five major philosophies are:

- *Engineering philosophy*. Engineering and traffic characteristics (design speed) are used as a basis of the speed limit system.
- *Driver speed choice philosophy*. With this approach the determination of a reasonable and safe travel speed is left to the drivers. Here in general the 85th percentile driving speed[1] provides the limit and both safety issues and the credibility of the maximum speed are taken into account. There are multiple

[1] 85th percentile driving speed: the speed at or below which 85 % of all vehicles are observed to travel under free flowing conditions past a nominated point (meaning the speed that is exceeded by 15 % of the person road users) (MetroCount, 2006).

factors that influence the drivers' choice of speed (see figure 2.1). However, according to Lu et al. (2003) it is difficult to quantify human factors and these factors are therefore often ignored.

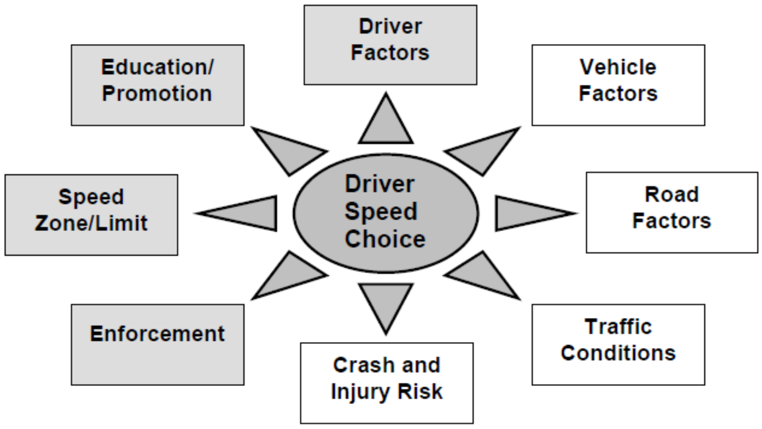


Figure 2.1: Factors affecting speed choice (Oxley and Corbon, 2002)

- *Economic optimization philosophy*. The speed limit is the speed at which the minimal total cost is realized. The costs are set to the costs associated with travel time, environmental issues (air quality and noise level) and with the number of injuries and deaths from motor vehicle accidents. A solution in this approach might be a lower speed limit, because at a lower speed limit the total costs are lower. A practical problem in this solution is the way the lower speed limit is communicated to the road user. The road user must understand why a lower speed limit is applied. A dynamic speed limit is a good option to deal with the implementation of a lower speed limit. For instance, the speed limit in densely built areas must be decreased in peak hours (because of the relatively higher intensities), so that a decrease of the pollution and the noise level can be realised.
- *Harm minimization philosophy*. This philosophy aims to limit the number of injuries and casualties on a specific road section, and the costs involved. However, it is not possible to measure life and health in terms of monetary costs. Rather a transport system is needed that does not accept fatalities as an inevitable cost of mobility.
- *Expert systems philosophy*. This is a computer program based on well-defined knowledge. It imitates an expert's thought process. Complex decision making processes for calculating speed limits are carried out. Several relevant factors (e.g. existing speed limit, land use, and accident history) serve as input for these processes.

Often a combination of philosophies is used (Aarts et al., 2008). By using a combination of philosophies, speed limits are assessed at more than one critical aspect. For instance, using a combination of an economic optimization philosophy and a harm minimization philosophy will lead to speed limits that consider both the minimization of the costs of driving and traffic safety issues.

2.1.2 Perspectives and their objectives

In section 2.1.1 five different philosophies were given. These philosophies are used in the determination of speed limits. In each philosophy a different perspective is chosen. Each perspective has its own viewpoint on the determination of a speed limit.

Elvik (2002) compared four perspectives when determining the speed limit. In this study the economic optimization philosophy for the countries of Norway and Sweden was used. In this approach Elvik (2002) determined the optimal speed limit in order to minimize the total costs on society for transport. The four applied perspectives are:

- The road authority perspective: minimizing the total cost for the whole of society;
- The road user perspective: minimizing the costs that the road user pays out of pocket. In this perspective the percentage of trucks must be incorporated in the calculation of the minimal costs, because passenger cars and trucks have a different value of time (VoT). This results in different costs;
- The taxpayer: minimizing the costs that are not subject to taxation of the use of motor vehicles;
- The residential perspective: minimizing the costs related to the residents along a road (environmental issues).

Apart from these perspectives other perspectives may be used as well. This research is carried out for Rijkswaterstaat, which is the road authority in the Netherlands. This is the reason why the road authority is chosen for this research. The mission of Rijkswaterstaat is maintaining and developing the infrastructural main networks in the Netherlands (Rijkswaterstaat, 2008). This is done in order to facilitate a good and safe traffic situation for the road user. So, the road user is also chosen as perspective in this research. However, the road user has a different objective than the road authority. The road user wants to travel as fast and cheap as possible, no matter what consequences this has for the surroundings. Furthermore, the residents along the road desire as little inconvenience as possible from the vehicles on the road. They prefer a low speed limit. A speed limit of zero (no traffic) is the ideal situation from this perspective and it is therefore not taken into account.

So, for this research only the road authority perspective and the road user perspective are considered. In table 2.1 the objectives concerning these perspectives are summarized.

Table 2.1: Objectives of the two chosen perspectives (Elvik, 2002)

Perspective	Objective
Road authority	Minimizing the costs of travel time, vehicle operating costs, road accident costs, costs of traffic noise and costs of air pollution.
Road user	Minimizing the costs of travel time and vehicle operating costs.

Table 2.1 shows the differences in the viewpoints of both perspectives. The road authority perspective (Rijkswaterstaat) considers more factors in the minimization of the total costs. The road user perspective includes those costs that can reasonably be assumed to be completely internalized by the road user in his or her choice of speed (Elvik, 2002). The road authority perspective considers also accident costs and environmental issues. The vehicle operating costs – which describe the costs of running a vehicle (Robertson and Ward, 1998) – and the costs of travel time are taken into account as well. As mentioned before, Rijkswaterstaat strives for a good traffic situation for the road user.

2.2 Current speed policies

There are several studies available that describe the set-up of speed policies in different countries. In section 2.2.1 the current speed policy in the Netherlands is described. It becomes clear how the speed policy in the Netherlands is built-up. Section 2.2.2 explains how the speed policy abroad is set-up. And lastly, section 2.2.3 features a comparison between the Dutch speed policy and speed policies abroad.

2.2.1 Current speed policy in the Netherlands

Aarts and Van Nes (2007) and Aarts et al. (2008) explain that current speed limits are set using a combination of the driver speed choice philosophy and the economical optimization philosophy. At the end of the eighties the speed limit on Dutch motorways was increased from 100 km/h to 120 km/h. This was done because of the desire to harmonize the vehicle speeds (so on behalf of the drivers speed choice philosophy). Recently speed limits were reduced to 100 km/h and in some cases even to 80 km/h. Environmental issues became more and more important in these cases which resulted in an economic optimization approach. Summarized the following principles are applied nowadays on Dutch motorways (DVS, 2011):

- 120 km/h if possible (on 80 % of the Dutch motorway network);
- 100 km/h when necessary because of traffic safety and environment issues (on 18 % of Dutch motorway network);
- 80 km/h as exception for the local air quality (on 2 % of the Dutch motorway network).

These principles are shown in figure 2.2.

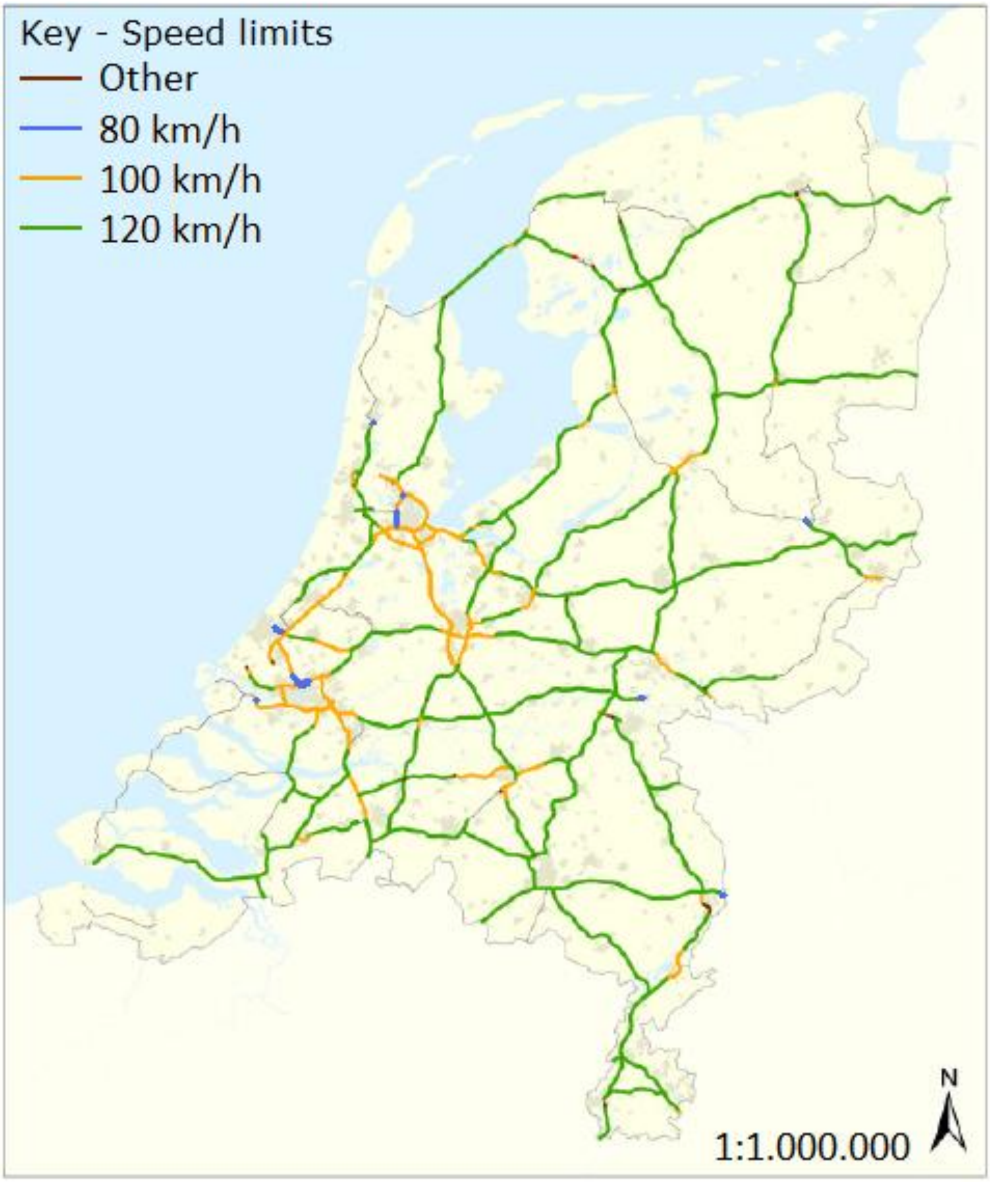


Figure 2.2: Current speed limits on Dutch Motorways (NIS, 2010)

Credibility of current speed limits on Dutch motorways

In practice it is important that speed limits correspond with the expectations of the road user. This complies with the Sustainable Safety vision which represents the current traffic safety policy in the Netherlands (Aarts and Wegman, 2005). Expectations of the road user are satisfied when a speed limit is credible. Aarts and Van Nes (2007) defined the credibility of a speed limit as follows: a speed limit is experienced as credible by the road user when a speed limit fits the road design and the current traffic circumstances. This means the speed limit which is expected when looking at the bare road, without signs or other explicit information about the applied rules. Van Nes et al. (2007) show that when a speed limit is experienced as 'too low' (and thus as less credible), road users tend to keep less to the speed limit. An example of experiencing a speed limit as 'too low' is when the speed limit is decreased because of environmental issues. When this motivation does not become clear to the road user, the decrease of the speed limit is not recognized. As a consequence, a relatively large amount of road users will exceed that speed limit. In order to cope with the credibility of speed limits, the speed limit can be increased during the off-peak hours of the day (dynamic speed limits). Another possibility is strict enforcement of the decreased speed limit. However, enforcement is out of the scope of this research.

Assessment framework used nowadays in the Netherlands

Aarts et al. (2008) mentioned that the approach of the speed limit system in the Netherlands — which is one of the world's safest countries concerning road casualties — is mainly based on harm minimization. This is applied in engineering measures, which means that the road layout is optimised for the least possible fatalities and injuries in the traffic system. In other words, due to the road layout it is possible to estimate a dangerous situation and as a result the applied speed limit can be adapted on the particular situation. This concept is known as the 'Sustainable Safety vision' which is internationally known as an appropriate example (Aarts and Wegman, 2005).

Apart from this harm minimization philosophy, the economic optimization philosophy is also taken into account (with a higher weight for safety issues). However, in the Netherlands only some general rules are applied to determine a safe speed limit (Aarts et al., 2008). As mentioned in chapter 1, there is no decision support instrument for speed management available yet. Figure 2.3 shows how a safe speed limit is defined for roads in the Netherlands with only a flow function (motorways where a higher speed is applied because of the absence of crossing traffic and/or pedestrians/bicycles). This flow chart depends only on the legal traffic situation and road design details. The reason why a general fit between fixed conditions of the road and the posted speed limit is used rather than actual accident data to define safety levels, is that accidents are relatively rare (Aarts et al., 2008). It would take many years of data collection to have sufficient data. The problem here is that the situation must be unchanged during this collection time and that is hard to reach (or even impossible).

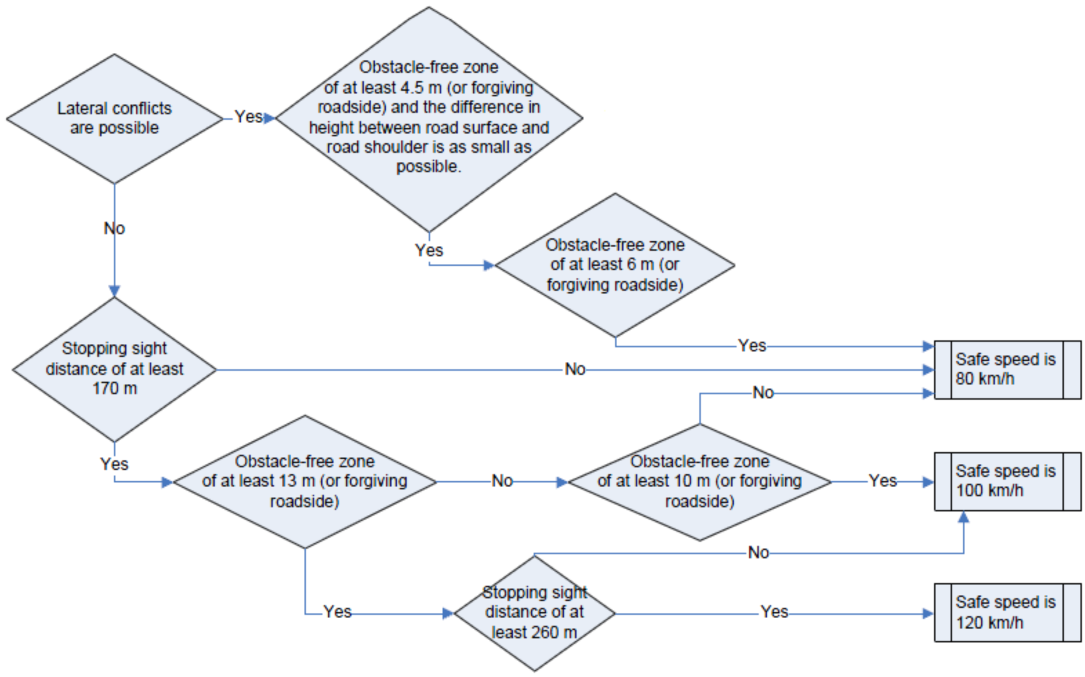


Figure 2.3: The last part of the detailed algorithm used in the Netherlands (Aarts et al., 2008)

Ambition: increasing the speed limit on Dutch motorways to 130 km/h

In relation with the credibility of the speed limits the Ministry of Infrastructure of Environment proposed a new speed management policy for the Netherlands. On November 28th, 2011, a letter to the Dutch parliament was sent. The general idea of this proposal is increasing the speed limit on Dutch motorways to 130 km/h. When this increasing is not permanently possible, a dynamic speed limit might be a solution. Generally the motto in this proposal is *faster if possible, slower when necessary*, where credibility towards the road user plays a leading role (as mentioned in the introduction of this report). In section 2.4, dynamic speed limits are described in more detail.

2.2.2 Speed policies abroad

At this moment a lot of research is being carried out all over the world concerning the speed limit policies. For instance, in 1995 the 104th Congress of the United States intended to repeal the National Maximum Speed Limit (NMSL) in the USA. Dougherty (2000) described that in 1995 many states, such as Georgia and Montana, rushed to increase the speed limits within their borders. One of the reasons for this increase — despite the concerns for the relationship between a higher vehicle speed and the safety on the highway — was the popularity of this increase. It was believed that a speed limit of 65 m/h (which equals to 105 km/h) is too restrictive and thereby affected peoples' lives by making the trip by car unnecessarily long.

This example makes clear that the speed policy is subject to many considerations. It turns out that countries use their own approach to set a speed limit. Fildes et al.

(2005) formulated the five major philosophies (section 2.1.1) used in different countries for the speed policy. In table 2.2 an overview of these five major philosophies applied in different countries is given, that is set-up by Fildes et al. (2005).

Table 2.2: Different applied philosophies in different countries

Country	Applied philosophy	Short description
United States (Fildes et al., 2005)	Driver speed choice	The speed limit is based on the speed limit a road user intends to drive.
New Zealand (Fildes et al., 2005)	Engineering	The speed limit is based on the level of the roadside development/road geometry.
Australia (Fildes et al., 2005)	Economic optimization	Variations in speeds and thus in travel time, vehicle operating costs and trauma costs are used to estimate optimal speed limits.
Australasian countries[2] (Fildes et al., 2005)	Expert system	A comprehensive range of road environment and driving condition factors is taking into account, incorporated into the 'expert' computer system series for setting speed limits.
Germany (Abraham, 2001)	Driver speed choice	Road users can choose their preferred speed limit. However, a recommended speed limit of 130 km/h is applied.
	Engineering	The speed limit is lowered at for instance dangerous curves.
France (OECD, 2006)	Engineering	There is a speed limit of 130 possible looking to the road geometry. During rainy conditions the speed limit is lowered to 100 km/h.
Sweden (Fildes et al., 2005)	Economic optimization	Setting monetary values to all costs of the factors involved at the determination of the speed limit; the optimal speed limit is the speed limit with the minimal total costs.
	Harm minimization	Vision Zero: striving for a speed limit that minimize the deaths and injuries in the traffic system.

[2] Australasian countries: region of Oceania comprising Australia, New Zealand, the island of New Guinea, and neighbouring islands in the Pacific Ocean.

[3] Australasian countries: region of Oceania comprising Australia, New Zealand, the island of New

Table 2.2 shows that countries often apply more than one philosophy. Thereby, the different philosophies have some overlaps and may share common factors as well. For example, in Sweden a combination of the harm minimization philosophy and the economic optimization philosophy is applied. In both philosophies safety measures and effects have an important weight (Aarts et al., 2008).

Furthermore, it needs to be recognized that there are numerous other philosophies and strategies for determining and setting speed limits than the five major philosophies mentioned by Fildes et al. (2005).

2.2.3 Comparison of speed policies abroad with the Netherlands

In table 2.3 an overview of the philosophies followed in different countries is shown. As said before, often a combination of philosophies is used. In the Netherlands this is the case as well.

Table 2.3: Different applied philosophies in different countries

Source	Country	Applied philosophy
(Fildes et al., 2005)	Netherlands	Engineering and harm minimization (Sustainable Safety)
(Fildes et al., 2005)	Sweden	Economic optimization and harm minimization (vision zero)
(Abraham, 2001)	Germany	Driver speed choice and engineering
(OECD, 2006)	France	Engineering
(Fildes et al., 2005)	United States	Driver speed choice
	New Zealand	Engineering
	Australia	Economic optimization
	Australasian countries[3]	Expert system

As is stated in section 2.2.1, the economic optimization philosophy is taken into account in the Netherlands, because safety issues have a higher priority. However, since this philosophy is not yet available in terms of a decision support instrument, it is not mentioned under the Netherlands in table 2.3.

An integral approach for setting the speed limit on Dutch motorways

In the problem definition of this research it is stated that, at this moment, an integral approach for setting the speed limit on Dutch motorways — which takes travel time, environmental targets, traffic safety issues and flow conditions into account — is not

[3] Australasian countries: region of Oceania comprising Australia, New Zealand, the island of New Guinea, and neighbouring islands in the Pacific Ocean.

available. The economic optimization philosophy is a proper way to deal with this problem, because in this philosophy factors like travel time, environmental targets, traffic safety issues and flow conditions are used to determine the optimal speed limit. Furthermore, the engineering philosophy takes care of the fact that the determined optimal speed limit is possible due to the road layout. For instance, it is possible that a relatively high optimal speed limit is determined. The question is whether or not this speed limit is still safe in the specific road layout.

When applying an economic optimization philosophy, more targets are considered in setting the speed limit. Wismans et al. (2011) performed a study on this. In the study the accessibility is plotted against four targets:

- Air quality (NO_x-emissions);
- Climate (CO_2-emissions);
- Traffic safety (number of accidents);
- Noise nuisance (noise emissions).

These relations are optimized, which results in Pareto optimal solutions. From these solutions one solution is chosen using for instance a form of multi criteria analysis[4]. Wismans et al. (2011) mention that there is not one solution which optimizes all targets on a linear line at the same time. This means that when for instance the accessibility is improved by increasing the speed limit, the air quality becomes worse. This principle gives information about the trade-offs (for instance when saving NO_x-emissions will result in longer travel times at lower speeds).

As mentioned in section 2.1.2, Elvik (2002) determined the optimal speed limit for Sweden using the economic optimization philosophy. In this research, the study of Elvik (2002) is used as inspiration to perform the economic optimization philosophy for the Netherlands. The results of the study are surprising and therefore interesting to use for the Netherlands as well. In appendix B the results of the study of Elvik (2002) are described. Furthermore, according to Fildes et al. (2005), there are many parallels between the speed policy in the Netherlands and the speed policy in Sweden. These speed policies are respectively called 'Swedish Vision Zero' and 'Dutch Sustainable Safety.' Both countries describe the setting of a speed limit as part of the overall harm minimization philosophy.

[4] In multi criteria analysis monetary and non-monetary information within alternative choice possibilities are used, to support decision processes in plans and projects; it is then possible to order the different alternatives and create a maximum scale differentiation for the decision-maker (Verhaeghe, 2009).

2.3 Significant factors affecting speed limits

This section presents different studies that indentify the factors that affect the speed limit (Aarts et al., 2007; Elvik, 2002; Fildes et al., 2005; Srinivasan et al., 2006). In section 2.3.1 an overview of factors affecting the speed limit is given. This overview is used for the selection of the significant factors as is applied in this research (section 2.3.2). Finally, in section 2.3.3 the relations between the significant factors and the speed limit are described.

2.3.1 Factors affecting the speed limit

In section 2.1.1 the five major existing philosophies for setting the speed limit are given. These philosophies each use their own factors that affect the speed limit. For the countries that Fildes et al. (2005) use to explain the five philosophies (see table 2.2), the factors that affect the speed limit are set out in this section. In table 2.4 an overview of the factors belonging to the specific philosophies is shown. In this way the differences and similarities between the philosophies and their factors become clear. For instance, the engineering philosophy and the economic optimization philosophy use completely different factors. Even though there are similarities between the engineering philosophy and the driver speed choice philosophy (both consider the roadway geometrics).

Table 2.4: Overview of factors affecting the speed limit per source

Country	Applied philosophy	Factors affecting the speed limit
Netherlands (Aarts and Van Nes, 2007)	Engineering and harm minimization	Crash statistics, operating speeds, the intensity, traffic composition and roadway geometrics
Sweden (Elvik, 2002)	Economic optimization and harm minimization	Travel time, vehicle operating costs, crash statistics, traffic noise and air pollution
United States (Srinivasan et al., 2006)	Driver speed choice	Operating speeds, roadway geometrics, cross-section (includes clear zones), crash statistics and major intersections/interchange spacing
Australasian countries (Fildes et al., 2005)	Expert system	Road characteristics, density of the roadside development, number and type of junctions, road function, traffic volume, adjoining speed limits and crash rates

As is explained in section 2.1.2, each philosophy contains different perspectives. These perspectives interpret the factors shown in table 2.4 all on a different way. For instance, in the engineering philosophy a road user – who prefers a short travel time –

wants to drive on straight roads with fewer delays. On the other hand, the road authority aims to have a safe traffic system. This results in a curved alignment of the road in order to reduce the speed of the road users.

2.3.2 Significant factors

Table 2.4 shows that each philosophy uses different factors that affect the speed limit. For this thesis, the economic optimization philosophy is used (see section 2.2.3). The results of the study of Elvik (2002) are used as inspiration for this thesis. In appendix B it is explained why this study is interesting.

As explained in the introduction of this report, the significant factors are the factors dependent on the chosen perspective. For this research the road authority perspective and the road user perspective are used to determine the optimal speed limit. In table 2.1 the objectives of both perspectives are shown. The road user considers travel time and vehicle operating costs: travelling as fast and as cheap as possible. For the road authority, more factors are considered. The road authority wants to facilitate a safe and good traffic situation for the road user. So, except traffic safety issues, also extern effects of driving vehicles are considered, like traffic noise and air pollution. CO_2-emissions are not considered. For CO_2-emissions the whole network is considered (Burgmeijer et al., 2010). In this research a road section is assessed, so CO_2 is not used in this research. That gives the following significant factors for the economic optimization philosophy applied in this research:

1. Travel time;
2. Vehicle operating costs;
3. Road accidents;
4. Traffic noise;
5. Air pollution.

The relation between the speed limit and these significant factors result in Pareto optimal solutions. As mentioned before, there is not one solution which optimizes all of the significant factors on a linear line at the same time. For this research, the optimal speed limit is determined which results in the lowest total costs.

2.3.3 Relation between the significant factors and the speed limit

For the economic optimization philosophy the significant factors mentioned in section 2.3.2 are expressed in costs. These costs are expressed as a function of the speed limit. For instance, the higher the speed limit, the higher the cost of traffic noise. In table 2.5 the relations between the five significant factors mentioned in section 2.3.2 and the speed are given. Below these relations are briefly described per significant factor.

Costs of travel time

When a road user is travelling on the road, it is desired to have a short travel time. There is a certain value given to the time needed for travelling (Value of Time, VoT). This means that when a road user has a low speed, it takes more time to travel the distance. Thus, the costs are high at low speeds. When the speed increases, it takes less time to travel a certain distance, which results in lower costs at higher speed (Vermeulen et al., 2004).

Note that at higher speeds the chance of turbulence in the traffic flow is higher (in terms of traffic breakdowns). These breakdowns leads to congestion and thus to higher costs due to time losses. To deal with this dynamic speed limits are applied. Section 2.4 will explain the relation between dynamic speed limits and congestion more in detail.

Vehicle operating costs

The vehicle operating costs describe the costs of running a vehicle (Robertson and Ward, 1998). The costs of running a vehicle are related to the fuel consumption of a vehicle. At low speeds the fuel consumption is high. The engine performance is not optimal at low speeds. In general, the costs related to fuel consumption tend to reach a minimum around 70 km/h (Elvik, 2002). When the speed increases, the air resistance grows, which results in more fuel consumption. Consequently, this results in higher costs (Robertson and Ward, 1998).

Road accident costs

At low speeds, the chance of an accident is relatively small (Aarts, 2004). In case an accident occurs, the consequences are relatively small. When the speed increases, the consequences of an accident become more severe (a higher chance on fatalities). Both a fatality and a seriously injured person can be expressed in monetary values. Here the costs of a fatality are far higher than the costs of an injured person (Witteveen+Bos, 2011):

- Costs of fatality: 2.690.108 euro;
- Costs of injured person: 276.568 euro.

So, at high speeds, these costs are larger compared to low speeds.

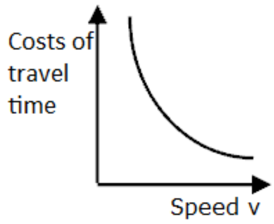
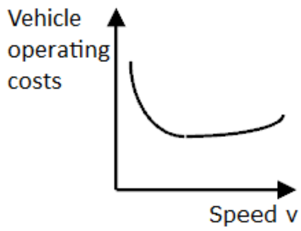
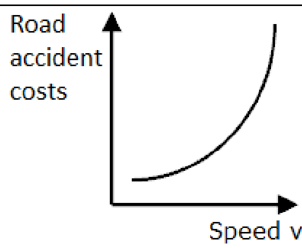
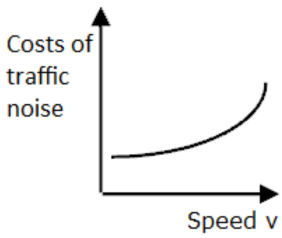
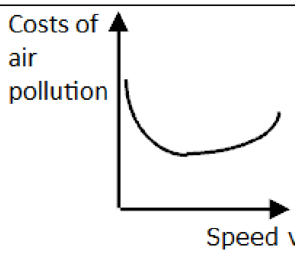
Costs of traffic noise

When vehicles travel at low speeds, the noise emissions are relatively low. At higher speeds, the noise production becomes higher. The vehicles on the road produce more noise because of the engine running more intensely at high speeds. Also, the tires of the vehicles produce more noise at high speeds due to the contact with the road surface (Florentina, 2008).

Costs of air pollution

The costs of air pollution are closely related to the vehicle operating costs. Elvik (2002) states that these costs tend to vary the same way vehicle operating costs do, reaching a minimum for the speed at which fuel consumption reaches its minimum (around 70 km/h). At low speeds, the engine of a vehicle does not perform optimally, which results in more pollution and thus in relatively high costs. When the speed increases, the air resistance grows, which results in more fuel consumption. And, just as the vehicle operating costs, the costs are higher at higher speeds (Robertson and Ward, 1998).

Table 2.5: Relation between the significant factors and the speed limit (Elvik, 2002)

Significant factor	Definition	Relation with speed
1. Costs of travel time	Costs related to the travel time → these costs falls monotonously as speed increases	
2. Vehicle operating costs	Costs related to fuel consumption → these costs are higher at very low speeds than at very high speeds (more efficient at higher speeds)	
3. Road accident costs	Costs that represents the fatality or the injury: monetary valuation of lost quality of life (pain, suffering). → these costs will increase exponentially as speed increases	
4. Costs of traffic noise	Costs related to the noise of traffic, specified to area (urban, natural) and type of vehicle (small, heavy). → these costs increases as speed increases	
5. Costs of air pollution	Costs related to emission, for highways only NO_2 and PM_{10} (DVS, 2011). → these costs falls in first instance, till a minimum, at higher speeds these costs increases	

2.4 Dynamic speed limits

Dynamic speed limits are a measure to harmonize the traffic flow at high volumes and hence influence the motorway capacity. Section 2.4.1 explains the effects of dynamic speed limits on traffic flow. The breakdown prevention approach and the homogenization approach are explained in section 2.4.2 and section 2.4.3 respectively. Furthermore, section 2.4.4 describes the effects of a speed limit measure on the traffic flow applied in the Netherlands: the 'speed blanket' ('snelheidsdeken'). Finally, the main conclusions of Dynamax, which aims to improve the traffic flow, traffic safety and air quality by means of the implementation of dynamic speed limits on Dutch motorways, are shown in section 2.4.5.

2.4.1 Effects of dynamic speed limits on traffic flow

Dynamic speed limits are a control measure for traffic flow on motorways. It takes care of the local circumstances, like weather conditions, environmental issues and traffic volumes (Schreuder, 2009). In the Netherlands, several tests are carried out to investigate the application of dynamic speed limits. For instance, because of the low level of air quality, the speed limit is reduced during peak hours (when the pollution is high due to the high number of vehicles on the road). Or the speed limit is reduced in case of bad weather conditions (because of the traffic safety). These measures are worked out in Dynamax. Dynamax is further explained in section 2.4.5.

For the development of the assessment framework, it is more relevant to recognize the effects of dynamic speed limits on the traffic state. Possible traffic states are: free flow, congested area and the transition phase in between (Hegyi et al., 2005). Dynamic speed limits are a proper measure to influence the traffic state. For instance, it is common that when a lot of vehicles are on a road section (a high density), vehicles use different speeds. As a result, faster driving vehicles have to brake for slower driving vehicles. This might result in dangerous situations (i.e. increased lane switching or a lot of braking which may result in head-on collisions). Dynamic speed limits can homogenize the speeds in order to reduce the speed differences between vehicles (Hegyi et al., 2005).

Except homogenizing speeds between vehicles, dynamic speed limits can dissolve stop-and-go waves in dense traffic. Herty and Illner (2007) explain that when a vehicle is driving on the motorway, following a seemingly endless line of cars, it is possible that the vehicle has to brake because a vehicle in front of him brakes as well for a certain reason. After a while, all vehicles accelerate to the origin speed limit again. For the road users, it is not clear why they had to brake. This phenomenon is called a stop-and-go wave. To illustrate a stop-and-go wave, the phenomenon is shown in figure 2.4.

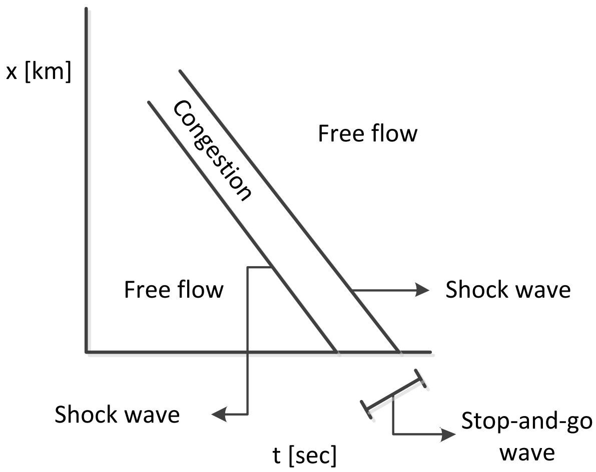


Figure 2.4: Stop-and-go wave in an x-t-diagram (Herty and Illner, 2007)

In figure 2.4 the location is shown on the vertical axis. The time is on the horizontal axis. Furthermore, the traffic states are indicated: the free flow states and the congestion area. It turns out that the stop-and-go wave is bordered by two shock waves. A shock wave is the border between two traffic states (Hegyi et al., 2005).

In order to describe how dynamic speed limits can dissolve stop-and-go waves, the traffic flow states described before are announced in terms of stable, metastable, and unstable traffic flow states (Hegyi et al., 2005). In case of a stable traffic flow state, any disturbances will vanish without any intervention. In the metastable state both free-flow traffic and a shock wave can remain existent for a long time. Small disturbances will vanish, but large disturbances will create a shock wave. And in case of an unstable state any disturbance will create a shock wave. When the goal is to dissolve a stop-and-go wave using dynamic speed limits, the traffic flow must be in the metastable state. Hegyi et al. (2005) explains that in the stable state a disturbance will disappear without control and in the unstable state any dynamic speed limit will create a new stop-and-go wave. In the metastable state the dynamic speed limit is able to spread out the stop-and-go wave into a disturbance that is small enough to vanish automatically.

The three states of a traffic flow (stable, metastable and unstable) can be indicated in the fundamental diagrams in figure 2.5. This is done in order to understand what happens with the intensity and the density of a flow when the speed limit changes. The fundamental diagram gives the relations between the macroscopic characteristics of a flow (Hoogendoorn, 2007):

- Speed u [km/h];
- Density k [veh/km]
- Volume q [veh/h].

The stable state is the part of q with a constant speed (between point A and B). This is the free flow state. As soon as speed decreases with increasing density, the unstable state is reached (between point B and C). The metastable state is somewhere in between of these two parts (point B).

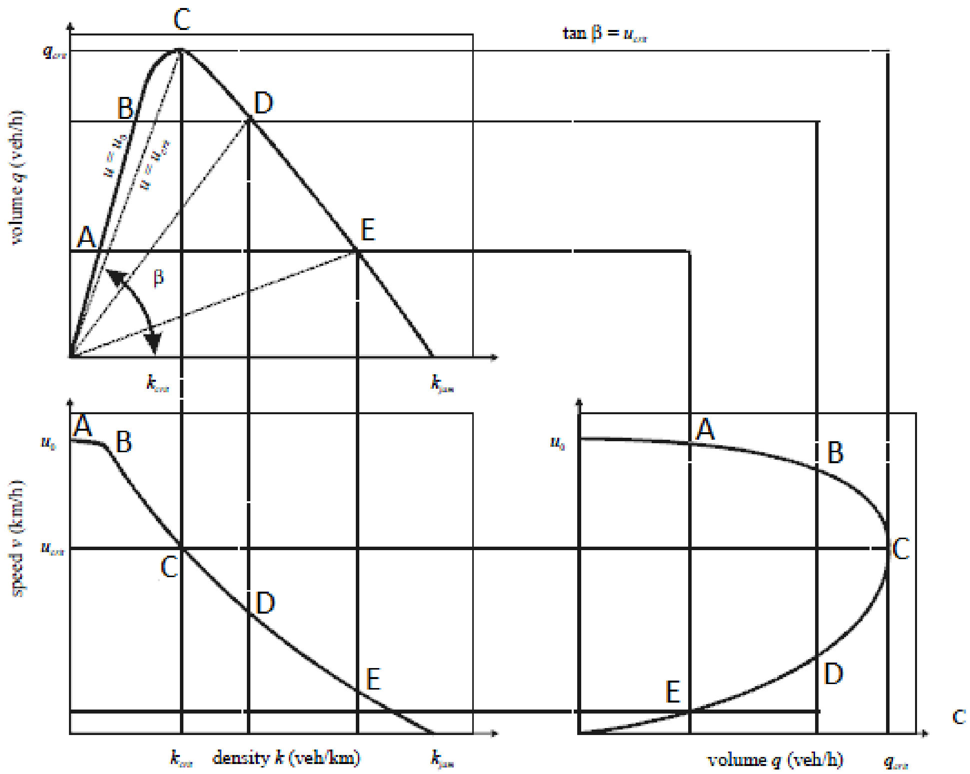


Figure 2.5: Fundamental diagrams of traffic behavior (Hoogendoorn, 2007)

When the density on a road section grows, the critical density will be reached after some time. Shock waves will occur, which will lead to lower speeds. When the mean speeds drop more, the volume will also decrease. This results in congestion. In order to deal with this, dynamic speed limits lower the speed limit in advance. The metastable state is reached and the shock wave will disappear automatically (Hegyi et al., 2005).

2.4.2 Breakdown prevention approach

In section 2.4.1, the presence of a stop-and-go wave is explained. In order to dissolve this phenomenon, the breakdown prevention approach can be applied. This approach uses a speed limit decrease in order to reduce the inflow to the jammed area (Hegyi et al., 2005). This speed limit is applied upstream of a shock wave. When the inflow is reduced to a lower value than its outflow, the jam will eventually dissolve. As a consequence, more vehicles can pass, which leads to more capacity during the peak hours (at a lower speed limit).

Hence, the breakdown prevention approach focuses on too high densities. This approach allows speed limits that are lower than the critical speed (speed at which the capacity of the road section is reached) in order to limit the inflow to the jammed area (Hegyi et al., 2005).

2.4.3 Homogenization approach

The homogenization approach can only increase the time to a breakdown (Hegyi et al., 2005). A lower speed limit will reduce the speed differences between vehicles, by which a more stable (and safer) flow can be achieved. At this approach the speed limit is above the critical speed (i.e. the speed that corresponds to the maximal flow; point C in figure 2.4). The lower speed limit will not limit the traffic flow, but only slightly reduce the average speed (and slightly increase the density) (Hegyi et al., 2005).

2.4.4 Speed blanket

Hoogendoorn and Daamen (2008) have performed a study investigating so called 'speed blankets' ('snelheidsdeken') applied in the Netherlands. A speed blanket is a measure which aims to postpone congestion by reducing the speed limit. The main goal in this measure is homogenizing the traffic flow (the homogenization approach). The measure consists of a speed limit (speed blanket) of 70 km/h and a speed limit of 90 km/h. The measure is implemented by three switch mechanism: fixed time slots, speed triggers and intensity triggers.

Hoogendoorn and Daamen (2008) concluded that the speed blankets of 70 km/h and 90 km/h do not result in clear different results for different tested sections. Despite the increase of the capacity on some sections due to the speed blanket, Hoogendoorn and Daamen (2008) have not found any evidence for this. However, for the switch mechanisms it is found that – in case of the aim to set a speed blanket before the congestion appears – intensity triggers and fixed time slots are switched on time.

2.4.5 Dynamax

In 2009 and 2010 Dynamax[5] was carried out in the Netherlands. The goal of Dynamax is using an extended set of data to evaluate how the behavior of road users changes due to dynamic speed limits and how the effects are on traffic flow, traffic safety and air quality (Wilmink and Schreuder, 2011). In Dynamax, for each aspect (traffic flow, traffic safety and air quality) the goals are formulated in relation to the dynamic speed limit. These goals are explained in table 2.6.

Furthermore, in Dynamax an approach is tested to eliminate shock waves on motorways, the so-called SPECIALIST-algorithm[6] (Hegyi and Hoogendoorn, 2011). This algorithm is applied on the second goal formulated in table 2.6: solving stop-and-

[5] Dynamax stands for (in Dutch): 'DYNAmische MAXimum snelheidslimieten'

[6] SPECIALIST = SPEed ControllIng Algorithm using Shock wave Theory

go waves. The content of this algorithm is based on the breakdown prevention approach, described in section 2.4.2. Hegyi and Hoogendoorn (2011) conclude after the test that it is in practice possible to limit the inflow of a traffic jam by dynamic speed limits while keeping the traffic flow stable.

Table 2.6: The goals formulated by Dynamax (Wilmink and Schreuder, 2011)

Goal of dynamic speed limit	Short description
Traffic flow → reducing travel times	The speed limit is increased in case of low intensities (off-peak hours, for instance late in the evening) from 100 km/h to 120 km/h
Traffic flow → solving stop-and-go waves	The speed limit is reduced from 120 km/h to 60 km/h when a solvable shock wave is detected (see section 2.4.1)
Environment → improving the air quality	The speed limit is reduced from 120 km/h to 80 km/h when the concentration of particulate matter (PM_{10}) almost reaches the critical value
Increasing the traffic safety	At rainy conditions the speed limit is reduced from 120 km/h to 100 km/h or even to 80 km/h

After Dynamax was finished, Wilmink and Schreuder (2011) concluded that the experiments provide the expected results. The goals stated in figure 2.6 are reached. So, dynamic speed limits are a proper measure to deal with changing circumstances (traffic flow, weather conditions and air quality) and thus can be used in order to vary a permanent speed limit due to the traffic flow, weather conditions and the air quality.

2.5 Conclusion

This chapter provides a literature review on the state of the art developments concerning speed limits. It turns out that there are several approaches available for setting speed limits. In this research, the engineering philosophy and the economic optimization philosophy are used. In each philosophy a different perspective is chosen. Each perspective has its own viewpoint in the determination of a speed limit. Examples of a perspective are the road authority or the road user. In the determination of a speed limit, significant factors are considered. The significant factors are the factors dependent of the chosen perspective. For this research, the significant factors are: travel time, vehicle operating costs, road accidents, traffic noise and air pollution.

Furthermore, dynamic speed limits are a control measure for traffic flow. By applying dynamic speed limits, two approaches can be applied: breakdown prevention approach (dissolving stop-and-go waves) or the homogenization approach (making the traffic flow more stable). Besides these approaches, the results of the project Dynamax can be used in order to deal with location and time dependent circumstances.

For most countries, the speed limit is set to minimize the number of accidents. When the number of vehicles on the road increases, the chance of an accident increases as well and thus the speed limit is reduced. In the Netherlands, only some general rules are applied. These rules make sure that driving with that speed limit is safe under the prevailing conditions. An integral approach for setting the speed limit — which takes for example travel time, environmental targets, traffic safety issues and flow conditions into account — is not available. In order to develop an integral approach, a combination of the engineering- and the economic optimization philosophy is chosen. The economic optimization philosophy takes care of the significant factors. And the engineering philosophy takes care of the fact that the determined optimal speed limit is possible under the actual road geometry.

Finally, in the next chapter the assessment framework is developed. The assessment framework is based on the chosen philosophies, perspectives and in relation with that the significant factors. This developed assessment framework is tested in a case study described in chapter 4.

3 Development of the Assessment Framework

The *goal* of this research is to develop an assessment framework, regardless of the chosen perspective, for determining the optimal speed limit for a road section on Dutch motorways, taking the local conditions and targets into account. In chapter 2 it was explained what philosophies are used in the development of the assessment framework: the engineering philosophy (considering the roadway geometry) and the economic optimization philosophy (determining the optimal speed limit). The motivation of the applied perspectives in this research, including the significant factors, was also given in this chapter.

This chapter describes the development of the assessment framework for speed limits on Dutch motorways. The structure of the assessment framework is based on the state of the art developments presented in chapter 2. The assessment framework is applied in chapter 4 for six existing road sections of the Dutch motorway network.

This chapter starts with the explanation of the structure of the assessment framework (section 3.1). The three steps in the assessment framework are described briefly. First, section 3.2 explains step 1. In this section, the engineering philosophy is described. Second, step 2 is explained in section 3.3. It becomes clear how the optimal speed limit is determined. Section 3.4 describes how the result of step 1 and step 2 looks like. In section 3.5, the input data for step 1 and step 2 is described. For both steps, a list of required data is given. In section 3.6, the last step of the assessment framework is explained: step 3. In this step, a comparison between the current speed limit and the determined optimal speed limit is made. Finally, the conclusions are given in section 3.7.

3.1 Structure of the assessment framework

This section explains how the structure of the assessment framework is built up. First, in section 3.1.1 it is described why an assessment framework is developed. In respectively section 3.1.2 and section 3.1.3 the choice for applying both the economic optimization philosophy and the engineering philosophy in the assessment framework is explained. Finally, section 3.1.4 describes how the last step in the assessment framework (step 3: comparison between the current speed limit and the optimal speed limit) works.

3.1.1 Reason for an assessment framework

In the problem definition of this report it is stated that an integral approach for setting the speed limit on Dutch motorways is not yet available. In an integral approach all significant factors[7] are considered in the determination of the speed limit. At this moment only some general rules are applied to determine a safe speed limit in the Netherlands (Aarts et al., 2008). The approach of the speed limit system is mainly based on harm minimization, which is applied in engineering measures. This means that it can be estimated by the road layout where a dangerous situation will occur. As a consequence, the speed limit is adapted on that particular road section.

Apart from this harm minimization philosophy, the economic optimization philosophy is also taken into account (with a higher priority for safety issues). However, in the Netherlands there is no decision support instrument for speed management available yet (Aarts et al., 2008).

3.1.2 Optimal speed limit

In order to develop an integral approach for setting the speed limit in the Netherlands, the economic optimization philosophy is a proper way to use in the assessment framework. In this philosophy the optimal speed limit is determined as the speed limit with the lowest total costs for society. The total costs are dependent of the significant factors (Elvik, 2002):

1. Travel time;
2. Vehicle operating costs;
3. Road accidents;
4. Traffic noise;
5. Air pollution.

Except for the vehicle operating costs (which are already expressed as such), these factors are converted into monetary values. This is explained later in this chapter. In this way the optimal speed limit is determined for a specific road section.

3.1.3 Engineering measures

In chapter 2 it has been explained that in the Netherlands the harm minimization approach is applied. Aarts and Wegman (2005) mentioned that this principle is known as the 'Sustainable Safety vision' which is internationally known as an appropriate example. This vision is applied in engineering measures (the engineering philosophy). So, this philosophy needs to be used in order to make sure that the determined optimal speed limit in the economic optimization philosophy is not so high that it becomes relatively unsafe for the particular road section (Fildes et al., 2005).

In concluding, the engineering- and the economic optimization philosophy function as the two steps in the developed assessment framework. First, the engineering philosophy is applied in order to determine the maximum possible speed limit on a

[7] Significant factors: factors dependent of the chosen perspective when determining a speed limit (for this research: the road authority- and the road user-perspective are chosen)

road section due to the road layout (step 1). This speed limit functions as the upper limit of the road section. Secondly, the economic optimization philosophy is applied in order to determine the optimal speed limit (step 2). This is the speed limit with the lowest total cost for society, considering the significant factors.

In figure 3.1 the structure of the developed assessment framework is shown. After gathering the relevant input data, step 1 and step 2 are implemented:

- Step 1: the engineering philosophy: determining the maximum speed limit on a road section due to the road layout;
- Step 2: the economic optimization philosophy: determining the optimal speed limit with the lowest total costs for society, considering the significant factors.

These two steps are explained in section 3.2 and section 3.3 respectively.

3.1.4 Comparison between the current speed limit and the determined optimal speed limit (step 3)

Step 1 and step 2 lead to an optimal speed limit, which belongs to the chosen perspective (the road authority or the road user). The determined optimal speed limit is compared to the current speed limit (step 3). This comparison leads to one of the following permanent results (speed limit applied during the whole day):

- Decreasing the current speed limit to the optimal speed limit;
- No change in the current speed limit;
- Increasing the current speed limit to the optimal speed limit.

Depending on traffic flow conditions (v/c-ratio)[8], a dynamic speed limit is applied. During peak hours, when traffic flow becomes sensitive to small disturbances that lead to breakdowns, a lower speed limit functions as a proper measure to deal with breakdowns. In section 2.4, two measures are described: reduction of the speed limit at below-critical densities (breakdown prevention approach) and homogenization of speeds (homogenization approach). The user of the assessment framework chooses the preferred measure: either solving the stop-and-go waves or homogenizing the traffic flow.

Furthermore, Dynamax – as described in section 2.4.5 – provides dynamic speed limits depending on traffic flow, weather conditions or air quality. For each permanent result, these dynamic speed limits might be used.

In section 3.6, the third step of the assessment (the comparison between the current speed limit and the determined optimal speed limit) is explained more in detail.

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[8] v/c-ratio = volume/capacity-ratio (indicator for the quality of the traffic flow) (Board, 1985)

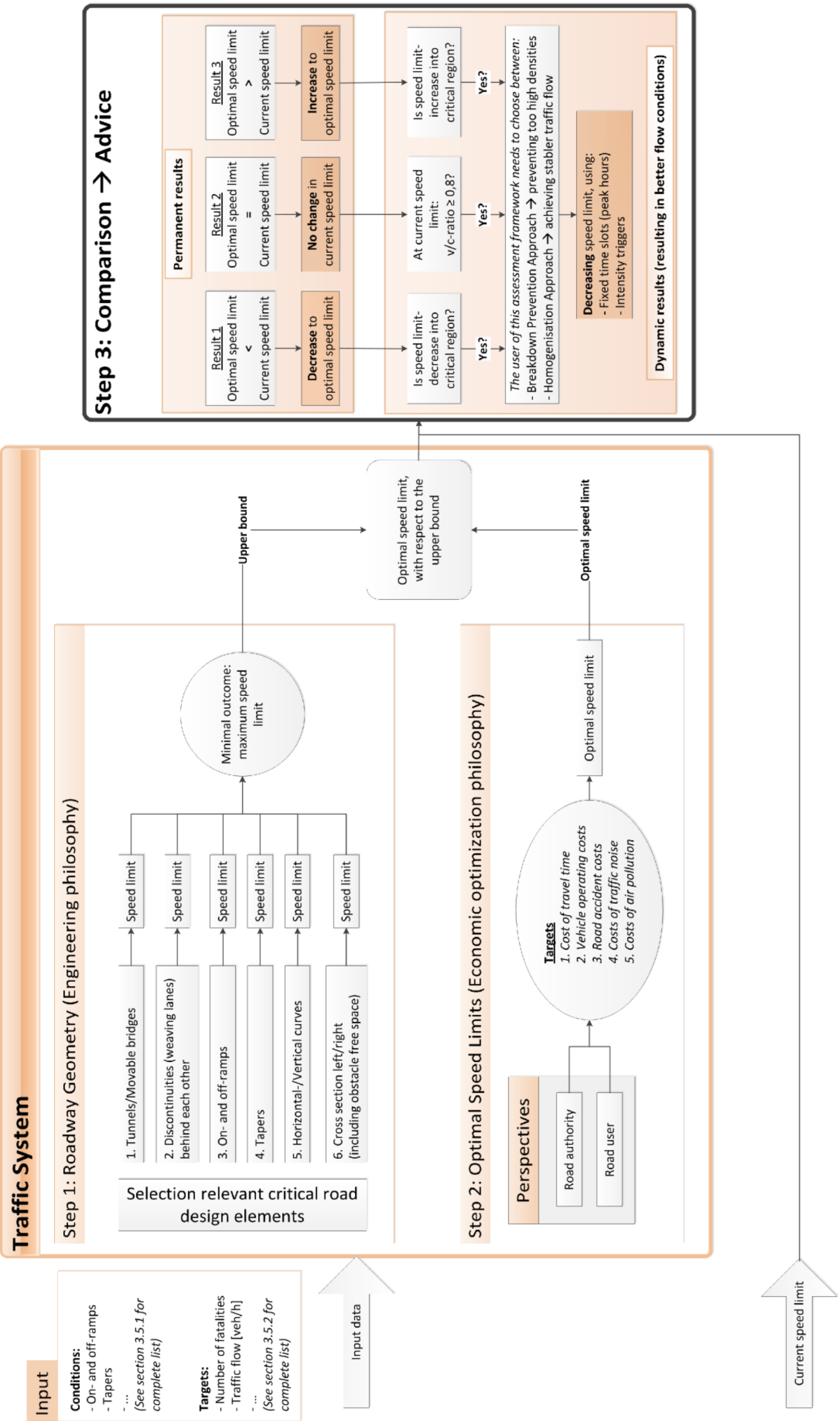

Figure 3.1: Structure of the assessment framework

3.2 Step 1: the engineering philosophy

In step 1 of the assessment framework the engineering philosophy is applied for determining the maximum speed limit on a road section. In the engineering philosophy, road layout characteristics are used to determine a speed limit, that is still safe under the prevailing conditions. For instance, because of the presence of a tunnel, the speed limit on that road section is often lower compared to road sections without a tunnel (AVV, 2007). Because of the closed construction of a tunnel, the risk of accidents in a tunnel is higher than on similar road sections outside the tunnel. That means that the consequences of an accident are more serious in a tunnel.

Critical road design elements

In chapter 2 the ambition of increasing the speed limit on Dutch motorways to 130 km/h is explained. For this proposal a study is performed into the critical road design elements for implementing a speed limit of 130 km/h (Van Delden and Broeren, 2011). In this study different specialists of Rijkswaterstaat from several disciplines (traffic safety, driving behaviour and road design) assessed the traffic safety issues resulting from the increase of the speed limit on the Dutch motorways to 130 km/h. A list of 14 critical road design elements was created. In order to determine the maximum possible speed limit on a road section (either 130 km/h or lower), these critical road design elements need to be considered in the engineering philosophy. According to Van Delden and Broeren (2011), this list of critical road design elements is as follows:

1. Tunnels;
2. Movable bridges;
3. Discontinuities behind each other;
4. Weaving lanes;
5. On- and off-ramps;
6. Tapers;
7. Horizontal curves;
8. Vertical curves;
9. The canting in the road;
10. The cross section left;
11. The cross section right;
12. Obstacle free space;
13. Rush hour- and plus lanes;
14. The traffic composition.

In appendix C, these critical road design elements are explained in more detail, including a photo impression of the road design elements.

For this thesis, the list is summarized to six critical road design elements. In table 3.1 an overview of this summation is shown. After table 3.1 is explained how this overview was derived.

Table 3.1: Critical road design elements, limited to six elements

Critical road design elements
1. Tunnels / Movable bridges
2. Discontinuities (weaving lanes) behind each other
3. On- and off ramps
4. Tapers
5. Horizontal- / Vertical curves
6. Cross section left / right (including obstacle free space)

Tunnels and movable bridges

The first critical road design element in table 3.1 consists of tunnels and movable bridges. Both tunnels and movable bridges often have a narrower cross section, or in other words: narrower driving lanes (Van Delden and Broeren, 2011). This results in a lower maximum speed limit in order to reduce the consequences of accidents. Because in general both tunnels and movable bridges contain similar road design elements for determining the maximum possible safe speed limit, these two characteristics are taken together.

Discontinuities (weaving lanes) behind each other

As is stated in appendix C at the fourth critical design element, discontinuities behind each other, weaving lanes can be seen as compositions of convergence (on ramps) and divergence points (off ramps). So, weaving lanes could be seen as discontinuities behind each other and thus are taken together with discontinuities behind each other (as the second critical design element in table 3.1).

Horizontal- / Vertical curves

The horizontal- and the vertical curves are taken together as the fifth critical road design elements in table 3.1. Both road design elements are assessed in relation to sight distances. This means that at a smaller curve (either horizontal or vertical) the speed limit is lower due to a lower sight distance.

The canting in the road

AVV (2007) states that the canting in the road has no influence on the determination of the speed limit. There is no relation between the canting of the road and the maximum possible safe speed limit. That is the reason that the canting in the road is not taken into account in the overview of the critical road design elements in table 3.1.

Cross section left / right (including obstacle free space)
For the cross section left, the cross section right and the obstacle free space, the widths of the different aspects in a cross section of a road section (lanes, redressing lane, escape space and the obstacle space) are used in the determination of the maximum possible safe speed limit. So, these road design elements are taken together as no. 6 in table 3.1.

Rush hour- and plus lanes
According to Van Delden and Broeren (2011), both a rush hour lane and a plus lane have a narrower widths compared to normal driving lanes. Because of this, the speed limit is often reduced, since it is safer to drive at a lower speed when the lanes are narrower. So, dependent on the width of the rush hour- or the plus lane, the speed limit is often reduced. But, the width of a lane is already taken into account at no. 6 cross section left / right (including obstacle free space) in table 3.1. When a rush hour- or a plus lane is located in a road section, the speed limit is decreased because of the narrower width of such a lane.

The traffic composition
As is stated in appendix C, the traffic composition is defined on the basis of two grounds: the volume/capacity-ratio (which is an indicator of the quality of the traffic flow) and the percentage of trucks. In an engineering philosophy only engineering measures are considered at the determination of a speed limit. The traffic composition is related to the number of vehicles on the road, so this critical road design element is not taken into account in the overview in table 3.1. However, the traffic composition is considered at the dynamic speed limit determination (step 3 in the developed assessment framework in figure 3.1). This is explained more in detail in section 3.4.

Maximum safe speed limit
The overview of the six critical road design elements, shown in table 3.1, is used to determine the maximum safe speed limit on a road section. In order to do this, the relations between the critical road design elements and the speed limit are needed. These relations are set in the 'New Design Directives Motorways' ('Nieuwe Ontwerprichtlijnen Autosnelwegen'), provided by AVV (2007). It gives the speed limits that belong to the specific dimensions of a road section, expressed in standard values. However, these standard values are not the only ones that may be applied. When other values are applied, arguments are necessary to satisfy the effects of these different values (i.e. measures in order to decrease the consequences of an accident) (AVV, 2007).

Relevant critical road design elements
For each road section the relevant critical road design elements summed up in table 3.1 are determined. Each road section has a different layout, so the relevant road

design elements are different for each road section. Except for no. 6 (Cross section left / right (including obstacle free space)). In all cases this critical road design element is used, because the width of the lanes (which differs for each road section) influences the speed limit. Furthermore, when a speed limit of 120 km/h is possible due to the relevant road design elements, this road layout is suitable for a speed limit of 130 km/h as well (DVS, 2011). As long as the relevant critical road design elements allow a speed limit of 120 km/h, a speed limit of 130 km/h is also possible due to the road layout.

Results of the engineering philosophy (step 1)

When all the relevant critical road design elements are investigated and all relevant data is collected, the speed limits are determined according to the standard values of AVV (2007). Dependent on the number of relevant critical road design elements, a set of speed limits is obtained. As explained before, these speed limits are based on the specific road layout. The boundaries of the road layout take care of the fact that a higher speed limit becomes unsafe for the road user. So, from the set of speed limits belonging to that specific road section, the minimal speed limit is taken, belonging to the normative road design element. A speed limit higher than this value is not considered safe. Thus, this speed limit functions as the upper bound in the assessment framework. When a higher speed limit is applied, safety issues become significant and engineering measures are needed to deal with this. For this research, it is assumed that no engineering measures need to be undertaken and that the standard values provided by AVV (2007) are leading.

The upper bound in the assessment framework

The upper bound found in this first step of the assessment framework deals with the fact that the optimal speed limit (which has to be determined in the second step of the assessment framework), is not so high that the determined optimal speed limit is not possible any more (in other words: an optimal speed limit which becomes unsafe). However, in chapter 2 of this report the ambition of increasing the speed limit on Dutch motorways to 130 km/h is explained. Taking the minimal speed limit due to a normative road design element (whether on a specific location on a road section, i.e. a movable bridge, or not), might cause a relatively low upper bound for the whole road section, while on the other sections a higher speed limit is possible. This is in contrast to the ambition of increasing the speed limit to 130 km/h explained earlier, because on several parts of the Dutch motorway network a lower speed limit than 130 km/h is determined while a speed limit of 130 km/h is possible. To deal with this, three possibilities are available:

1. Choose the boundaries of the road section differently, for instance in the normative road design element;
2. Lower the speed limit locally, for instance at the normative road design element;

3. Apply engineering measures in order to allow a higher speed limit that is still safe (however, in this research it is assumed that engineering measures are not desirable).

The user of the assessment framework is free to choose one of these possibilities. In the next chapter, it becomes clear how this choice can be made.

In the remainder of this section the six critical road design elements shown in table 3.1 are explained, including the relation with the speed limit. All values used in the relations are derived from AVV (2007).

1. Tunnels / Movable bridges

When either a tunnel or a movable bridge is present in a road section, the speed limit is often reduced to the speed limit that is possible under those conditions. In this case the layout of the road results in severe consequences in case of an accident (because of the tunnel wall and the cross section with narrower lanes at bridges for example). Furthermore, at movable bridges a complete stop is needed when the bridge is open (and thus a lower speed limit in order to be able to standstill in time).

Both tunnels and movable bridges contain similar conditions which determine the speed limit. These conditions are depicted on the left side of figure 3.2. Tunnels have two more conditions to consider: foot curves in the road and horizontal curves. For the condition 'slope' the relation with the speed limit is shown on the right of figure 3.2. The slope is defined as the ratio of the height of the vertical distance (value h in figure 3.2) and the length of the slope (value l in figure 3.2), expressed in percent (AVV, 2007). In the flow chart in the top right corner in figure 3.2, there is no difference in slope between the design speed 120 / 130 km/h and 100 km/h. It turns out that when the slope is greater or equal than 3 %, the design speed of that road section is 80 km/h. When the slope of the road section is smaller than 3 %, the design speed should be 130 km/h. For the bottom flow chart in figure 3.2, the same reasoning applies.

The rest of the conditions mentioned on the left side of figure 3.2 refer to the conditions which are described later on in this section (e.g. *see no. 5* means that the relation with the speed limit is explained at critical road design element no. 5).

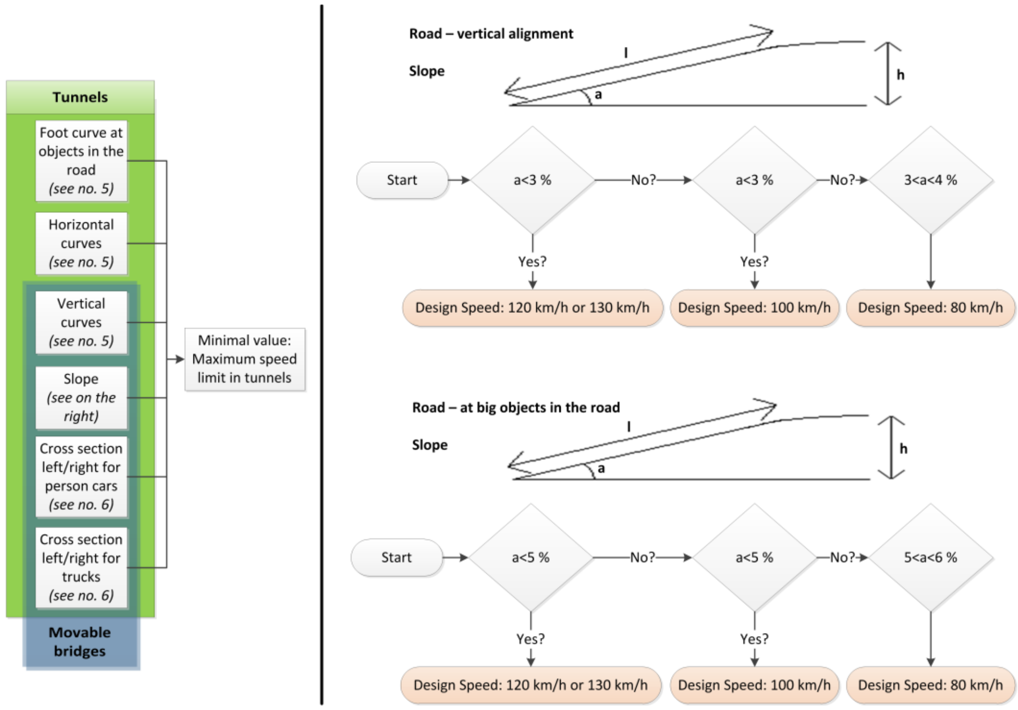

Figure 3.2: Relation with speed for tunnels / movable bridges (values derived from AVV (2007)

2. Discontinuities (weaving lanes) behind each other

A discontinuity is a disturbance in the smooth layout of the road. Two types of discontinuities exist: convergence points (on-ramps) and divergence points (off-ramps). When on- and off-ramps are located close behind each other, weaving lanes are a proper measure to deal with this. Weaving lanes result in no unnecessary movements of vehicles, entering and leaving the main road. Van Delden and Broeren (2011) state that the length between on- and off-ramps is dependent on the number of lanes of both the main road and the entering road (as is distinguished in figure 3.3 as well). However, this is generally only applied when its length is smaller than 1300 meters. When this distance is longer, weaving lanes are not used.

In figure 3.3, the distances for the weaving lane L1 are given as a function of the speed limit. The length of the weaving lane must be large enough in order to provide enough distance to enter or leave the main road in a safe way. First the lengths are shown for symmetric weaving lanes. This means that the number of incoming lanes on the left in figure 3.3 is similar to the number of outgoing lanes on the right.

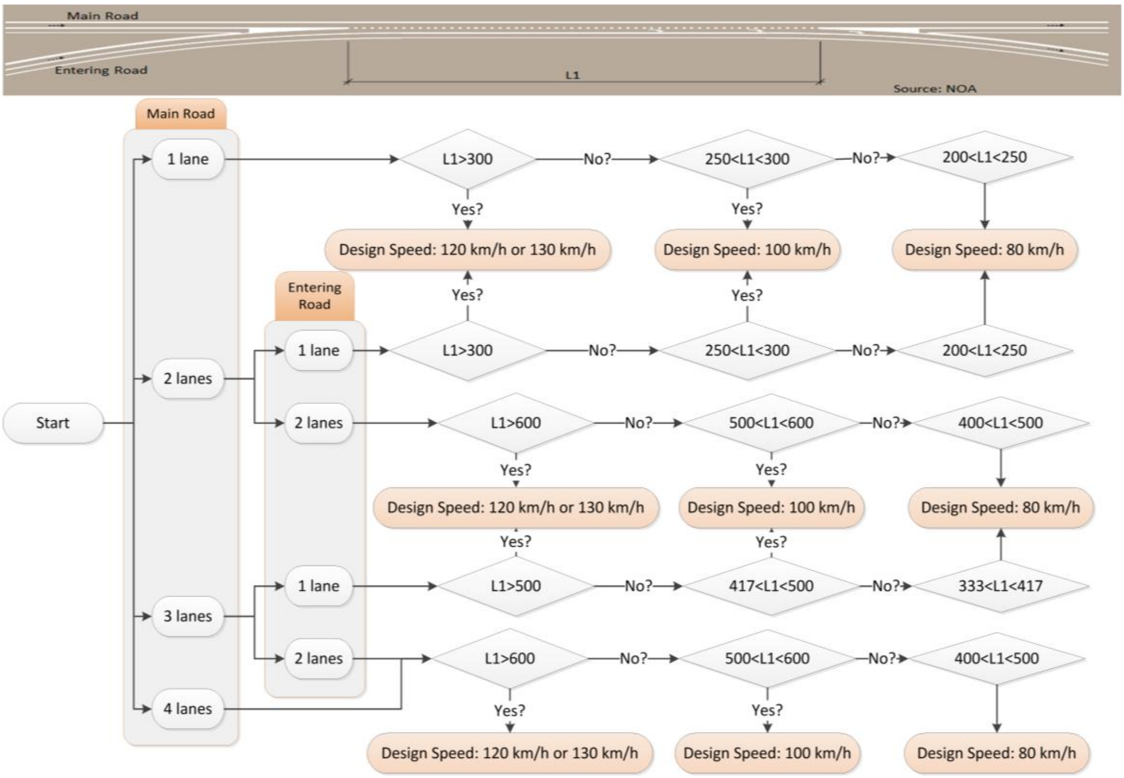

Figure 3.3: Relation with speed for discontinuities (weaving lanes – symmetric) behind each other (values in meters, derived from AVV (2007))

In figure 3.4 the relation between the speed limit and asymmetric weaving lanes is shown. The difference with symmetric weaving lanes is that the entering road has a different number of lanes than the leaving road. Consequently, the inflow of vehicles differs from the outflow of vehicles, simply because the capacity of the inflow differs from the capacity of the outflow. As a result, the distances needed for the weaving lanes are much larger at asymmetric weaving lanes than at symmetric weaving lanes.

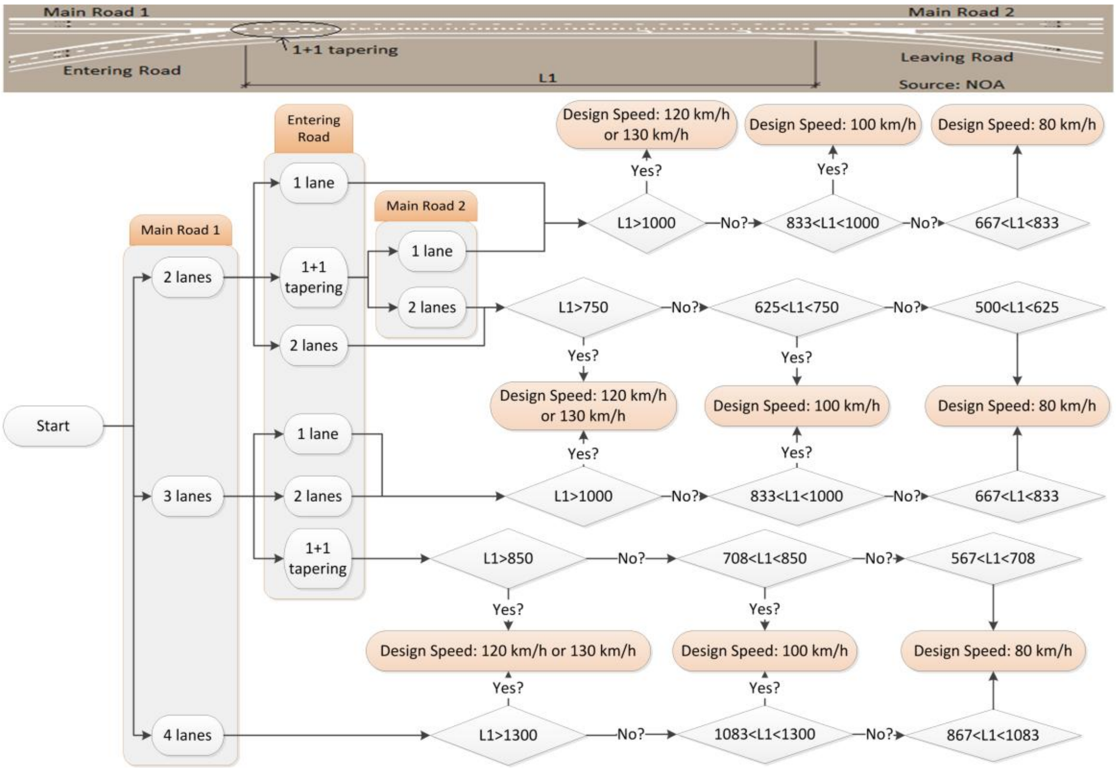

Figure 3.4: Relation with speed for discontinuities (weaving lanes – asymmetric) behind each other (values in meters, derived from AVV (2007))

3. On- and off ramps

In figure 3.5 the relation between the length of an on ramp and the speed limit is shown. The speed limit depends of the available length for accelerating (L1) and the available length L2. This length influences the speed limit, because the length must provide enough space to accelerate to the speed limit. A smaller length results in a lower speed limit, with a minimum length L1 of 155 m.

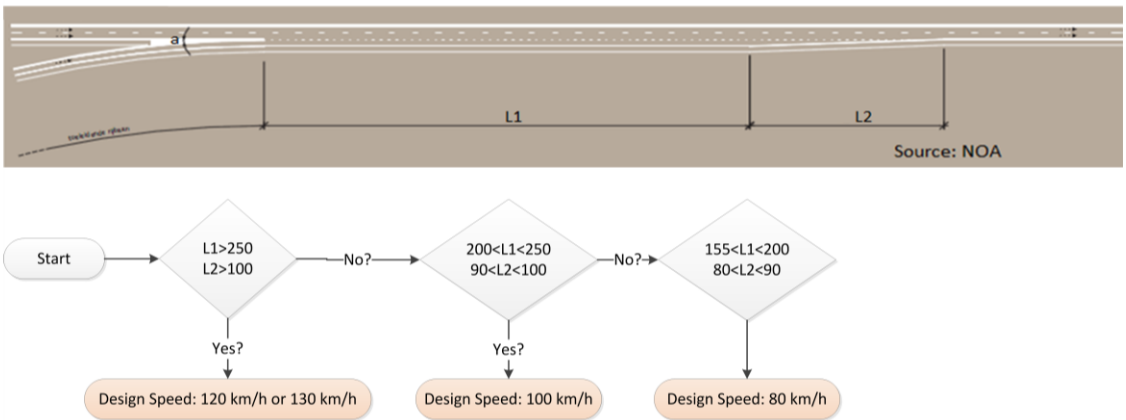

Figure 3.5: Relation with speed for on ramps (values in meters, derived from AVV (2007))

For off ramps other critical lengths exist. In figure 3.6 the critical lengths for off ramps are given. It turns out that the needed distance of decelerating lanes are shorter than the distance of accelerating lanes. The time for accelerating to the speed limit is higher than the time for decelerating to the speed at which a road can be leaved on a safe way. The tangent *a* in figure 3.6 is equal to the tangent between the leaving lane and the main road (in percent) (AVV, 2007).

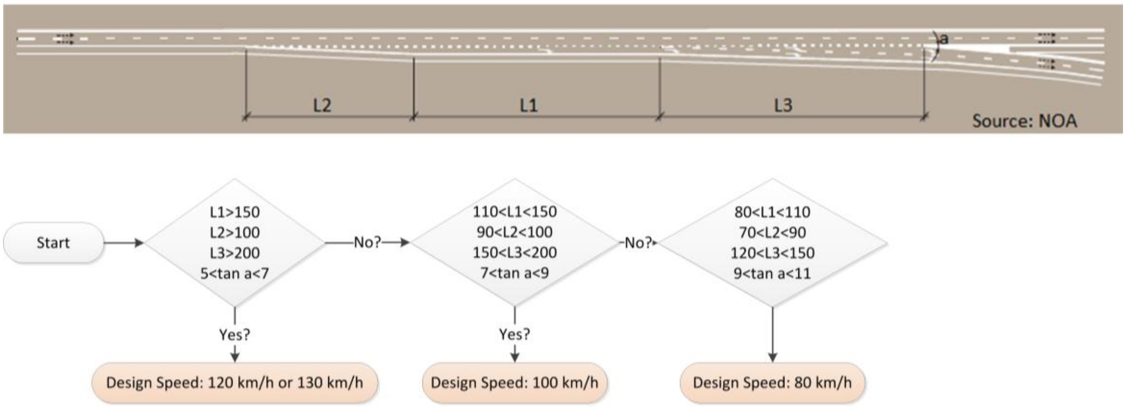

Figure 3.6: Relation with speed for off ramps (values in meters, derived from AVV (2007))

4. Tapers

Tapers are special versions of 'two lanes on ramps' and 'two lanes off ramps.' In figure 3.7 a 'two lanes on ramp' is shown. On length L1 the mean speed must be unchanged. In this situation one lane of the joining road merges into the main road. The length of this manoeuvre (L1) determines the speed limit.

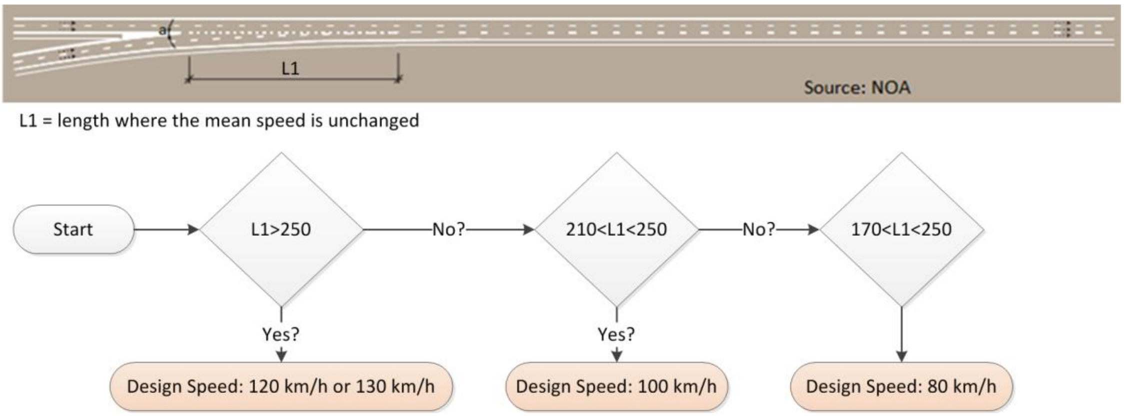

Figure 3.7: Relation with speed for tapers (joining motorways) (values in meters, derived from AVV (2007))

In figure 3.8 three configurations of 'two lane off ramps' are depicted. These 'two lane off ramps' are interpreted as splits of the motorway and are situated at junctions of motorways. For the three configurations shown in figure 3.8, the values for respectively L1 and L2 are similar. The higher this value, the higher the design speed. The tangent *a* in figure 3.8 is equal to the tangent at which the two lanes split (in percent) (AVV, 2007).

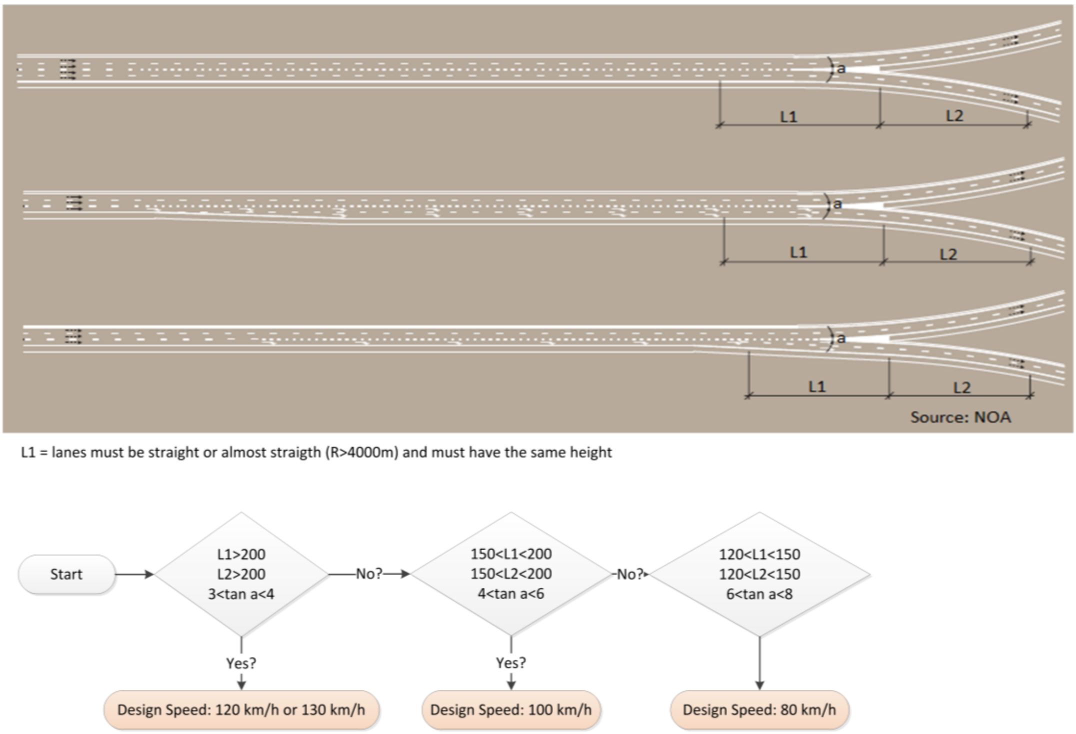

Figure 3.8: Relation with speed for tapers (divided motorways) (values in meters, derived from AVV (2007))

5. Horizontal- / Vertical curves

In figure 3.9 respectively figure 3.10 the relation between the speed limit and the horizontal and the vertical curves in the road alignment are given. For horizontal curves, there are three different possibilities. In figure 3.9 these possibilities are clarified. It turns out that the bigger the radius, the higher the speed limit. For radius R3, sharp horizontal curves are not possible at all. The minimal value for R3 must be at least 3000 meters.

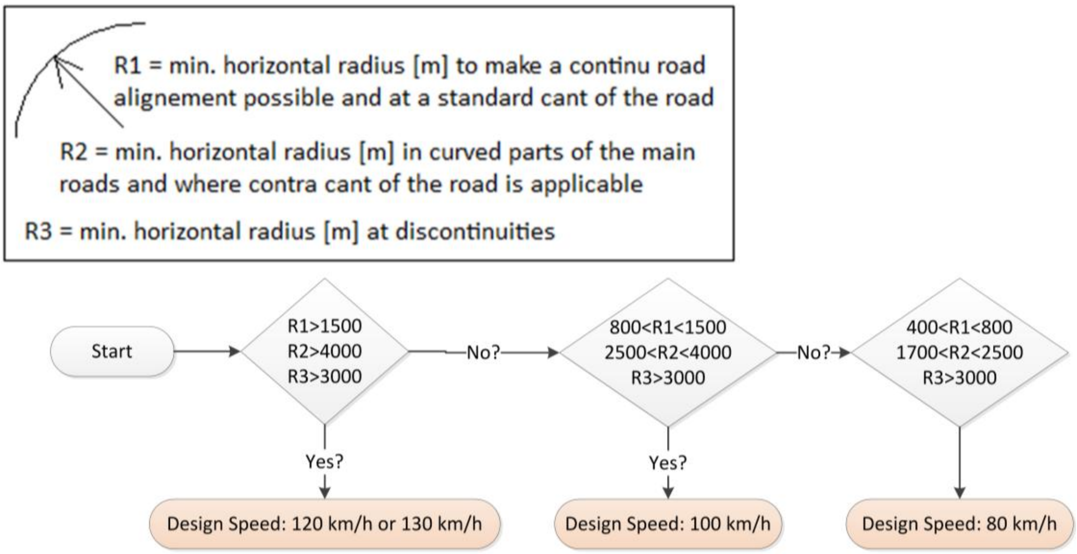

Figure 3.9: Relation with speed for horizontal curves (values in meters, derived from AVV (2007))

As explained in appendix C at no. 8, vertical curves are applied in order to overcome height differences (i.e. tunnels or movable bridges). For vertical curves a distinction is made between vertical curves at objects in the road (mostly in tunnels) and vertical curves as a top curve (mostly at (movable) bridges). In figure 3.10 these two vertical curves are displayed, including the values of the radius R.

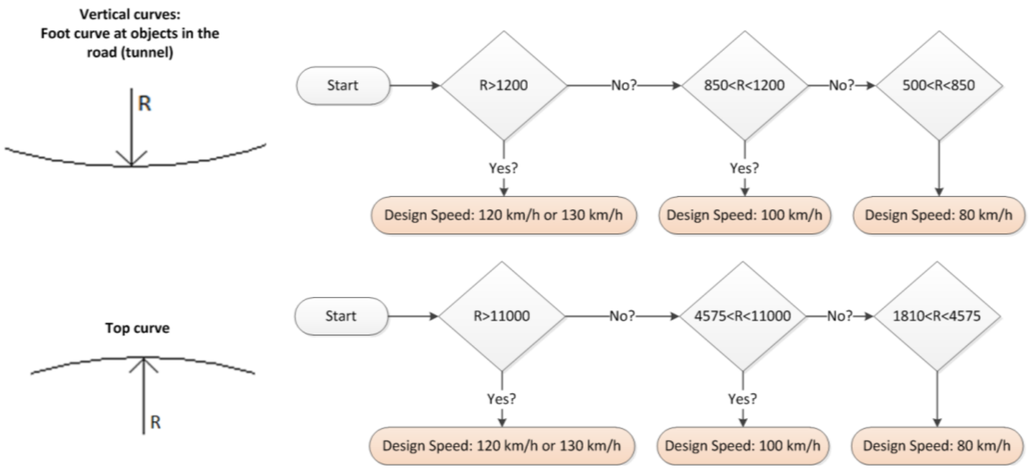

Figure 3.10: Relation with speed for vertical curves (values in meters, derived from AVV (2007))

6. Cross section left / right (including obstacle free space)

As mentioned before, the cross section of a road section is determined in all cases for setting a speed limit. Van Delden and Broeren (2011) explain that at higher speeds the lace corridor[9] of a vehicle increases. This results in a higher chance of accidents when the lanes are smaller. Hence, the speed limit is lower when the lanes are smaller.

This critical road design element is applied to one cross section on a road section. The cross section is chosen by the user of the assessment framework. It is expected that the user of the assessment framework can decide where the road section is the most narrow and thus where to apply it at the road section.

In figure 3.11 a cross section of a road section is shown in the upper left corner. This cross section applies to passenger cars. Apart from the function of the lane itself, the functions of the lanes on the left and on the right influence the speed limit as well. After determining the width of each lane in the cross section, the speed limit is determined for that cross section. Logically, for trucks higher widths are used for determining the speed limit. These relations are shown in figure 3.12.

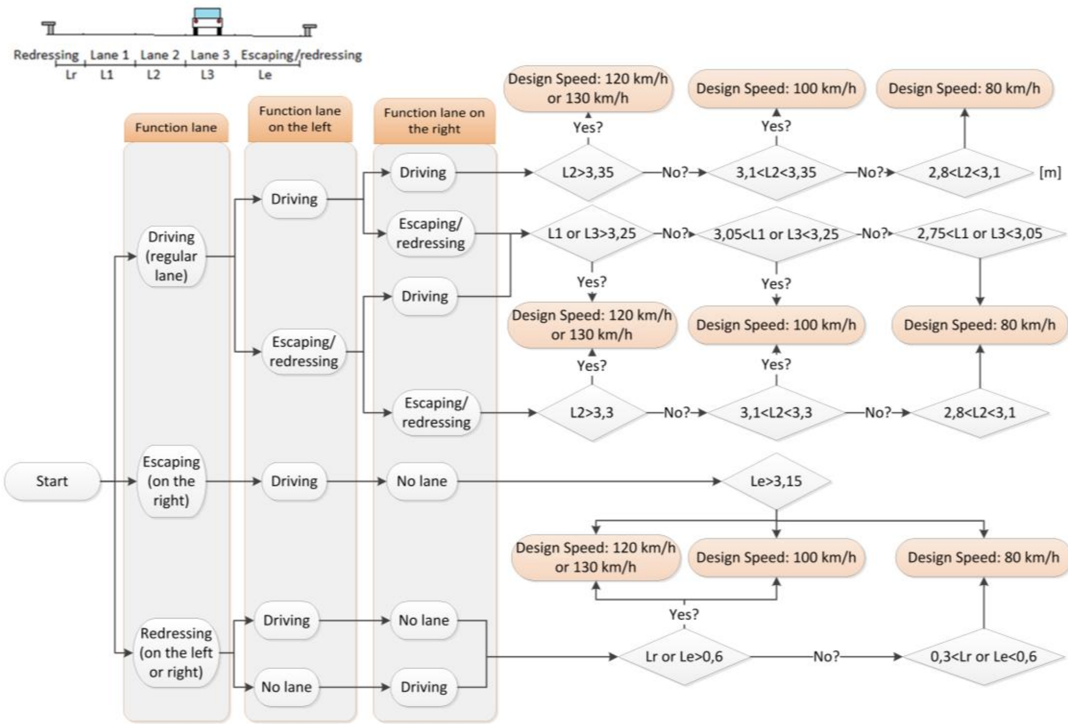

Figure 3.11: Relation with speed and the cross section on the left / right for passenger cars (values in meters, derived from AVV (2007))

[9] Lace corridor (in Dutch: 'vetergang') of vehicles is the deviation from a straight line due to disturbing forces and course-corrections. The higher the speed, the higher the lace corridor (Van Delden and Broeren, 2011).

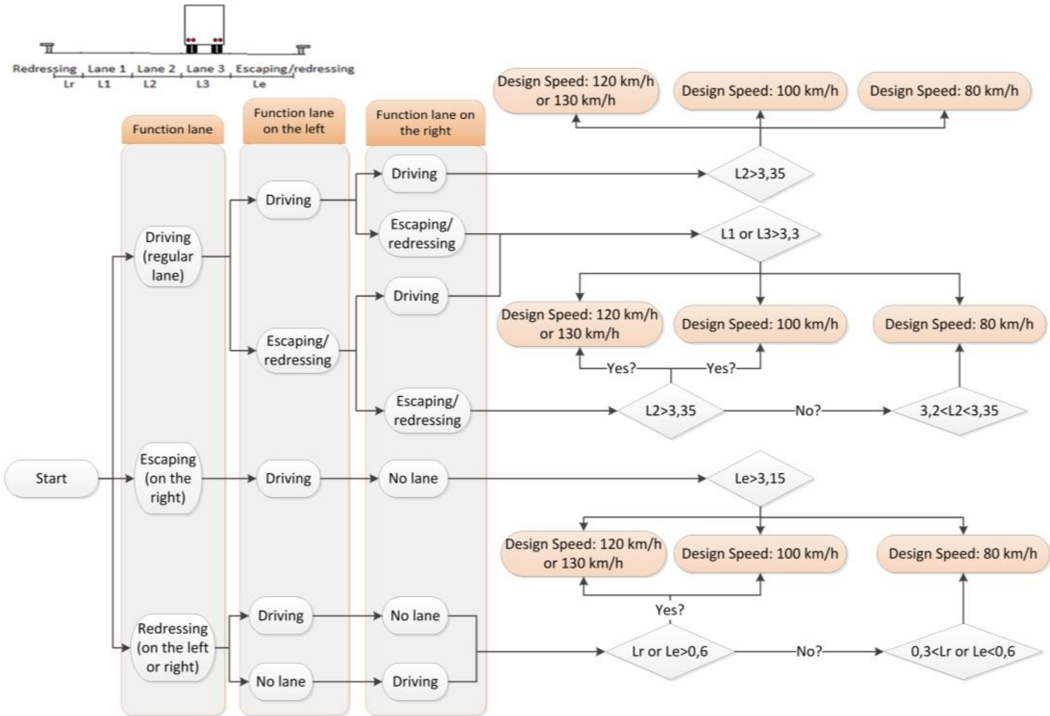

Figure 3.12: Relation with speed and the cross section on the left / right for trucks (values in meters, derived from AVV (2007))

Except for the cross section, the obstacle free space also influences the speed limit. In figure 3.13 the relation between the distances and the speed limit is depicted. Note that when it is not possible to have an obstacle free space due to buildings or other objects, a guard rail can be used to protect the road user in case of an accident. Only when a guard rail is not used, this determination is applied.

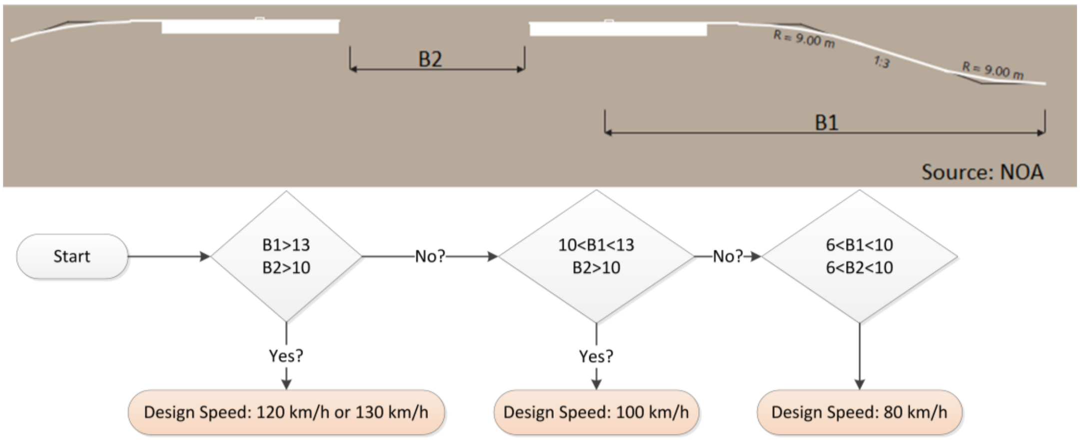

Figure 3.13: Relation with speed and the obstacle free space (values in meters, derived from AVV (2007))

3.3 Step 2: the economic optimization philosophy

The second step of the assessment framework is determining the optimal speed limit at which the total costs for society are the lowest possible. In this determination significant factors are considered. As is explained in chapter 2, the significant factors are the factors dependent of the chosen perspective.

Chosen perspectives: road authority and road user

For this research, the road authority- and the road user perspective are chosen. The road authority is chosen because the assessment framework is developed for Rijkswaterstaat (which is the road authority in the Netherlands). It is of practical relevance for Rijkswaterstaat to determine the optimal speed limit on a road section, because then Rijkswaterstaat has the ability to obtain the speed limit that results in the lowest costs for society. As a consequence, the current speed limit can be adapted (either dynamically or statically). Furthermore, the mission of Rijkswaterstaat is maintaining and developing the infrastructural main networks in the Netherlands (Rijkswaterstaat, 2008). This is done in order to facilitate a good and safe traffic situation for the road user. So, the road user is also chosen as perspective in this research. However, the road user has a different objective than the road authority. The road user wants to travel as fast and cheap as possible, no matter what consequences this has for the surroundings.

Objectives of the perspectives

In table 3.2 the two chosen perspectives are shown: the road authority and the road user. In chapter 2 it was motivated which significant factors belong to these perspectives. Each perspective has its own objective. The road user considers travel time and vehicle operating costs: travelling as fast and as cheap as possible. For the road authority, more factors are considered. The road authority wants to facilitate a safe and good traffic situation for the road user. So, except traffic safety issues, also external effects of driving vehicles are considered, like traffic noise and air pollution. In table 3.2 this is indicated for the five significant factors using a 'V'.

Table 3.2: Significant factors for the optimal speed limit determination

Significant factors	Road authority	Road user
1. Costs of travel time	V	V
2. Vehicle operating costs	V	V
3. Road accident costs	V	-
4. Costs of traffic noise	V	-
5. Costs of air pollution	V	-

Regardless of the chosen perspective

For this research, the road authority- and the road user perspective are chosen in the economic optimization philosophy (step 2 of the assessment framework). Because the assessment framework is developed for Rijkswaterstaat (which is the road authority in the Netherlands) and Rijkswaterstaat aims to facilitate a good and safe traffic situation for the road user, these two perspectives are chosen. However, the user of the assessment framework is free to choose the desired perspective. When another perspective is chosen, different significant factors are applied in the economic optimization philosophy.

Determination of the optimal speed limit

In order to find the optimal speed limit at which the total costs for society belonging to a certain perspective are minimal, the relation between the speed limit and the significant factors mentioned in table 3.2, is needed. In appendix B, typical relationships between the significant factors and the speed limit are shown, derived in the study performed by Elvik (2002). The relationships are expressed in a formula. This formula describes the cost of the significant factors as a function of the speed limit. These formulas are converted to the Microsoft Excel format. In Microsoft Excel, it is possible to sum up the formulas in an easy way. This summation results in an overall function. This function has a minimum in the costs at a certain speed limit. This speed limit is the optimal speed limit for that road section.

Applied unit in the economic optimization philosophy

The costs in the optimal speed limit determination are expressed in euro / vehicle kilometer. These are the costs of one individual vehicle travelling one kilometer. This unit is chosen in order to be able to sum up the significant factors expressed in costs shown in table 3.2, which leads to the overall function. For the costs of travel time, the vehicle operating costs and the costs of air pollution, the costs belonging to one individual vehicle are determined. For instance, the vehicle operating costs of one vehicle are the fuel costs of one vehicle travelling from A to B. Furthermore, for the other two significant factors (road accident costs and costs of traffic noise), the costs for the total number of vehicles are determined. For those two significant factors, the costs are converted to the costs per vehicle. How this is done is explained later in this section. So, the unit euro / vehicle kilometer is chosen, because all the significant factors shown in table 3.2 can be expressed rather easy into this unit.

Speed limit range in the economic optimization philosophy

In the calculation of the optimal speed limit a speed limit range is chosen from 50 km/h to 160 km/h. 50 km/h is to be assumed low enough, because on the Dutch motorway network only vehicles are allowed which can and may drive with a speed of at least 60 km/h[10]. So, 50 km/h is a speed limit that is certainly low enough. The upper value of 160 km/h is to be assumed high enough. The highest posted speed limit in the world is 160 km/h, which was applied in Abu Dhabi in 2005 (Hoath, 2005). However, in 2010 it was decided to reduce this speed limit back to 140 km/h to ensure road safety (Staff, 2010). It was concluded that 160 km/h is an unsafe speed limit and thus a higher speed limit is not to be recommended at all. In the next chapters (the case study and the evaluation of the case study) it is evaluated whether or not this speed limit range is chosen correctly. Note that for trucks only the costs are determined for a speed limit of 90 km/h. Van Hout et al. (2005) mentioned that in Europe a truck is equipped with a speed limiter of 90 km/h. That is the reason why it is assumed that a truck will drive maximally 90 km/h.

Results of the economic optimization philosophy (step 2)

As explained above, the summation of the formulas in Microsoft Excel leads to an overall function. The optimal speed limit is the speed limit for that road section where the costs are minimal. It needs to be mentioned that Pareto optimal solutions are found in this calculation. In chapter 2 it has been explained that there is not one solution which optimizes all targets on a linear line at the same time (Wismans et al., 2011). At the optimal speed limit, the total costs are minimal. Because at different speed limits the costs of the significant factors differ, it is not possible to have the lowest costs for all significant factors. Compromises have to be made. That means that for instance when the accessibility is improved by increasing the speed limit (shorter travel time), the air quality becomes worse.

In the remaining of this section, the five formulas representing the five significant factors shown in table 3.2, are explained.

1. Costs of travel time

Elvik (2002) defines the costs of travel time as the Value of Time (VoT) divided by the speed limit. The formula is:

$$\frac{VoT}{v} \text{ [euro/vehicle kilometer]} \qquad (3.1)$$

With:

- VoT = Value of Time [euro/h]; this is the monetary value for one hour travelling
- v = speed limit [km/h]

[10] http://www.rijksoverheid.nl/onderwerpen/wegen/vraag-en-antwoord/wat-is-de-minimumsnelheid-voor-het-wegverkeer.html

For the VoT-value, a distinction is made between the VoT for passenger cars and the VoT for trucks. Each road class has a different VoT-value. For the year 2010 the following values are used (Witteveen+Bos, 2011):

- VoT-value for passenger cars: 10,67 euro/h;
- VoT-value for trucks: 45,78 euro/h.

The VoT-value for passenger cars is a mean value derived for all motives. The VoT-value for trucks applies to road transport. These VoT-values are not used in a one-to-one-ratio. The number of trucks differs from the number of passenger cars. To deal with this difference, the truck percentage is used to calculate the mean VoT-value for a road section. The truck percentage is different for each road section. Below it is explained how the applied truck percentages are determined. In the calculation, the VoT-value for trucks is multiplied by the truck percentage of that road section. For the VoT-value for cars, the same is done, but then multiplied with the value: 100 – the truck percentage. In this way, the VoT-values are used in proportion to the number of cars and trucks on the road.

For this thesis, the truck percentages provided by Van Rij and Henkens (2009) are used in order to calculate the specific VoT-value. Van Rij and Henkens (2009) has determined which percentage of the passing traffic consists of trucks. Those measurements are based on data obtained by the nearest MTR-counting point of the cross section where the truck percentage is determined. The determined truck percentages are counted during the peak periods of the day (both 6:00 AM – 10:00 AM and 3:00 PM – 8:00 PM). The truck percentages are given for the years 2005 and 2006. The mean of those two years (calculated for the peak periods in these years) is used in the calculation of the optimal speed limit in this research. In this calculation it is assumed that this mean value functions as a proper value in the determination of the optimal speed limit.

2. Vehicle operating costs

TAG (2011) defines the formula that estimates the fuel consumption as follows:

$$L = \frac{a}{v} + b + c * v + d * v^2 \text{ [L / km]} \qquad (3.2)$$

With:

- a, b, c, d = parameters defined for each road class
- v = speed limit [km/h]

Formula 3.2 provides the latest vehicle operating costs recommended by the Department of Transport of Great Britain (TAG, 2011). The parameters given in table 3.3 are used in this formula. These parameters are based on the vehicle fleet of Great Britain for the year 2002. It is assumed that the vehicle fleet of Great Britain is overall comparable with the vehicle fleet of the Netherlands. The Dutch vehicle fleet is to be assumed to have roughly the same fuel consumption (L / km) as the vehicle fleet in Great Britain.

Table 3.3: Parameters for formula 3.2 for the vehicle fleet of Great Britain in 2002 [L / km] (TAG, 2011)

Vehicle class	a	b	c	d
Average passenger car	0,96	0,05	$-1{,}30*10^{-4}$	$2{,}54*10^{-6}$
Average truck	1,16	0,06	$-4{,}50*10^{-4}$	$8{,}64*10^{-6}$

In table 3.3 it can be seen that the average values for the parameters (in L / km) for a passenger car and a truck are used. After computing the fuel consumption in L / km with formula 3.2 per vehicle class (a passenger car and a truck), the outcome is converted into euro / vehicle km. This is done by multiplying this outcome by the latest mean price for one liter of fuel (the mean value for petrol and diesel). This gives the fuel consumption of the Dutch vehicle fleet per vehicle class for one vehicle in euro / km, or in other words: in euro / vehicle km per vehicle class.

When the fuel consumption of the Dutch vehicle fleet per vehicle class (a car and a truck) is determined in euro / vehicle km, this fuel consumption is converted to the fuel consumption in relation to the traffic composition. As is done for the costs of travel time as well, the fuel consumption for a truck is multiplied with the truck percentage for that road section. For the fuel consumption of a car, the same is done, but then multiplied with the value: 100 – the truck percentage. How the truck percentages are derived, is explained at the previous significant factor (costs of travel time).

Finally, after determining the fuel consumptions for both a car and a truck dependent of the truck percentage, the fuel consumptions are summed up for each speed limit in the range 50 km/h – 160 km/h. This results in the fuel consumption in euro / vehicle km.

3. Road accident costs

Nilsson (2004) presents a model that describes the relationship between speed changes and traffic safety. The primary objective of this model is to describe the effect of changing vehicle speeds on the number of accidents. This model is applied on a macro level (for a road network). In this thesis the focus is on a lower level (a road section). It is assumed that the model works properly on a lower model as well. In chapter 5 the economic determination philosophy is evaluated to see whether or not it has worked properly, based on the case study presented in chapter 4.

In appendix D, the model of Nilsson is summarized. This model contains six formulas (the power functions). For this thesis only two formulas are used to determine the road accident costs. These formulas are (Nilsson, 2004):

Fatalities: $$z_1 = \left(\frac{v_1}{v_0}\right)^4 * y_0 + \left(\frac{v_1}{v_0}\right)^8 * (z_0 - y_0) \quad (3.3)$$

Fatalities and severely injured: $$z_1 = \left(\frac{v_1}{v_0}\right)^3 * y_0 + \left(\frac{v_1}{v_0}\right)^6 * (z_0 - y_0) \quad (3.4)$$

With:

- z_1 = number of injuries at new optimal speed limit [number/year]
- z_0 = number of injuries at current speed limit [number/year]
- v_1 = new optimal speed limit [km/h]
- v_0 = current speed limit [km/h]
- y_0 = fatal accidents at current speed limit [number/year]

Formula 3.3 and 3.4 are used, because only the costs of fatalities and severely injured are applied in the road accidents costs. The accident costs are not considered. Furthermore, these formulas calculate the change in fatalities and severely injured in relation to the current speed limit. The formulas are applied for both an increase and a decrease of the current speed limit.

Current crash statistics[11] are used to predict the crash statistics at the new optimal speed limit. These predicted crash statistics are multiplied by the price for a fatality and for a seriously injured person. Witteveen+Bos (2011) provides the following prefixes:

- Cost per fatality: 2.690.108 euro;
- Cost per seriously injured person: 276.568 euro.

These prefixes are determined for the year 2010 and are known as the most actual values (Witteveen+Bos, 2011).

After multiplying the predicted crash statistics with the prefixes for the costs, the costs of the accidents at a certain speed limit is found. These costs are applicable to that road section. In order to get the costs / vehicle km, the costs of the accidents are divided by the total number of vehicle km for passenger cars and trucks together on Dutch motorways. Flikkema (2003) estimates that for the year 2010 this total number of vehicle km is 46.000.000.000 km. This estimation is based on the outcomes of the

[11] Crash statistics are derived from the 'record of registered accidents in the Netherlands' ('Bestand geRegistreerde Ongevallen in Nederland' (BRON)).

'National Model System Traffic and Transport' ('Landelijk Modelsysteem Verkeer en Vervoer') of the Advice Service Traffic and Transport (AVV).

The total number of vehicle kilometers represents the total numbers of kilometers driven by all vehicles on Dutch motorway network. It is imaginable that on busy motorways (for instance in the Randstad in the Netherlands) far more vehicles occupy the motorway and thus more vehicle kilometers are driven on that motorway. It is not representative to divide the road accident costs by this total number of vehicle kilometers. In order to deal with different road sections, the ratio of the length of that specific road section and the total length of the Dutch motorway network is used to convert the total number of vehicle kilometers to a more representative number of vehicle kilometers for that road section. This is done by multiplying that ratio with the total number of vehicle kilometers, where after the new value is used to determine the road accident costs / vehicle km. Although this is a very rough method, it is assumed that this conversion is sufficient enough to produce valuable results. Further research is needed to calculate more precisely the vehicle kilometers for a road section. What further research is needed is explained in more detail in chapter 5.

4. Costs of traffic noise

In InfoMil (2009) it is described how the equivalent noise level is determined. The formula for the equivalent noise level is set as the 'Standard Calculation Method' ('Standaard Rekenmethode'). The formula is as follows:

$$L_{Aeq} = 10 \lg \sum_{i=1}^{8} \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{m=lv}^{zv} 10^{L_{eq,i,j,n,m}/10} \quad \text{[dB(A)]} \qquad (3.5)$$

Width:

$$L_{eq,i,j,n,m} = L_E + \Delta L_{OP} + \Delta L_{GU} - \Delta L_L - \Delta L_B - C_M - \Delta L_{SW} - \Delta L_R - 58,6 \quad \text{[dB(A)]} \qquad (3.6)$$

In formula 3.6, the Δ-factors are ignored or are equal to zero. In table 3.4 it is explained why.

Table 3.4: Explanation of the Δ-factors in formula 3.6 (InfoMil, 2009)

Δ-factor	Explanation	Reason for ignoring the Δ-factor
ΔL_{OP}	*Acceleration surcharge* (correction term due to the deceleration and the acceleration of traffic)	At motorways only level crossings are applied, so traffic does not have to decelerate and accelerate due to junctions on motorways.
ΔL_{GU}	*Geometrical expansion term* (resistance that noise encounter when 'travelling' through the air)	For this term specific data is necessary, for instance the opening angle of the noise sector. Further research is necessary on how to use this term. For this thesis it is assumed that this term is zero.
ΔL_{L}	*Air damping*	For this term, the same reasoning applies as for the term ΔL_{GU}: Further research is necessary how to use this term. For this thesis is assumed that this term is zero.
ΔL_{B}	*Soil damping*	According to InfoMil (2009), this term is almost zero. That is the reason that for this thesis is assumed that the term is equal to zero.
C_M	*Meteo correction term*	C_M = 0 when $R \le 10*(h_b + h_w)$. R is the distance between the source and the observation point. And h is the height of those two points. For this thesis, this condition applies and thus C_M = 0.
ΔL_{SW}	*Shading effect*	This term is only used if applicable. For the motorways applied in the case study of this thesis, there is no shade present. That means that this term is zero.
ΔL_{R}	*Level reduction due to reflections*	This term is used when absorption is present. It is assumed that this is not the case and thus this term is not applicable.

So, that means that formula 3.6 transfers in the following formula:

$$L_{eq,i,j,n,m} = L_E - 58,6 \text{ [dB(A)]} \qquad (3.7)$$

In formula 3.7, L_E is the emission term, which is calculated as follows:

$$L_{E_{i,m}} = 10\lg\left(\frac{Q_m}{v_m}\right) + \alpha_{i,m} + \beta_{i,m}\lg\left(\frac{v_m}{v_{0,m}}\right) \text{ [dB(A)]} \qquad (3.8)$$

Width:

- Q = mean intensity of the relevant road class [h^{-1}]
- v = speed limit of the relevant road class [km/h]

- v_0 = reference speed limit for the relevant road class; for lv (passenger cars): 80 km/h and for mv and zv (trucks): 70 km/h
- The α- and β-value are represented by fixed vales, both for eight octave bands and for the three road classes (InfoMil, 2009)

Formula 3.8 explains that L_E is dependent on the mean intensity and the current speed limit. The mean intensity is derived from the website of the 'NSL monitoringstool'[12] for both passenger cars and trucks. Here the mean intensity is calculated by summing up the intensity at the beginning and at the end of the specific road section for the year 2011. This value is then divided by 2.

By filling formula 3.8 into formula 3.7 and furthermore formula 3.7 into formula 3.5, the equivalent noise level L_{Aeq} is determined for each speed limit.

In Witteveen+Bos (2011) the costs of noise per dB(A) per person are given. Furthermore, Rijkswaterstaat has developed a website[13] where an interactive noise map is shown. The total number of people affected by the traffic noise from motorways is provided on this web site. This number is converted to the number of people living along the relevant road section. This is done using the ratio of the length of the road section divided by the total length of the Dutch motorway network. Although this is a very rough estimation, it is assumed that it represents the real total number of people affected by the traffic noise from motorways very closely.

Having all this data, including the total number of vehicle kilometers for passenger cars and trucks on Dutch motorways for 2010 (provided by Flikkema (2003), as explained at the road accidents costs), the costs per vehicle kilometer for traffic noise is calculated. Despite of this very rough method, the results are expected to be representative for this thesis.

Because the traffic noise is experienced as more unpleasant at road sections which are located in areas where a lot of residents live (near cities), a factor is added. This factor gives a higher weight to the costs of traffic noise and thus a higher influence on the optimal speed limit near cities. The height of the factor is variable for each road section. In the next chapter, the influence of this factor is defined in order to demonstrate the possible heights of this factor.

[12] http://www.nsl-monitoring.nl/rekenen/

[13] http://www.rijkswaterstaat.nl/wegen/plannen_en_projecten/geluid_rond_snelwegen_nederland/geluidskaart/

5. Costs of air pollution

DVS (2011) states that for the assessment of the air quality at motorways only PM_{10} and NO_2 are significant. The other pollutants are not critical along Dutch motorways. For CO_2 the whole network is considered (Burgmeijer et al., 2010). In this thesis a road section is assessed, so CO_2 is not used in this thesis.

For PM_{10} and NO_2 the emission rates [kg/km] are determined. De Lange et al. (2011) and Drewes (2006) give the emission rates for these pollutants. Here a distinction is made between the emission rate for passenger cars and for trucks. For passenger cars, the emission rates are determined for different speed limits between the range 50 km/h – 160 km/h. For trucks, only emission rates between 50 km/h and 90 km/h are determined. Table 3.5 shows for which speed limits the emission rates are determined. The emission rates calculated for the year 2010 are used because these values seem to be representative enough.

Table 3.5: Speed limits for which the emission rates are determined

Vehicle class	Speed limits [km/h]				
Passenger car	50	80	100	120	130
Truck	50	60	70	80	90

These values are chosen as basic values. At these basic values, it is rather easy to determine the corresponding emission rates. Furthermore, in table 3.5 it can be seen that the maximum speed limit for passenger cars at which the emission rates are determined, is 130 km/h, and not 160 km/h as is indicated as the upper bound of the speed limit range in the economic optimization philosophy. The reason for this is that it has never been tested at the TNO laboratory[14] what the emission rates are at 160 km/h. The highest speed at which this was tested is 130 km/h. To deal with this issue, the emission rates for passenger cars at higher speeds than 130 km/h are estimated. Although it is not recommended to inter- or extrapolate the emission rates due to the unfamiliarity whether or not the relation between speed and emission rates is linear or exponential, these emission rates for the speeds above 130 km/h are estimated for this research. In general, there is not a simple relation between the speed and emission rates[13].

In Witteveen+Bos (2011), the prices per kg PM_{10} and per kg NO_2 are given. In order to find the costs of air pollution, the emission rates for both pollutants are multiplied by those prices. Afterwards, the costs per vehicle kilometer are summed up for both PM_{10} and NO_2.

[14] This information was provided by Drs. A. Hensema, Technical Consultant Mobility at TNO

As with traffic noise, air pollution is experienced as more unpleasant at road sections which are located in areas where a lot of residents live (near cities). This is the reason why a factor is added to this factor in order to give a higher weight to the costs of air pollution and thus a higher influence on the optimal speed limit near cities. The value of the factor is variable for each road section, as is the case for traffic noise. Again, in the next chapter the influence of this factor is defined in order to demonstrate the possible values of this factor.

3.4 Result of step 1 and step 2

After performing step 1 and step 2 described in the previous two sections, an optimal speed limit is determined for a road section. Here the optimal speed limit is determined for a road section, belonging to the chosen perspective (in this research: road authority- and road user perspective). This optimal speed limit results in the lowest costs for society. Furthermore, the engineering philosophy takes care of the fact that the determined optimal speed limit is possible on the road section (upper bound). This means that the optimal speed limit is safe under the prevailing road layout. As mentioned before in section 3.2.1, there are three possibilities available when the optimal speed limit is higher than the upper bound found in step 1 of the assessment framework:

1. Choose the boundaries of the road section differently, for instance in the normative road design element;
2. Lower the optimal speed limit locally, for instance at the normative road design element;
3. Apply engineering measures in order to allow the higher (optimal) speed limit that is still safe (however, it is assumed that engineering measures are not desirable in this research).

The user of the assessment framework is free to choose between these possibilities. The most optimal choice depends per situation. This is explained in the case study (chapter 4).

Note that when possibility no. 1 is chosen, different boundaries are applied to the economic optimization philosophy as well. This might result again in a higher optimal speed limit and as a consequence the choice between the three possibilities has to be made again.

In conclusion, after performing step 1 and step 2, the optimal speed limit determined in step 2 of the assessment framework is compared to the current speed limit. How this works is explained in section 3.6. First, the input data for the assessment framework is explained in section 3.5.

3.5 Input data

In order to carry out step 1 and step 2 in the assessment framework, shown in figure 3.1, the input data is needed for these two steps. This section describes the input data that is needed to perform step 1 (engineering) and step 2 (optimal speed limit) of the developed assessment framework. First, in section 3.5.1 the input data for the engineering philosophy is described. It becomes clear what data is needed to perform the engineering philosophy. Furthermore, in section 3.5.2 the input data for the economic optimization philosophy is set out. This data is used in Microsoft Excel in order to determine the optimal speed limit.

3.5.1 Input data for the engineering philosophy

In section 3.2 it is explained that the engineering philosophy is carried out for six critical road design elements:

1. Tunnels / Movable bridges;
2. Discontinuities (weaving lanes) behind each other;
3. On- and off ramps;
4. Tapers;
5. Horizontal- / Vertical curves;
6. Cross section left / right (including obstacle free space).

In order to determine the speed limit on a road section based on these six critical road design elements, input data on the road characteristics needs to be collected.

In table 3.6 a list is shown containing the needed input data for these six critical road design elements. All yellow blocks need to be filled in, if relevant. Google Earth was used to gather this data. With this program it is possible to obtain the required distances of the considered road section in an easy way.

It needs to be stated that the critical road design elements are not considered for each road section. This means that, for instance, a movable bridge is only located on several locations in the Dutch motorway network. As a consequence, this critical road design element is not considered for every road section. In table 3.6 at each critical road design element the question 'Is present?' is displayed (except at no. 6). If the answer on this question is found to be 'No', then the road design element is ignored. If the answer is 'Yes', the data is collected, where after the speed limit is determined using the flow charts described in section 3.2. For no. 6, the question 'Is present?' is not displayed. This critical road design element needs to be considered for each road section. Logically, the width of the lanes influences the speed limit in all cases (that is the reason why no. 6 is marked with a bold frame in table 3.6).

Note that both gradient α and tan α (mentioned in figure 3.6 for instance) are not taken into account in this thesis. It is assumed that these values are properly designed in the current layout of Dutch motorways in order to drive with a speed of 130 km/h.

Table 3.6: Input data for the engineering philosophy

1. Tunnels / Movable bridges → *Is present?*							
Tunnels							
Foot curve	*Horizontal-/Vertical curve*	*Cross section left/right*	*Slope*				
See no. 5	See no. 5	See no. 6	Not considered				
Movable bridges							
Vertical curves	*Cross section left/right*	*Slope*					
See no. 5	See no. 6	Not considered					
2. Discontinuities (weaving lanes) behind each other → *Is present?*							
Layout	Symmetric/Asymmetric						
Symmetric							
Number of lanes main road		*Number of lanes entering road*		*Length L1 [m]*			
Asymmetric							
Number of lanes main road		*Number of lanes entering road*		*Number of lanes main road 2*		*Length L1 [m]*	
3. On- and off ramps → *Is present?*							
On ramps	*Length L1 [m]*		*Length L2 [m]*				
Off ramps	*Length L1 [m]*		*Length L2 [m]*		*Length L3 [m]*		
4. Tapers → *Is present?*							
Layout	Two lanes on ramp/Two lanes off ramp						
Two lanes on ramp	*Length L1 [m]*						
Two lanes off ramp	*Length L1 [m]*		*Length L2 [m]*				
5. Horizontal-/Vertical curves → *Is present?*							
Horizontal curves	*Length R1/Length R2/Length R3 [m]*						
Vertical curves	*Foot curve at objects: length R [m]*						
	Top curve: length R [m]						
6. Cross section left/right (including obstacle free space)							
Passenger cars							
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*				
Trucks							
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*				
Obstacle free space	*Width B1 [m]*		*Width B2 [m]*				

3.5.2 Input data for the economic optimization philosophy

As is explained in section 3.3, the optimal speed limit is determined considering the following five significant factors:

1. Costs of travel time;
2. Vehicle operating costs;
3. Road accident costs;
4. Costs of traffic noise;
5. Costs of air pollution.

The data is collected for each significant factor. An assumption is that all data found is representative for the reference year 2010, no matter the year to which the data applies. The reference year 2010 is chosen because most of the data found was obtained in this year. This assumption is made in order to gain all the relevant data in the available time for this thesis. For instance, the parameters applied at the vehicle operating costs are for the year 2002. For the sake of simplicity, it is assumed that these parameters have not significantly changed during the years up to 2010.

In table 3.7 a list containing the data necessary for the economic optimization philosophy is shown. This data is used as input for Microsoft Excel where the developed overall function leads to the optimal speed limit (speed limit with the lowest costs for society). Here the developed overall function is derived according to the summation of the functions of the five significant factors explained before.

In the list in table 3.7 the yellow blocks are to be filled in. This data is specific for each road section and needs to be determined for each road section again. Note that there are similarities in the data needed. For instance, the truck percentage is needed for the cost of travel time, the vehicle operating costs and the road accident costs. Of course, the truck percentage contains the same value for each factor.

Furthermore, it needs to be stated that not all the data is variable for each road section. In the list in table 3.7, some data is already filled in. This data is indicated with a red block and is fixed for every road section. For this fixed data, the source is displayed as well in table 3.7. However, note that the user of the assessment framework is free to choose this data. For this research, the presented data in the red blocks is chosen, because this data is found in the available sources or is estimated in a way that the data is as close to reality as possible.

Table 3.7: Input data for the economic optimization philosophy

1. Cost of travel time		
VoT-value for passenger cars (all motives) for the year 2010 [euro/h]	10,67	*(Witteveen+Bos, 2011)*
VoT-value for trucks (road transport) for the year 2010 [euro/h]	45,78	*(Witteveen+Bos, 2011)*
Truck percentage [%]		

2. Vehicle operating costs				
Parameters for the vehicle fleet in 2002 [L/km] *(TAG, 2011)*				
	a	*b*	*c*	*d*
Average passenger car	0,96	0,05	-1,30*10^{-4}	2,54*10^{-6}
Average truck	1,16	0,06	-4,50*10^{-4}	8,64*10^{-6}
	Euro 95	*Diesel*		
Price per L at March 2012 [euro/L]	1,813	1,499	*(Autoweek, 2012)*	
Truck percentage [%]				

3. Road accident costs				
Price per fatality [euro/person]	2.690.108	*(Witteveen+Bos, 2011)*		
Price per severely injured [euro/person]	276.568	*(Witteveen+Bos, 2011)*		
	Number of accidents			
Fatal accidents				
Severely injured				
Current speed limit v0 [km/h]		*Length of road section [km]*		
Truck percentage [%]		*Total length of Dutch motorway network [km]*	2500	*(Rijkswaterstaat, 2012a)*
Total number of vehicle km for passenger cars and trucks on Dutch motorways [km]	46 * 10^9	*(Flikkema, 2003)*		

4. Costs of traffic noise			
Mean intensity of passenger cars per hour [veh/h]		*Length of road section [km]*	
Mean intensity of trucks per hour [veh/h]		*Factor for city [-]*	
Price of noise per dB(A) per person [euro/dB(A)/person]	27,97	*(Witteveen+Bos, 2011)*	
Total number of vehicle km for passenger cars and trucks on Dutch motorways [km]	46 * 10^9	*(Flikkema, 2003)*	
Total length of Dutch motorway network [km]	2500	*(Rijkswaterstaat, 2012a)*	
Total number of people affected by traffic noise [number]	238.000	*(Rijkswaterstaat, 2012b)*	

(pink)	Means: fixed data	(yellow)	Means: variable data

Table 3.8 continued: Input data for the economic optimization philosophy

5. Costs of air pollution					
Price per kg PM_{10} (for motorways) [euro/kg]		376,91	*(Witteveen+Bos, 2011)*		
Price per kg NO_2 (for motorways) [euro/kg]		15,08	*(Witteveen+Bos, 2011)*		
Factor for city [-]					
Emission rates for PM_{10} and NO_2 [kg/km] *(Drewes, 2006) and (De Lange et al., 2011)*					
Emission rates for PM_{10} for cars [kg/km]			*Emission rates for PM_{10} for trucks [kg/km]*		
50 km/h	$3,3 * 10^{-5}$		50 km/h	$8,0 * 10^{-5}$	
80 km/h	$3,3 * 10^{-5}$		60 km/h	$7,5 * 10^{-5}$	
100 km/h	$3,8 * 10^{-5}$		70 km/h	$7,0 * 10^{-5}$	
120 km/h	$3,9 * 10^{-5}$		80 km/h	$6,0 * 10^{-5}$	
130 km/h	$4,0 * 10^{-5}$		90 km/h	$5,2 * 10^{-5}$	
Emission rates for NO_2 for cars [kg/km]			*Emission rates for NO_2 for trucks [kg/km]*		
50 km/h	$1,8 * 10^{-4}$		50 km/h	$17,50 * 10^{-4}$	
80 km/h	$2,2 * 10^{-4}$		60 km/h	$16,00 * 10^{-4}$	
100 km/h	$2,8 * 10^{-4}$		70 km/h	$13,00 * 10^{-4}$	
120 km/h	$4,2 * 10^{-4}$		80 km/h	$11,25 * 10^{-4}$	
130 km/h	$5,0 * 10^{-4}$		90 km/h	$11,20 * 10^{-4}$	
	Means: fixed data			Means: variable data	

Collecting all input data for the engineering philosophy (step 1) and the economic optimization philosophy (step 2) explained in respectively table 3.6 and table 3.7, makes it possible to determine the optimal speed limit, with respect to the determined upper bound. As a next step, this optimal speed limit is compared to the current speed limit. This comparison leads to a result: an advice (step 3). In the next section, this third step is explained.

3.6 Step 3: comparison

In the developed assessment framework, the determined optimal speed limit dependent of the chosen perspective is compared with the current speed limit on a road section. There are three possible results for this comparison:

- Result 1: optimal speed limit < current speed limit;
- Result 2: optimal speed limit = current speed limit;
- Result 3: optimal speed limit > current speed limit.

In figure 3.14, the last part of the developed assessment framework is shown again: the comparison (step 3). For each of the three results introduced above, a distinction is made between two different types of results: permanent results and dynamic results. Permanent results are about the implementation of the new optimal speed limit for the whole day. That means that the speed limit is applied during every hour of the day. This speed limit is not dependent of the time of the day and in relation with that the intensity on the road.

On the other side, dynamic results do take into account the time dependency of the intensity. As is explained in the chapter 2, two approaches are available when the traffic state becomes worse:

- The breakdown prevention approach;
- The homogenisation approach.

It is advised to implement these approaches by using either intensity triggers or fixed time slots, as is explained in section 2.4.

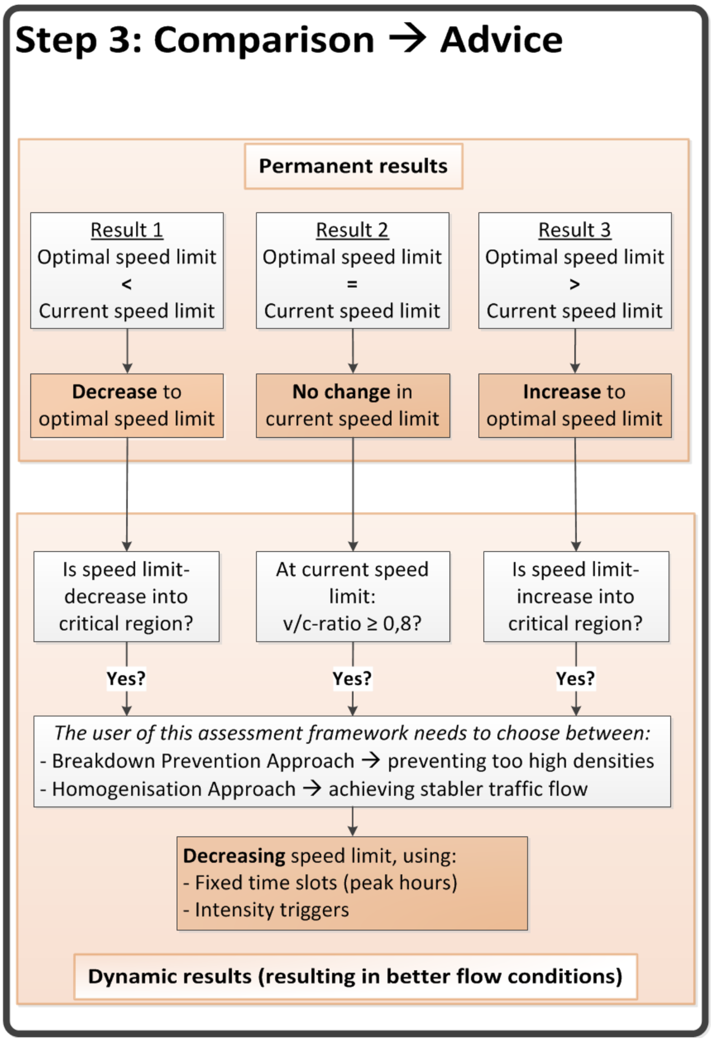

Figure 3.14: Step 3 from the assessment framework: the comparison

In figure 3.14, four dark orange squares can be seen: three at the permanent results and one at the dynamic results. These dark orange squares indicate what advice is given in relation to the current speed limit. The white squares indicate what requirements are taken into account. Dependent of these requirements, a permanent result is chosen. Note that the optimal speed limit is taken to be the same as the current speed limit, when the optimal speed limit is within a range of -5 km/h and +5 km/h of the current speed limit. Furthermore, the traffic flow conditions (v/c-ratio)[15] determine whether or not a dynamic speed limit is applied in order to improve the traffic flow conditions at the optimal speed limit (if necessary). It might be the case that the current speed limit is de- or increased into the critical region of the fundamental diagram (the critical speed limit). This is explained later on in this section. However, stop-and-go waves cannot dissolve automatically by itself anymore. Several measures are available to deal with this issue. In respectively section 3.6.1, section 3.6.2 and section 3.6.3, the measures are explained for each result.

In section 2.4, Dynamax is explained. Dynamax provides dynamic speed limits depending of the traffic flow, weather conditions or air quality (Wilmink and Schreuder, 2011). For each permanent result, the speed limit is decreased in case of bad weather conditions (in order to improve the traffic safety under these circumstances) or when the concentration of particulate matter (PM_{10}) almost reaches the critical value. Except for this speed decrease, a speed increase is also possible. The speed limit is increased when the intensity is relatively low in comparison with the capacity of the road (during off-peak hours, i.e. late in the evening). At these low intensities it is possible to drive at a higher speed in a safe way.

In the remainder of this section, each result of the assessment framework is explained in respectively section 3.4.1, section 3.4.2 and section 3.4.3.

3.6.1 Result 1: optimal speed limit < current speed limit

When the determined optimal speed limit is smaller than the current speed limit, result 1 is the case. For this result, the current speed limit is decreased to the optimal speed limit which is applied permanently (during all hours of the day).

It might be the case that the speed limit decrease is into the critical region of the fundamental diagram (the critical volume). This depends on the intensity on the road at the (new) optimal speed limit. According to Hegyi et al. (2005), the critical region is the unstable traffic flow state where any disturbance in the traffic flow will create a stop-and-go wave in the traffic flow. Furthermore, in section 2.4 it is explained that there are two main approaches available to improve the traffic flow state (and going from the unstable state to the metastable or the stable state) (Papageorgiou et al., 2011):

- *Breakdown prevention approach*: reduction of the mean speed at under critical densities. When the mean speed is reduced in advance, the inflow of vehicles

[15] v/c-ratio = volume/capacity-ratio, which is an indicator for the quality of the traffic flow (Board, 1985)

becomes lower than the outflow. This results in the disappearing of the shock wave;

- *Homogenization approach*: homogenization of speeds. This approach cannot suppress or resolve existing shock waves. It can only increase the time to a breakdown, because the speed differences are made smaller. Smaller speed differences lead to a safer traffic situation.

At both approaches, the speed limit is decreased in order to deal with the unstable traffic flow state in the fundamental diagram. In figure 3.15, two fundamental diagrams are shown: the u-k-diagram and the u-q-diagram. In these diagrams, the critical region, as is described above, is shown as well with the red circle.

In general, when there are no delays in the traffic system, the traffic flow state is somewhere between point A and C in figure 3.15 (stable- or metastable state). In this case, the current speed limit is reduced to the optimal speed limit. This results in a higher density (more vehicles per kilometre due to the lower speed limit). When the critical density is reached (point C in figure 3.15), the critical capacity is reached and congestion occurs (Hoogendoorn, 2007).

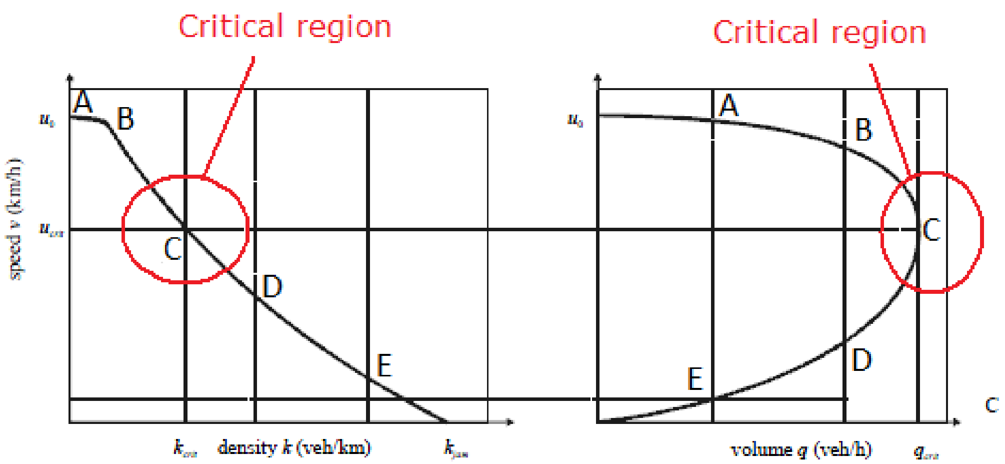

Figure 3.15: Critical region in fundamental diagrams (Hoogendoorn, 2007)

When the critical region shown in figure 3.15 is reached, the user of the assessment framework has to choose between the two approaches described before: the breakdown prevention approach or the homogenization approach. In this way, shock waves are taken care of: the shock waves disappear completely (breakdown prevention approach) or the traffic flow is only made more stable (homogenization approach). These measures are carried out using one of the following speed decreases (Hegyi et al., 2005):

- At the breakdown prevention approach, the optimal speed limit is decreased to a speed limit that is *below* the critical speed limit (below point C in figure 3.15). In this way, vehicles will drive slower than the critical speed limit. Because of the fact that vehicles at the critical capacity drive faster, the outflow is higher that the inflow. As a result, the congestion will disappear;

- At the homogenization approach, the optimal speed limit is decreased to a speed limit that is *above* the critical speed limit (above point C in figure 3.15). An example of such speed limit is the speed limit that corresponds to the maximal flow (so just above point C in figure 3.15). These speed limits only slightly reduce the average speed. They do not limit the traffic flow, while the speed limits at the breakdown prevention approach will limit the traffic flow.

The user of the assessment framework has to choose between the two approaches. The choice depends of the perspective that is used. For this thesis the user of the assessment framework is Rijkswaterstaat. Rijkswaterstaat decides what priority is used: either the shock waves are preferred to be dissolved automatically (breakdown prevention approach) or the traffic flow is preferred to be more stable (and safer). This choice is up to the user of the assessment framework.

Furthermore, when one of the approaches is chosen to deal with shock waves, two practical measures are advised to use. Hoogendoorn and Daamen (2008) performed a study to the speed blanket applied in the Netherlands (see section 2.4.4). The conclusions of this study are that fixed time slots and intensity triggers are proper measures for the two approaches mentioned before.

3.6.2 Result 2: optimal speed limit = current speed limit

In the case that the determined speed limit is similar to the current speed limit, this speed limit needs to be implemented. As explained before, the optimal speed limit is taken to be the same as the current speed limit, when the optimal speed limit is within a range of -5 km/h and +5 km/h of the current speed limit.

For this result, the quality of the traffic flow is determined at the current speed limit. Board (1985) defines the quality of the traffic flow as the ratio between the volume v [veh/h] and the capacity c [veh/h] (abbreviated as v/c-ratio). For the capacity the free capacity is used. The free capacity is the maximum intensity that a road section can assimilate just before congestion starts. Van Rij and Henkens (2009) provides these free capacities. They investigate the actual capacity values for motorways. The volume is derived from the Regiolab Delft[16].

[16] Regiolab Delft is a laboratory for regional traffic monitoring. Traffic data is obtained from systems and integrated in a traffic information system. This information is used to analyze a region under different conditions (website: http://www.citg.tudelft.nl/en/about-faculty/departments/transport-and-planning/research /facilities/software/regiolab-delft/)

After determining both the volumes and the free capacity, it is possible to obtain the v/c-ratio. This is done for each of the three days for each half an hour. In this way, an overview is obtained of the v/c-ratios for an average day with a time frame of 6:00 AM up to 8:00 PM.

Furthermore, when the v/c-ratio exceeds 0,8, the traffic flow is sensitive to shock waves (Van Rij and Henkens, 2009). In the overview described before, it is possible to obtain the first time that the v/c-ratio exceeds the value 0,8. Of course it is also possible that this value is not exceeded at all. Then the traffic flow is not sensitive to shock waves and measures to deal with these shock waves are not necessary.

In conclusion, when the v/c-ratio exceeds the value of 0,8, the user of the assessment framework chooses between the breakdown prevention approach and the homogenization approach. See section 3.4.1 for an explanation of this choice.

3.6.3 Result 3: optimal speed limit > current speed limit

When the optimal speed limit is higher than the current speed limit, the current speed limit is raised permanently to the optimal speed limit. As explained before, the optimal speed limit is taken to be the same as the current speed limit, when the optimal speed limit is within a range of -5 km/h and +5 km/h of the current speed limit.

When the current speed limit is raised to the optimal speed limit, it is only possible to come in the critical region (see section 3.4.1 for an explanation of the critical region) when the current speed limit is in the unstable state in advance. This means around point C in figure 3.15. When the speed limit is increased to the optimal speed limit, the density will reduce and so the traffic flow improves.

For the dynamic part in this result, it should be investigated whether or not the traffic state is still in the critical region when the optimal speed limit is applied. In case the traffic state is in the critical region, the same measures should be used as described in section 3.4.1. However, as was mentioned in chapter 1 in the scope of the research, it is beyond the scope of this research how dynamic speed limits work in detail. This is subject to further research.

3.7 Conclusion

This chapter presents the developed assessment framework. In figure 3.1, the structure of the assessment framework is shown. The developed assessment framework consists of three steps.

Step 1 and step 2 result in an optimal speed limit, taking the roadway geometry into account. In step 1, the roadway geometry is considered when determining the maximum possible speed limit. This speed limit functions as the upper bound in the assessment framework. In step 2, the optimal speed limit is determined. This is the speed limit with the lowest costs for society. At this determination, the significant factors are considered. The significant factors are the factors dependent of the chosen perspective: the road authority or the road user.

Step 3 compares the determined optimal speed limit to the current speed limit. In this comparison, three permanent results – which are applied during all hours of the day – are possible:

- Result 1: optimal speed limit < current speed limit;
- Result 2: optimal speed limit = current speed limit;
- Result 3: optimal speed limit > current speed limit.

At the chosen permanent result, the project Dynamax is applied. Dynamax provides dynamic speed limits depending on traffic flow, weather conditions or air quality. For traffic flow, the applied dynamic speed limits lead to better traffic flow conditions. Depending on these traffic flow conditions, a dynamic speed limit is applied. During peak hours, when the traffic flow becomes sensitive to small disturbances that lead to breakdowns in the traffic flow, a lower speed limit functions as a proper measure to deal with breakdowns. Available approaches to deal with this issue are the breakdown prevention approach and the homogenization approach.

The user of the assessment framework chooses the preferred measure: either solving the shock waves or homogenizing the traffic flow. There are two practical measures advised to use within this choice:

- Fixed time slots;
- Intensity triggers.

In the next chapter, the developed assessment framework is tested in a case study. The results of the case study show whether or not the assessment framework works properly in practice. In chapter 5, the results of the case study are evaluated. After this evaluation, it is possible to make an overall judgment about the current speed policy of Dutch motorways.

4 Case study

In this chapter, the assessment framework developed in chapter 3 is tested on a set of road sections on Dutch motorway network. On the basis of these results it is possible to conclude whether or not the steps in the developed assessment framework work properly. Furthermore, the results of the case study are used to evaluate the current speed policy of Dutch motorways. This is done in chapter 5. In this evaluation, the usefulness of the assessment framework in practice becomes clear.

In this case study, a set of road sections to be tested has been selected. This set of road sections consists of six road sections. The choice for these road sections is based on the formulated motto in chapter 2: *faster if possible, slower when necessary*. Here, the credibility towards the road user plays a leading role. This means that the road sections for this case study are chosen where it may be expected that a higher speed limit (either dynamic or static) should be applied. On these road sections, the current speed limit seems to be experienced as too low. In this sense, two motorways where the speed limit was recently increased to 130 km/h are tested in this case study as well.

First, section 4.1 starts with the set-up of the case study. In section 4.2 to 4.7 the assessment framework is applied to the six road sections. Finally, the conclusions are given in section 4.8 (including a summary of the results).

4.1 Set-up of the case study

In this section, the set of road sections which are tested in the case study are described. As is explained in the introduction of this chapter, the set of road sections is based on the expectation that road users experience the current speed limit as too low. In the first section, the set of road sections is described. This set consists of six road sections in the Dutch motorway network. Furthermore, in section 4.1.2, the relevant characteristics of these road sections are shown. These characteristics are needed to determine the optimal speed limit.

4.1.1 The chosen set of road sections for the case study

For this case study, a set of road sections has been selected to test in the assessment framework. In total six road sections were selected. In table 4.1, the selected road sections are described. These road sections are all situated in the Dutch motorway network. The 'R' behind the highway number indicates that only one direction is considered: only the direction of increasing kilometres on the (green) hectometer poles placed every 100 meters next to the motorway.

Table 4.1: The set of road sections for the case study

Motorway	Traject	Hectometer poles [km]
A2R	Junction Holendrecht → Maarssen	37,1 – 55,8 → 18,7 km
A2R	Junction Everdingen → Junction Deil	75,0 – 89,5 → 14,5 km
A4R	Junction Burgerveen → Leidschendam	19,2 – 43,5 → 24,3 km
A13R	Berkel en Rodenrijs → Junct. Kleinpolderplein	16,5 – 18,6 → 2,1 km
A16R	Junction Klaverpolder→ Junction Princeville	47,3 – 60,6 → 13,3 km
A20R	Jun. Kleinpolderplein → Jun. Terbrechtseplein	29,4 – 34,8 → 5,4 km

The six road sections mentioned in table 4.1 are displayed in figure 4.1.

Figure 4.1: Set of six road sections for the case study (source: maps.google.nl)

The scope of this research mentioned in chapter 1 applies to the six road sections used in this case study. Furthermore, three more assumptions for this case study are made. These assumptions are as follows:

- It is assumed that the road sections are in normal condition. The construction zones which might lead to a lower allowed speed limit (i.e. due to the smaller driving lanes at construction zones), are not taken into account. For this case study, the optimal speed limit is determined for the finished situation. When not all data is available for the new situation, old data from before the road works is used.

- Recently, speed limits were increased on three of the five 80 km/h zones in the Netherlands. The 80 km/h zones are implemented near large cities in the Netherlands (Amsterdam, Utrecht, The Hague and Rotterdam) and are set because of environmental issues and/or noise nuisance[16]. One of these 80 km/h zones is the A13R between Berkel en Rodenrijs and Junction Kleinpolderplein (near Rotterdam). On this road section, the speed limit is increased from 80 km/h to 100 km/h. On the website of Rijkswaterstaat[17] it is explained that because of the improvement of the air quality during the last few years, a higher speed limit of 100 km/h is allowed. For this case study, this increased speed limit to 100 km/h is used as the current speed limit (see table 4.2).
- On these days, the speed limit on the A4R at Leiderdorp is equal to 80 km/h, while originally the speed limit on the A4R was 100 km/h on this whole section. For this case study, the situation without the sunken part of the road section at Leiderdorp (with a speed limit of 80 km/h) is considered. Instead of the sunken part, the movable bridge located in the A4R is taken into account. This choice is made, because data for the new situation is not yet available.

In appendix E, impressions of the six road sections are displayed. Photos are shown of the road sections, including the current speed limit (the current speed limits are given in table 4.2 as well). The reader of this report can decide by himself whether or not the current speed limits displayed at the photos in appendix E are credible.

4.1.2 Relevant characteristics of the road sections for the case study

For the six road sections, relevant characteristics were gathered. The relevant characteristics function as input data for the economic optimization philosophy (step 2 in the assessment framework). In table 4.2, the relevant characteristics, which are marked as variable data in the list in table 3.7, are shown. Those characteristics are:

- Current speed limit [km/h];
- Truck percentage [%];
- Intensity (traffic demand) [veh/h];
- Crash statistics [number/year]

The length of the road sections is derived from table 4.1 (the difference between the hectometer poles). For the engineering philosophy, the input data (roadway dimensions) is gathered and described in the next sections where the determination of the upper bound in het assessment framework due to the road layout is provided.

[17] Rijkswaterstaat: http://www.rijkswaterstaat.nl/wegen/innovatie_en_onderzoek/maximumsnelheden/

Table 4.2: Relevant characteristics of the road sections for the case study

Road section	Current speed limit [km/h]	Truck percent-tage [%]	Intensity (traffic demand) [veh/h]	Crash statistics [number]
A2R: Jun. Holendrecht → Maarssen	100	10,0	Passenger cars: 5422	Fatalities: 1
			Trucks: 588	Serious injured: 10
A2R: Jun. Everdingen → Jun. Deil	130	12,2	Passenger cars: 4338	Fatalities: 0
			Trucks: 912	Serious injured: 2
A4R	100	9,2	Passenger cars: 4481	Fatalities: 0
			Trucks: 575	Serious injured: 7
A13R	100	9,0	Passenger cars: 6285	Fatalities: 0
			Trucks: 559	Serious injured: 0
A16R	130	9,1	Passenger cars: 4730	Fatalities: 0
			Trucks: 540	Serious injured: 2
A20R	80	9,4	Passenger cars: 6819	Fatalities: 0
			Trucks: 607	Serious injured: 6

Some remarks on table 4.2:

- As explained in section 3.3, the truck percentages are provided by Van Rij and Henkens (2009) as a mean value for the years 2005-2006 and is used to calculate the mean VoT-values for both passenger cars and trucks.
- The intensity on a road section (which can be read as the traffic demand as well) is distracted from the NSL monitoringstool. This is a website[18] where for each road section both the number of passenger cars and trucks is provided for the year 2011. This distinction is needed for this research as well, because trucks cause more noise than passenger cars and thus have a higher influence on the traffic noise.
- The crash statistics are derived from the 'record of registered accidents in the Netherlands' ('Bestand geRegistreerde Ongevallen in Nederland' (BRON)) for the year 2010. Distinction is made between fatalities and serious injured in order to fill in the two power function of Nilsson (2004) described in section 3.3.

[18] http://www.nsl-monitoring.nl/rekenen/

Note that it is assumed that all data found is representative for the reference year 2010, no matter the year in which the determined data applies.

In the remainder of this chapter, the assessment framework is applied to the six road sections mentioned in table 4.2. In section 4.2, the application of the assessment framework on the A2R: Junction Holendrecht → Maarssen is described in detail. It exemplifies how the steps in the developed assessment framework work. For the rest of the case studies, the application of the assessment framework is described more briefly to avoid unnecessary repetition. Sections 4.3 to 4.8 describe the rest of the case studies respectively. Finally, the results of the case study are summarized in the conclusion in section 4.9.

4.2 Application of the assessment framework on the A2R: Junction Holendrecht → Maarssen

This section describes the case study for the A2R: Junction Holendrecht → Maarssen. First, the collected input data for this road section is described. In section 4.2.2, step 1 of the assessment framework is applied to this road section. Section 4.2.3 describes the results of step 2. The results of step 1 and step 2 are explained in section 4.2.4. Finally, in section 4.2.5 the comparison between the current speed limit and the determined optimal speed limit is shown. An advice that is derived from the comparison is included as well.

4.2.1 Collected input data

In this section, the input data for the A2R: Junction Holendrecht → Maarssen is collected. First, the critical road design elements of this road section are investigated which are used in the engineering philosophy. For this investigation, the road section is displayed in a schematically way. Secondly, the data needed for the determination of the optimal speed limit is explained.

Data for the engineering philosophy

The relevant critical road design elements are determined using the program Google Earth. With this program, the road layout characteristics needed for the engineering philosophy are determined in an easy way. In figure 4.2, the schematic overview of the A2R: Junction Holendrecht → Maarssen is shown, including the critical road design elements.

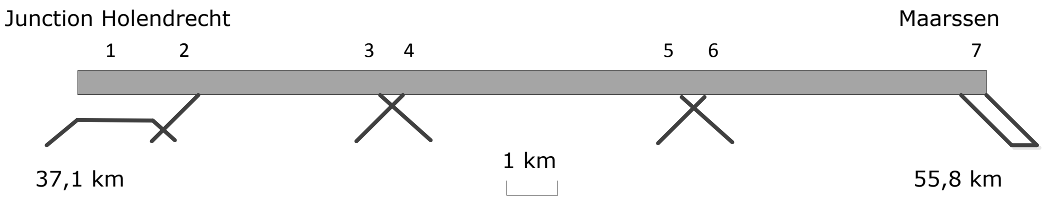

Figure 4.2: Schematic overview of A2R: Junction Holendrecht → Maarssen

In figure 4.2, the critical road design elements are indicated with numbers. These numbers are explained in table 4.3.

Table 4.3: Critical road design elements A2R: Junction Holendrecht → Maarssen

No.	Critical road design element
1	Weaving lane (asymmetric)
2	On ramp
3	Off ramp
4	On ramp
5	Off ramp
6	On ramp
7	Taper (divided motorways)

Except for the critical road design elements mentioned in table 4.3, the cross section of the road section is also considered. The location of the cross sections is chosen by the user of the assessment framework. It is expected that the user of the assessment framework is capable to decide where the road section is the most narrow and thus where the normative cross section is located. The determined data for both the critical road design elements in table 4.3 and the cross section of the road section is depicted in the list in appendix F.1.

Data for the economic optimization process

In order to determine the optimal speed limit, the list given in table 3.7 is filled in. This list is also shown in appendix F.1 as the second list. In this list, some data is coloured red and other data is coloured yellow. The red blocks are fixed data and are the same for each road section. For the yellow blocks, all the needed data is given in table 4.2, where the relevant characteristics for the road sections are shown. The length of the road section is derived from table 4.1.

Furthermore, for the determination of the factor for a city, a website[19] developed by Rijkswaterstaat is used. On this website, an interactive noise map is shown. The noise map shows how much noise is produced by the traffic on Dutch motorways for the year 2006. It is assumed that this noise production applies for the reference year 2010. On this map, it is also shown where a lot of urbanized area is located. On this way, it can be investigated whether or not a road section is situated in urbanized area.

For this road section applies that the road section is not located near urbanized area. That is the reason why the factor for the city is chosen to be equal to 1 in this case.

For the remainder of the case studies, table 4.2 is used as input data for the economic optimization philosophy as well. The lists with this data are not mentioned any more in appendix F for the rest of the case studies. This is done to avoid the presence of almost similar lists. Only the value of the factor for a city is considered for each case study.

4.2.2 Step 1: application of the engineering philosophy on the A2R: Junction Holendrecht → Maarssen

In appendix F.1, the data for the critical road design elements is given. Applying this data to the flow charts presented in section 3.2 gives a set of speed limits, belonging to the road layout. In table 4.4, this set of speed limits is shown. For each critical road design element the speed limit (upper bound) is depicted.

Table 4.4: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	Weaving lane (asymmetric)	120 / 130 km/h
2	On ramp	120 / 130 km/h
3	Off ramp	120 / 130 km/h
4	On ramp	120 / 130 km/h
5	Off ramp	120 / 130 km/h
6	On ramp	120 / 130 km/h
7	Taper (divided motorways)	120 / 130 km/h
	Cross section	120 / 130 km/h

In table 4.4, the lowest value, which functions as the upper bound, is **120 / 130 km/h** (this is the speed limit which is still safe under the prevailing conditions for this road section).

[19] http://www.rijkswaterstaat.nl/wegen/plannen_en_projecten/geluid_rond_snelwegen_nederland/geluidskaart/

4.2.3 Step 2: application of the economic optimization philosophy on the A2R: Junction Holendrecht → Maarssen

As is explained in section 4.2.1, the data needed for the determination of the optimal speed limit is depicted in the list shown in table 3.7, where the data in table 4.2 is filled in. For this case study, the list is shown in appendix F.1. The data in the list is used in Microsoft Excel. Here, for each significant factor a formula is set up which describes the relation between the speed limit and the costs / vehicle kilometre (as explained in section 3.2). In order to obtain the optimal speed limit, the five formulas are summed up in order to derive the overall function. This overall function gives the total cost. The speed limit with the lowest costs / vehicle kilometre in this function is the optimal speed limit. Next, this is performed for the chosen perspectives in this research, first for the road authority perspective and second for the road user perspective.

Road authority perspective

In figure 4.3, the optimal speed limit is indicated with a red dot for the case that the road authority perspective has chosen. The cost functions of the significant factors are all applied with the weight equal to 1. This means that each factor is considered in the same ratio. The road authority considers each significant factor in the same way (as is explained in the mission of Rijkswaterstaat (the road authority) in the state of the art-chapter).

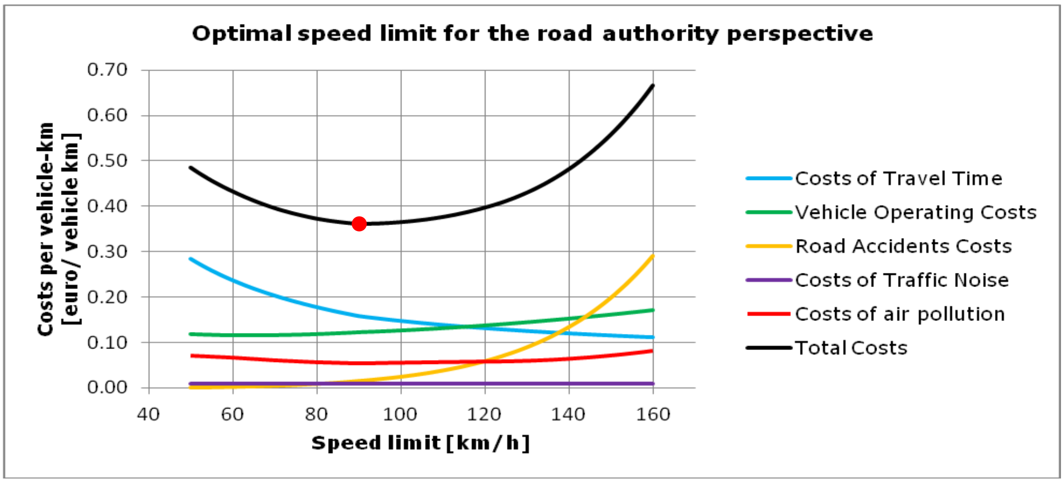

Figure 4.3: Optimal speed limit for the road authority perspective

Figure 4.3 shows that the optimal speed limit for the road authority is equal to **90 km/h**. This is the speed limit at which the costs / vehicle kilometre are the lowest (in the overall function or the total costs-curve).

Furthermore, figure 4.3 shows that the costs of traffic noise are relatively small (almost zero) in comparison to the other factors. On the scale applied in figure 4.3, it seems to be that the costs of traffic noise are a linear line. However, this line increases as the speed limit increases (logically, at higher speed limits, a vehicle produces more noise due to the friction between the tires and the asphalt). Nevertheless, the influence of the costs of traffic noise on the optimal speed limit is nil. This is more or less the case for the costs of air pollution as well. These solutions are called Pareto optimal solutions. There is not one solution which optimizes all targets on a linear line at the same time (Wismans et al., 2011).

Road user perspective

For the road user perspective, not all significant factors are considered. Only the costs of travel time and the vehicle operating costs are considered. In the state of the art-chapter it has been explained that the road user wants to travel as fast and cheap as possible, no matter what consequences this has for the surroundings. In figure 4.4, the optimal speed limit for the road user perspective is shown. The red dot indicates an optimal speed limit of **121 km/h**. The list containing the data for the determination of the optimal speed limit, shown in table 3.7, shows that only the truck percentage influences the optimal speed in case of the road user perspective. The other data is fixed for each road section.

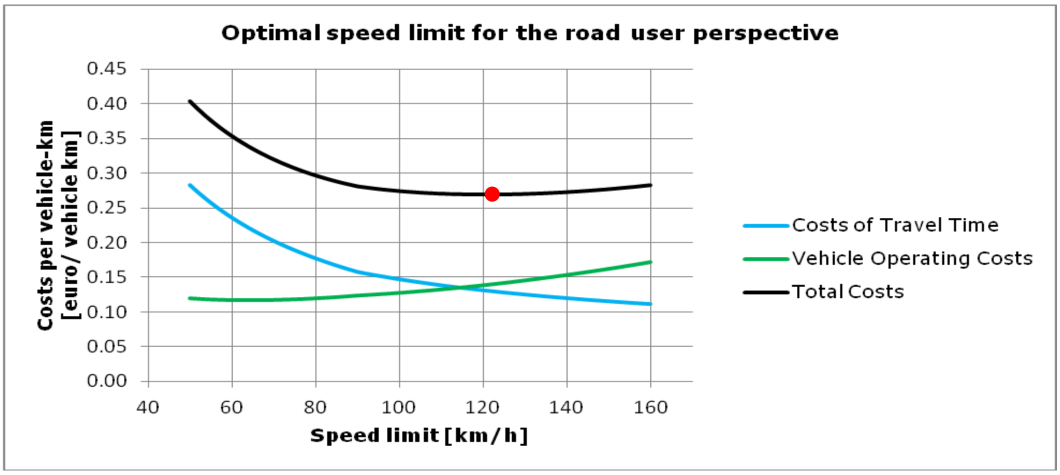

Figure 4.4: Optimal speed limit for the road user perspective

4.2.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 120 / 130 km/h
- Step 2:
  - Road authority perspective: 90 km/h
  - Road user perspective: 121 km/h

→ For both perspectives, the determined optimal speed limit is lower than the determined upper bound. So, these optimal speed limits are used in step 3: comparison with the current speed limit.

4.2.5 Step 3: comparison, resulting in an advice for the A2R: Junction Holendrecht → Maarssen

In this last step of the developed assessment framework, the current speed limit on the road section is compared to the determined optimal speed limits for both perspectives. In table 4.2, the current speed limit is shown. In this case, the current speed limit is 100 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

The comparison is as follows: 90 km/h < 100 km/h. This comparison means that the permanent result (applied during all hours of the day) is result 1: Decrease to the optimal speed limit.

For the dynamic result, the intensity must be measured at the (new) optimal speed limit of 90 km/h. When due to this intensity stop-and-go waves occur (and thus the critical region is reached as described in section 3.6.1), the user of the assessment framework can choose between the breakdown prevention approach or the homogenization approach to deal with the stop-and-go waves. When the critical region is reached, it is advised to apply the homogenization approach. Rijkswaterstaat is the user of the developed assessment framework and their mission is to create a good and safe traffic situation for the road user. The homogenization approach achieves a more stable traffic flow, which will result in safer traffic circumstances. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Road user perspective

The comparison is as follows: 121 km/h > 100 km/h. This comparison means for the permanent result result 3: Increase to the optimal speed limit.

In section 3.6.3 it is explained that when the current speed limit is raised to the optimal speed limit, it is only possible to come in the critical region when the current speed limit is in the unstable state in advance. For the dynamic part in this result, it should be investigated whether or not the traffic state is still in the critical region when the optimal speed limit is applied. In case the traffic state is in the critical region, the user of the assessment framework may once again choose between the breakdown prevention approach and the homogenization approach. In this case, it is advised to apply the breakdown prevention approach. The road user has the objective to travel as fast and cheap as possible. The breakdown prevention approach prevents high densities as inflow. In a certain amount of time, the stop-and-go waves disappear and the traffic state is stable again. So, further research is needed about whether or not the traffic state is still in the critical region at the (new) optimal speed limit due to the intensity at that optimal speed limit.

Overview of the results

In table 4.5, an overview of the results for this case study is summarized. Here a distinction is made between the road authority and the road user. The advice per chosen perspective is shown as well.

Table 4.5: Overview of the results of the A2R: Junction Holendrecht → Maarssen

Road authority perspective		**Road user perspective**	
Step 1	120 / 130 km/h	*Step 1*	120 / 130 km/h
Step 2	90 km/h	*Step 2*	121 km/h
Optimal speed limit	90 km/h	*Optimal speed limit*	121 km/h
Current speed limit	100 km/h	*Current speed limit*	100 km/h
Permanent result	Decrease	*Permanent result*	Increase
Dynamic result	Further research	*Dynamic result*	Further research
Advice: → Permanent: decrease to optimal speed limit; → Dynamic: further research to critical region, if yes: apply homogenization approach.		*Advice:* → Permanent: increase to optimal speed limit; → Dynamic: further research to critical region, if yes: apply breakdown prevention approach.	

As mentioned before, only the first case study is described in detail (in section 4.2). The rest of the case studies are described more briefly in order to avoid unnecessary repetitions.

4.3 Application of the assessment framework on the A2R: Junction Everdingen → Junction Deil

In this section, the application of the assessment framework on the A2R: Junction Everdingen → Junction Deil is described.

4.3.1 Collected input data

In this section, the input data for the A2R: Junction Everdingen → Junction Deil is collected.

Data for the engineering philosophy

In figure 4.5, the schematic overview of the A2R: Junction Everdingen → Junction Deil is shown.

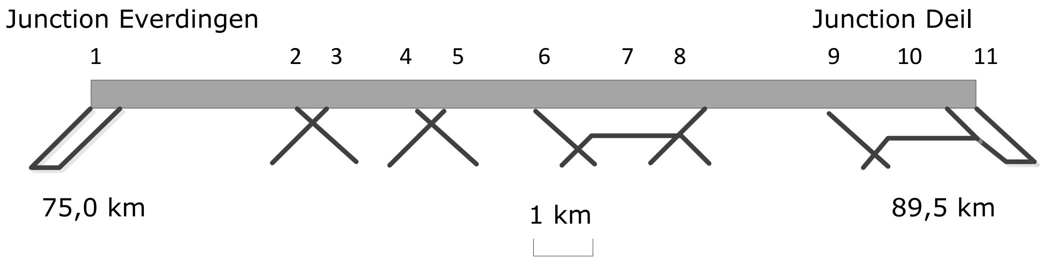

Figure 4.5: Schematic overview of A2R: Junction Everdingen → Junction Deil

In figure 4.5, the critical road design elements are indicated with numbers. These numbers are explained in table 4.6.

Table 4.6: Critical road design elements A2R: Junction Everdingen → Junction Deil

No.	Critical road design element
1	Taper (joining motorways)
2	Off ramp
3	On ramp
4	Off ramp
5	On ramp
6	Off ramp
7	Weaving lane (symmetric)
8	On ramp
9	Off ramp
10	Weaving lane (symmetric)
11	Taper (divided motorways)

The determined data for both the critical road design elements in table 4.6 and the cross section of the road section is depicted in the list in appendix F.2.

Data for the economic optimization process

On the interactive noise map is found that the road section does not run through urbanized area. For this reason, the factor for the city is chosen equal to 1.

4.3.2 Step 1: application of the engineering philosophy on the A2R: Junction Everdingen → Junction Deil

In table 4.7, the speed limit (upper bound) is displayed for each critical road design element.

Table 4.7: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	Taper (joining motorways)	120 / 130 km/h
2	Off ramp	120 / 130 km/h
3	On ramp	120 / 130 km/h
4	Off ramp	120 / 130 km/h
5	On ramp	120 / 130 km/h
6	Off ramp	120 / 130 km/h
7	Weaving lane (symmetric)	120 / 130 km/h
8	On ramp	120 / 130 km/h
9	Off ramp	120 / 130 km/h
10	Weaving lane (symmetric)	120 / 130 km/h
11	Taper (divided motorways)	120 / 130 km/h
	Cross section	120 / 130 km/h

In table 4.7, the lowest value is **120 / 130 km/h**.

4.3.3 Step 2: application of the economic optimization philosophy on the A2R: Junction Everdingen → Junction Deil

In this section, the optimal speed limit is determined for the road authority perspective and the road user perspective respectively.

Road authority perspective

In figure 4.6, the optimal speed limit is indicated with a red dot: **112 km/h**.

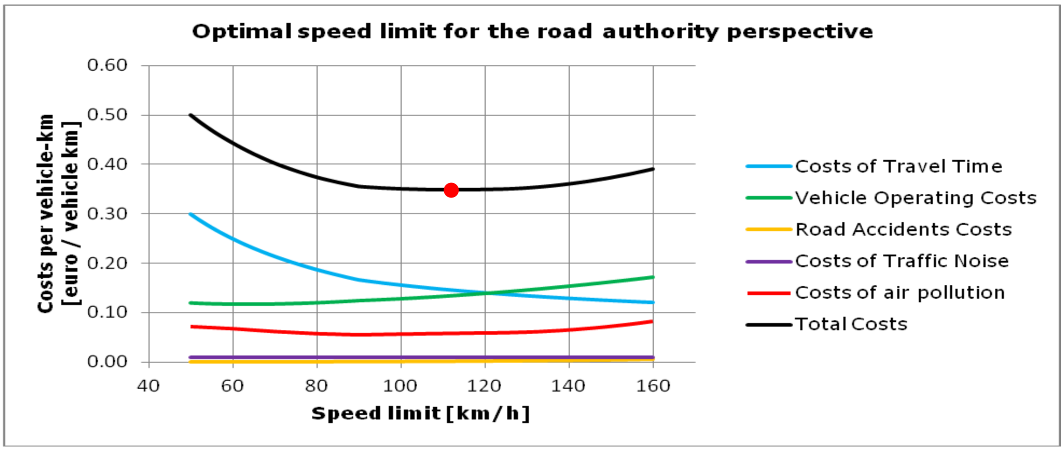

Figure 4.6: Optimal speed limit for the road authority perspective

Road user perspective

In figure 4.7, the optimal speed limit is indicated with a red dot: **121 km/h**.

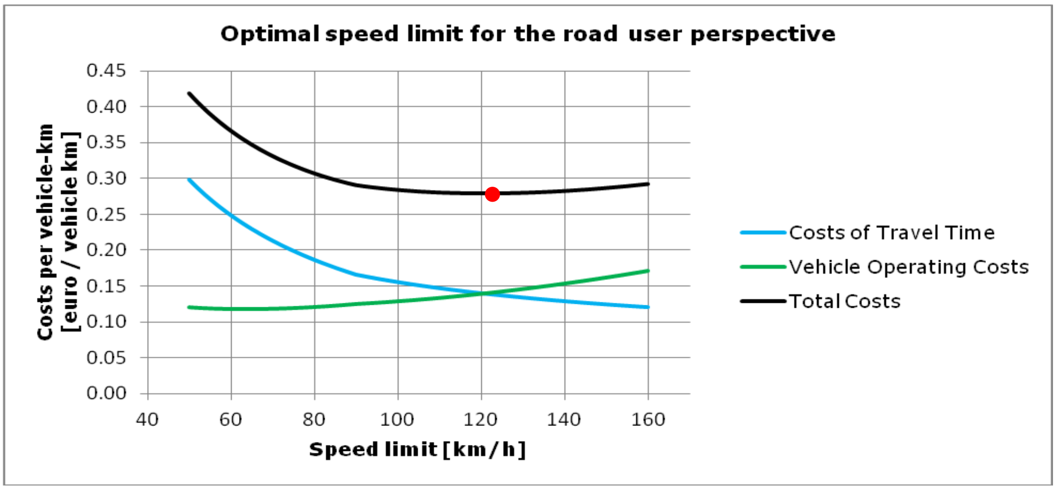

Figure 4.7: Optimal speed limit for the road user perspective

4.3.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 120 / 130 km/h
- Step 2:
  - Road authority perspective: 112 km/h
  - Road user perspective: 121 km/h

➔ For both perspectives, the determined optimal speed limit is lower than the determined upper bound. Therefore, these optimal speed limits are used in the next step: comparison with the current speed limit.

4.3.5 Step 3: comparison, resulting in an advice for the A2R: Junction Everdingen → Junction Deil

According to table 4.2, the current speed limit for this road section is 130 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

Comparison: 112 km/h < 130 km/h.

- Permanent result: result 1: Decrease to the optimal speed limit.
- Dynamic result: advice: apply the homogenization approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Road user perspective

Comparison: 121 km/h < 130 km/h.

- Permanent result: result 1: Decrease to the optimal speed limit.
- Dynamic result: advice: apply the breakdown prevention approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Overview of the results

In table 4.8, an overview of the summarized results for this case study can be found.

Table 4.8: Overview of the results of the A2R: Junction Everdingen → Junction Deil

Road authority perspective		**Road user perspective**	
Step 1	120 / 130 km/h	*Step 1*	120 / 130 km/h
Step 2	112 km/h	*Step 2*	121 km/h
Optimal speed limit	112 km/h	*Optimal speed limit*	121 km/h
Current speed limit	130 km/h	*Current speed limit*	130 km/h
Permanent result	Decrease	*Permanent result*	Decrease
Dynamic result	Further research	*Dynamic result*	Further research
Advice: → Permanent: decrease to optimal speed limit; → Dynamic: further research to critical region, if yes: apply homogenization approach.		*Advice:* → Permanent: decrease to optimal speed limit; → Dynamic: further research to critical region, if yes: apply breakdown prevention approach.	

4.4 Application of the assessment framework on the A4R: Junction Burgerveen → Leidschendam

In this section, the application of the assessment framework on the A4R is described.

4.4.1 Collected input data

In this section, the input data for the A4R is collected.

Data for the engineering philosophy

In figure 4.8, the schematic overview of the A4R is shown. For this road section, the old situation is considered. The sunken part of the road section at Leiderdorp (which was opened recently) is not taken into account. Instead, the movable bridge (no. 6 in figure 4.8) is considered, because data for the new situation is not yet available.

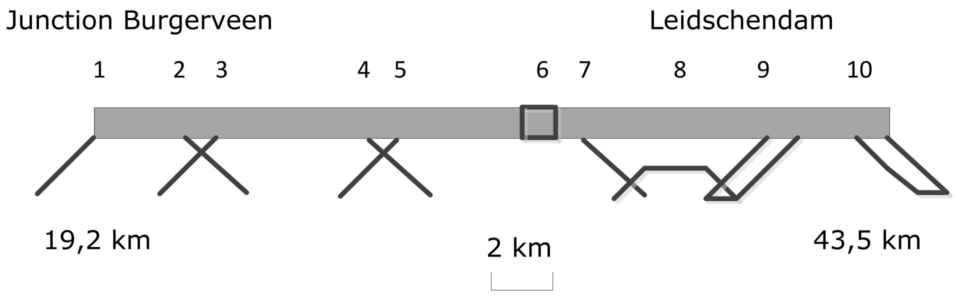

Figure 4.8: Schematic overview of A4R

In figure 4.8, the critical road design elements are indicated with numbers. These numbers are explained in table 4.9.

Table 4.9: Critical road design elements A4R

No.	Critical road design element
1	On ramp
2	Off ramp
3	On ramp
4	Off ramp
5	On ramp
6	Movable bridge
7	Off ramp
8	Weaving lane (symmetric)
9	Taper (joining motorways)
10	Taper (divided motorways)

The determined data for both the critical road design elements in table 4.9 and the cross section of the road section is depicted in the list in appendix F.3.

Data for the economic optimization process

On the interactive noise map is found that the road section does not run through urbanized areas. For this reason, the factor for the city is chosen equal to 1.

4.4.2 Step 1: application of the engineering philosophy on the A4R

In table 4.10, the speed limit (upper bound) is displayed for each critical road design element.

Table 4.10: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	On ramp	120 / 130 km/h
2	Off ramp	120 / 130 km/h
3	On ramp	120 / 130 km/h
4	Off ramp	120 / 130 km/h
5	On ramp	120 / 130 km/h
6	Movable bridge	100 km/h
7	Off ramp	120 / 130 km/h
8	Weaving lane (symmetric)	120 / 130 km/h
9	Taper (joining motorways)	120 / 130 km/h
10	Taper (divided motorways)	120 / 130 km/h
	Cross section	120 / 130 km/h

In table 4.10, the lowest value is **100 km/h**.

4.4.3 Step 2: application of the economic optimization philosophy on the A4R

In this section, the optimal speed limit is determined for the road authority perspective and the road user perspective respectively.

Road authority perspective

In figure 4.9, the optimal speed limit is indicated with a red dot: **94 km/h**.

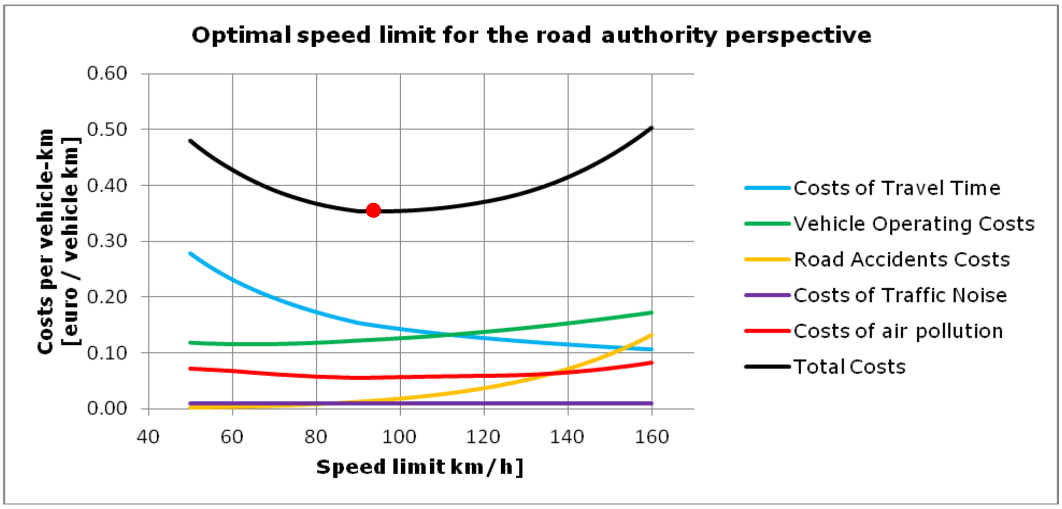

Figure 4.9: Optimal speed limit for the road authority perspective

Road user perspective

In figure 4.10, the optimal speed limit is indicated with a red dot: **121 km/h**.

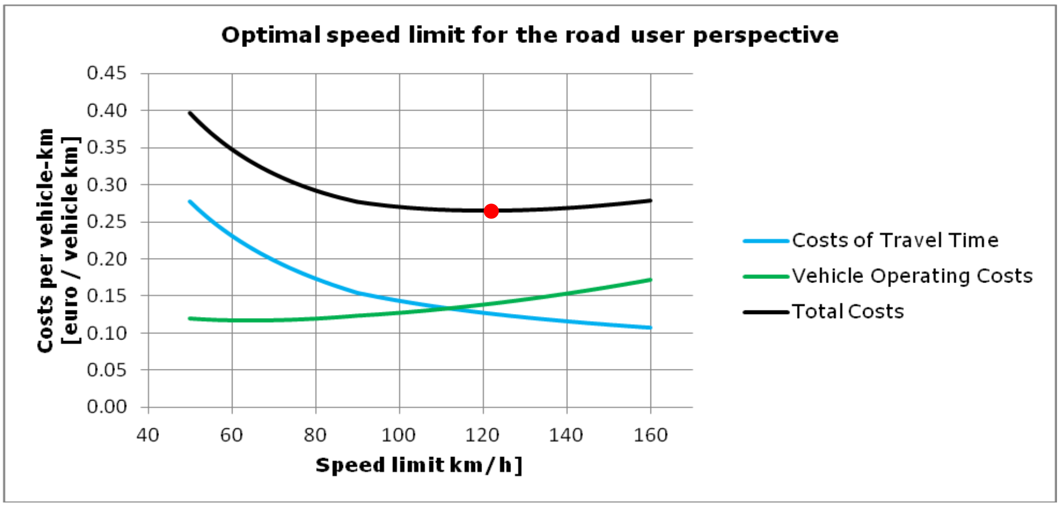

Figure 4.10: Optimal speed limit for the road user perspective

4.4.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 100 km/h
- Step 2:
  - Road authority perspective: 94 km/h
  - Road user perspective: 121 km/h

➔ For the road authority perspective, the determined optimal speed limit is lower than the upper bound. So, in case of the road authority perspective, 94 km/h is chosen.

➔ For the road user perspective, the determined optimal speed limit is higher than the upper bound. In section 3.4 it is explained that when the optimal speed limit is higher than the upper bound, a choice needs to be made between three possibilities:

1. Choose the boundaries of the road section differently, for instance in the normative road design element;
2. Lower the optimal speed limit locally, for instance at the normative road design element;
3. Apply engineering measures in order to allow the higher (optimal) speed limit that is still safe (however, it is assumed that engineering measures are not desirable in this research).

In table 4.10 it can be seen that only because of the movable bridge an upper bound of 100 km/h is selected. For the other critical road design elements, an upper bound of 120 /130 km/h is allowed.

Because the road user only considers the costs of travel time and the vehicle operating costs, it does not make sense to choose possibility 1. In case of the road user perspective, only the truck percentage changes. Possibility 2 is sufficient enough and the speed limit should be lowered at the movable bridge to 100 km/h. On this road section, an optimal speed limit is chosen equal to 121 km/h for the road user perspective.

4.4.5 Step 3: comparison, resulting in an advice for the A4R

According to table 4.2, the current speed limit for this road section is 100 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

Comparison: 94 km/h < 100 km/h.

- Permanent result: result 1: Decrease to the optimal speed limit.
- Dynamic result: advice: apply the homogenization approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Road user perspective

Comparison: 121 km/h > 100 km/h.

- Permanent result: result 3: Increase to the optimal speed limit.
- Dynamic result: advice: apply the breakdown prevention approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Overview of the results

In table 4.11, an overview of the results for this case study is summarized.

Table 4.11: Overview of the results of the A4R

Road authority perspective		**Road user perspective**	
Step 1	100 km/h	*Step 1*	100 km/h
Step 2	94 km/h	*Step 2*	121 km/h
Optimal speed limit	94 km/h	*Optimal speed limit*	121 km/h, with lower speed limit of 100 km/h at movable bridge
Current speed limit	100 km/h	*Current speed limit*	100 km/h
Permanent result	Decrease	*Permanent result*	Increase
Dynamic result	Further research	*Dynamic result*	Further research
Advice: ➔ Permanent: decrease to optimal speed limit; ➔ Dynamic: further research to critical region, if yes: apply homogenization approach.		*Advice:* ➔ Permanent: increase to optimal speed limit, with a speed limit of 100 km/h at the movable bridge; ➔ Dynamic: further research to critical region, if yes: apply breakdown prevention approach.	

4.5 Application of the assessment framework on the A13R: Berkel en Rodenrijs → Junction Kleinpolderplein

In this section, the application of the assessment framework on the A13R is described.

4.5.1 Collected input data

In this section, the input data for the A13R is collected.

Data for the engineering philosophy

In figure 4.11, the schematic overview of the A13R is shown.

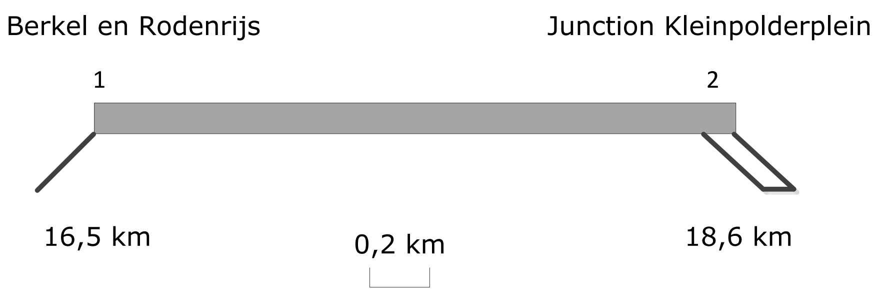

Figure 4.11: Schematic overview of A13R

In figure 4.11, the critical road design elements are indicated with numbers. These numbers are explained in table 4.12.

Table 4.12: Critical road design elements A13R

No.	Critical road design element
1	On ramp
2	Taper (divided motorways)

The determined data for both the critical road design elements in table 4.12 and the cross section of the road section is depicted in the list in appendix F.4.

Data for the economic optimization process

On the interactive noise map it is found that the road section is located near urbanized areas (at the city of Rotterdam). This means that for this road section a factor for a city must be applied, because near a city noise- and air pollution are assessed as more unpleasant. As a consequence, the cost of traffic noise and the cost of air pollution are taken into account with a higher weight in comparison to the other significant factors. In section 4.5.3 it is shown what the influence of the factor for a city on the optimal speed limit is.

4.5.2 Step 1: application of the engineering philosophy on the A13R

In table 4.13, the speed limit (upper bound) is displayed for each critical road design element.

Table 4.13: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	On ramp	120 / 130 km/h
2	Taper (divided motorways)	120 / 130 km/h
	Cross section	100 km/h

In table 4.13, the lowest value is **100 km/h**.

4.5.3 Step 2: application of the economic optimization philosophy on the A13R

For this road section it is first investigated what the influence of the factor for a city is on the optimal speed limit. For the road user perspective the factor for a city is not considered, because the road user does not consider the cost of traffic noise and the cost of air pollution. Only for the road authority perspective the factor for a city is investigated.

Road authority perspective

In figure 4.12, the optimal speed limit is indicated with a red dot: **115 km/h**. This is the optimal speed limit when the factor for a city is equal to 1. In table 4.14 the optimal speed limits for different factors for a city are shown.

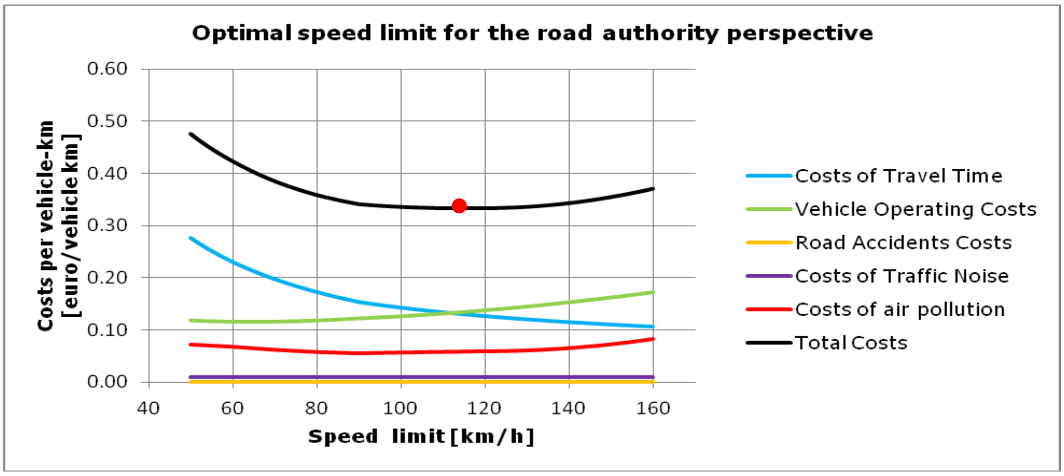

Figure 4.12: Optimal speed limit for the road authority perspective

Table 4.14: The optimal speed limit for different factors for a city

Factor for a city [-]	Optimal speed limit [km/h]
1	115 (see figure 4.12)
2	109
3	104
4	96
5	92
6	90
7	90
…	90

It turns out that the optimal speed limit never drops below the 90 km/h. The influence of the factor for a city on the optimal speed limit and what factor for a city to choose are considered in the next chapter.

Road user perspective

In figure 4.13, the optimal speed limit is indicated with a red dot: **121 km/h**.

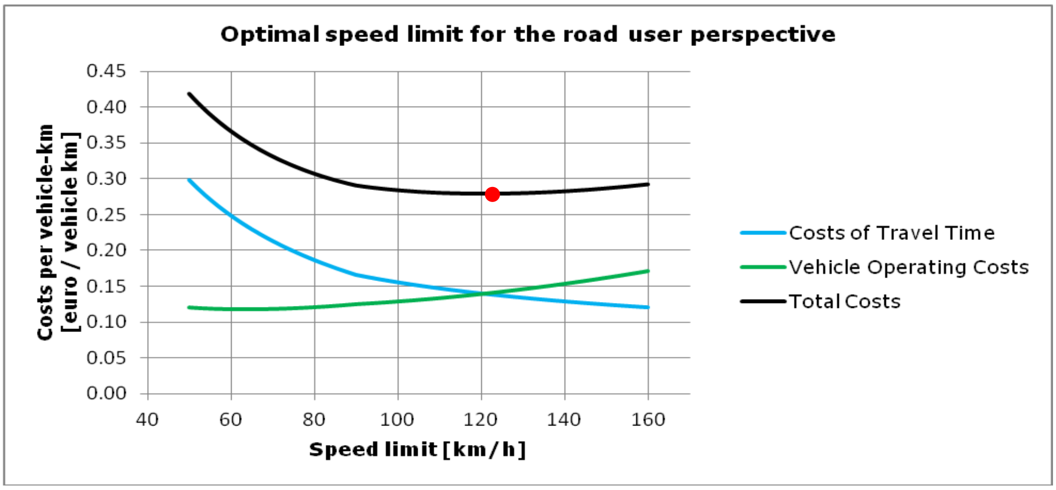

Figure 4.13: Optimal speed limit for the road user perspective

4.5.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 100 km/h
- Step 2:
  - Road authority perspective: dependent of the factor for a city
  - Road user perspective: 121 km/h

➔ For the road authority perspective the optimal speed limit depends on the factor for a city. However, because of the upper limit of 100 km/h (because of the width of the lanes) an optimal speed limit higher than 100 km/h is not possible. This means that the factor for a city is at least 3. As mentioned before, the value of the factor for a city is discussed in more detail in the next chapter. The results for the road authority perspective are worked out further in that chapter as well.

➔ For the road user perspective, the determined optimal speed limit is higher than the upper bound. In table 4.13 it can be seen that the upper bound of 100 km/h is set because of the cross section (the width of the lanes). This means that because of the width of the lanes it is not safe to drive faster than 100 km/h. As a consequence, the road user perspective can only apply an optimal speed limit of 100 km/h.

4.5.5 Step 3: comparison, resulting in an advice for the A13R

According to table 4.2, the current speed limit for this road section is 100 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

Because the factor for a city is set in the next chapter, it is not possible to carry out a comparison for the road authority perspective in this section. Therefore this comparison is worked out in the next chapter.

Road user perspective

Comparison: 100 km/h = 100 km/h.

- Permanent result: result 2: No change in the current speed limit.
- Dynamic result: whether or not a dynamic result is needed to improve the traffic flow depends on the quality of the traffic flow. The quality of the traffic flow is determined at the current speed limit (the current speed limit is equal to the determined optimal speed limit in this case).

  Board (1985) defines the quality of the traffic flow as the ratio between the volume v [veh/h] and the capacity c [veh/h] (abbreviated as v/c-ratio). For the capacity the free capacity is used. The free capacity is the maximum intensity that a road section can assimilate just before congestion starts. Van Rij and Henkens (2009) provides these free capacities. They investigated the actual capacity values for motorways. Furthermore, the volume (or intensity) is derived from the Regiolab Delft[20]. The volume is determined for three consecutive recent days:
    - Tuesday, March 20, 2012;
    - Wednesday, March 21, 2012;
    - Thursday, March 22, 2012.

  These three days represent three normal average days. The data for each day is aggregated for half an hour with a time range of 6:00 AM up to 8:00 PM.

  The free capacity is equal to: 6774 veh/h (Van Rij and Henkens, 2009). In appendix G the v/c-ratios are given for the three consecutive days.

  In appendix G it can be seen that the v/c-ratio of 0,8 has already been exceeded at 6:30 AM for each considered day. This means that shock waves occur and thus one of the approaches needs to be chosen.

  In this case the road user perspective is considered. The objective of the road user is to travel as fast and as cheap as possible. So it is advised to lower the current speed limit in both the morning peak hours and the evening peak hours (see appendix G where the v/c-ratio exceeds the 0,8 during these hours)**.** Lower the current speed using the breakdown prevention approach.

[20] Regiolab Delft is a laboratory for regional traffic monitoring. Traffic data is obtained from systems and integrated in a traffic information system. This information is used to analyze a region under different conditions (website: http://www.citg.tudelft.nl/en/about-faculty/departments/transport-and-planning/research /facilities/software/regiolab-delft/)

Overview of the results

In table 4.15, an overview of the results for this case study is summarized.

Table 4.15: Overview of the results of the A13R

Road authority perspective		**Road user perspective**	
Step 1	100 km/h	*Step 1*	100 km/h
Step 2	Dependent of factor for a city	*Step 2*	100 km/h
Optimal speed limit	Dependent of factor for a city	*Optimal speed limit*	100 km/h
Current speed limit	100 km/h	*Current speed limit*	100 km/h
Permanent result	See chapter 5	*Permanent result*	No change
Dynamic result	See chapter 5	*Dynamic result*	Lower the speed limit during both morning- and evening peak hours.
Advice: → The advice depends on the choice of the factor for a city. This is worked out in chapter 5.		*Advice:* → Permanent: no change in the current speed limit; → Dynamic: lower the speed limit during both morning- and evening peak hours using the breakdown prevention approach.	

4.6 Application of the assessment framework on the A16R: Junction Klaverpolder→ Junction Princeville

In this section, the application of the assessment framework on the A16R is described.

4.6.1 Collected input data

In this section, the input data for the A16R is collected.

Data for the engineering philosophy

In figure 4.14, the schematic overview of the A16R is shown.

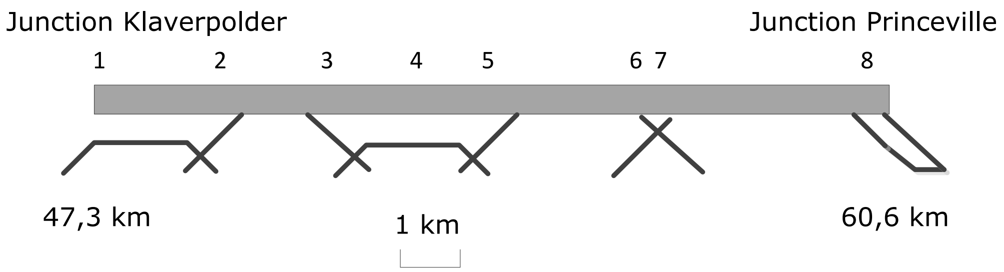

Figure 4.14: Schematic overview of A16R

In figure 4.14, the critical road design elements are indicated with numbers. These numbers are explained in table 4.16.

Table 4.16: Critical road design elements A16R

No.	Critical road design element
1	Weaving lane (symmetric)
2	On ramp
3	Off ramp
4	Weaving lane (symmetric)
5	On ramp
6	Off ramp
7	On ramp
8	Taper (divided motorways)

The determined data for both the critical road design elements in table 4.16 and the cross section of the road section is depicted in the list in appendix F.5.

Data for the economic optimization process

On the interactive noise map it is found that the road section does not run through urban areas. For this reason, the factor for the city is chosen equal to 1.

4.6.2 Step 1: application of the engineering philosophy on the A16R

In table 4.17, the speed limit (upper bound) is displayed for each critical road design element.

Table 4.17: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	Weaving lane (symmetric)	120 / 130 km/h
2	On ramp	120 / 130 km/h
3	Off ramp	120 / 130 km/h
4	Weaving lane (symmetric)	120 / 130 km/h
5	On ramp	120 / 130 km/h
6	Off ramp	120 / 130 km/h
7	On ramp	120 / 130 km/h
8	Taper (divided motorways)	120 / 130 km/h
	Cross section	120 / 130 km/h

In table 4.17, the lowest value is **120 / 130 km/h**.

4.6.3 Step 2: application of the economic optimization philosophy on the A16R

In this section, the optimal speed limit is determined for the road authority perspective and the road user perspective respectively.

Road authority perspective

In figure 4.15, the optimal speed limit is indicated with a red dot: **112 km/h**.

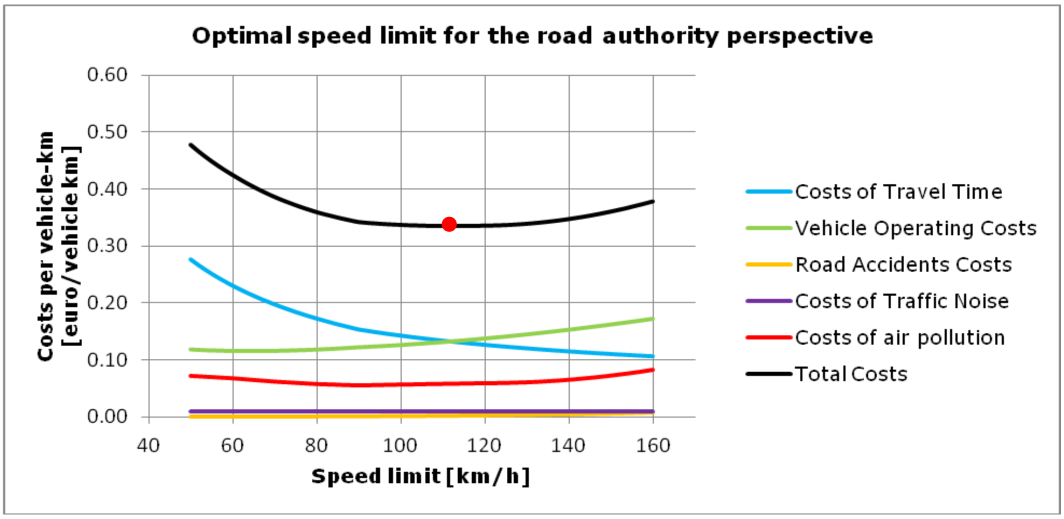

Figure 4.15: Optimal speed limit for the road authority perspective

Road user perspective

In figure 4.16, the optimal speed limit is indicated with a red dot: **121 km/h**.

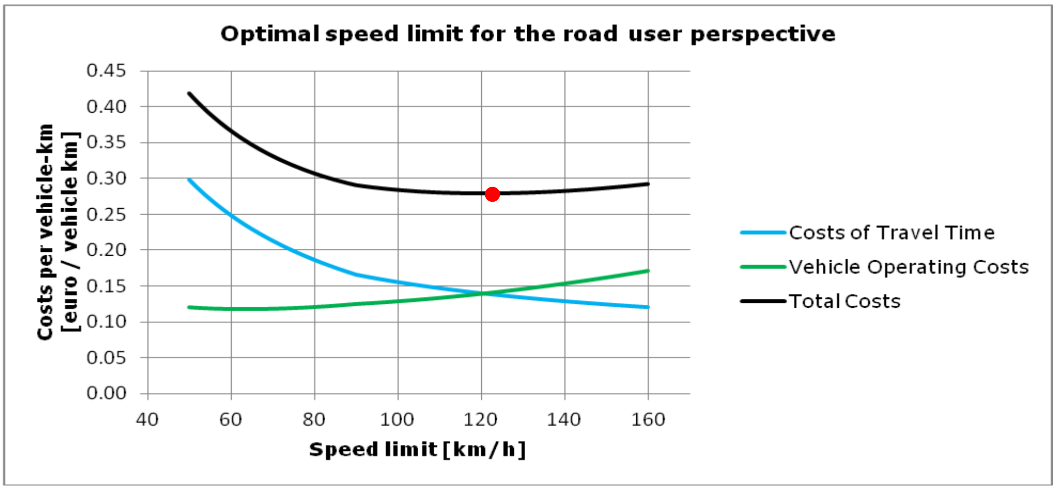

Figure 4.16: Optimal speed limit for the road user perspective

4.6.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 120 / 130 km/h
- Step 2:
    - Road authority perspective: 112 km/h
    - Road user perspective: 121 km/h

➔ For both perspectives, the determined optimal speed limit is lower than the determined upper bound. So, these optimal speed limits are used in the next step: comparison with the current speed limit.

4.6.5 Step 3: comparison, resulting in an advice for the A16R

According to table 4.2, the current speed limit for this road section is 130 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

Comparison: 112 km/h < 130 km/h.

- Permanent result: result 1: Decrease to the optimal speed limit.
- Dynamic result: advice: apply the homogenization approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Road user perspective

Comparison: 121 km/h < 130 km/h.

- Permanent result: result 1: Decrease to the optimal speed limit.

- Dynamic result: advice: apply the breakdown prevention approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Overview of the results

In table 4.18, an overview of the results for this case study is summarized.

Table 4.18: Overview of the results of the A16R

Road authority perspective		**Road user perspective**	
Step 1	120 / 130 km/h	*Step 1*	120 / 130 km/h
Step 2	112 km/h	*Step 2*	121 km/h
Optimal speed limit	112 km/h	*Optimal speed limit*	121 km/h
Current speed limit	130 km/h	*Current speed limit*	130 km/h
Permanent result	Decrease	*Permanent result*	Decrease
Dynamic result	Further research	*Dynamic result*	Further research
Advice: ➔ Permanent: decrease to optimal speed limit; ➔ Dynamic: further research to critical region, if yes: apply homogenization approach.		*Advice:* ➔ Permanent: decrease to optimal speed limit; ➔ Dynamic: further research to critical region, if yes: apply breakdown prevention approach.	

4.7 Application of the assessment framework on the A20R: Junction Kleinpolderplein→ Junction Terbrechtseplein

In this section, the application of the assessment framework on the A20R is described.

4.7.1 Collected input data

In this section, the input data for the A20R is collected.

Data for the engineering philosophy

In figure 4.17, the schematic overview of the A20R is shown.

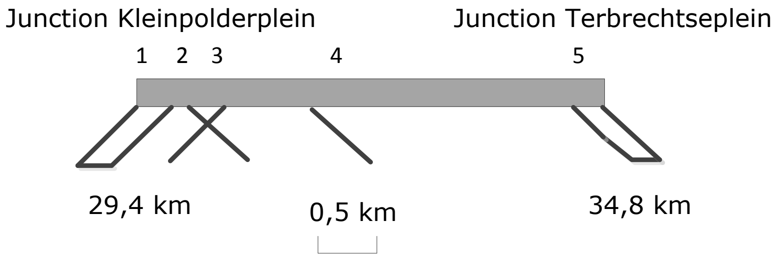

Figure 4.17: Schematic overview of A20R

In figure 4.17, the critical road design elements are indicated with numbers. These numbers are explained in table 4.19.

Table 4.19: Critical road design elements A20R

No.	Critical road design element
1	Taper (joining motorways)
2	Off ramp
3	On ramp
4	Off ramp
5	Taper (divided motorways)

The determined data for both the critical road design elements in table 4.19 and the cross section of the road section is depicted in the list in appendix F.6.

Data for the economic optimization process

On the interactive noise map it is found that the road section is located near an urban area (the city of Rotterdam). This means that for this road section a factor for a city must be applied, because near a city noise- and air pollution are assessed as more unpleasant. As a consequence, the cost of traffic noise and the cost of air pollution are taken into account with a higher weight in comparison to the other significant factors. In section 4.7.3 it is shown what the influence of the factor for a city on the optimal speed limit is.

4.7.2 Step 1: application of the engineering philosophy on the A20R

In table 4.20, the speed limit (upper bound) is displayed for each critical road design element.

Table 4.20: Outcomes of the flow charts presented in section 3.2

No.	Critical road design element	Speed limit (upper bound)
1	Taper (joining motorways)	120 / 130 km/h
2	Off ramp	120 / 130 km/h
3	On ramp	120 / 130 km/h
4	Off ramp	120 / 130 km/h
5	Taper (divided motorways)	120 / 130 km/h
	Cross section	120 / 130 km/h

In table 4.13, the lowest value is **120 / 130 km/h**.

4.7.3 Step 2: application of the economic optimization philosophy on the A20R

For this road section first it is investigated what the influence of the factor for a city on the optimal speed limit. For the road user perspective the factor for a city is not considered, because the road user does not consider the cost of traffic noise and the cost of air pollution. Only for the road authority perspective the factor for a city is investigated.

Road authority perspective

In figure 4.18, the optimal speed limit is indicated with a red dot: **85 km/h**. This is the optimal speed limit when the factor for a city is equal to 1. In table 4.21 the optimal speed limits for different factors for a city are shown.

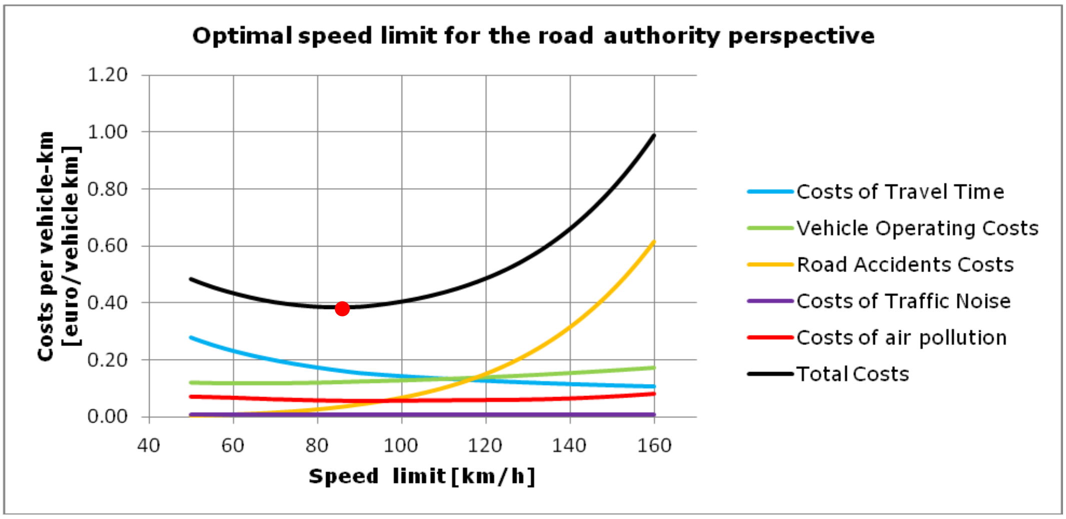

Figure 4.18: Optimal speed limit for the road authority perspective

Table 4.21: The optimal speed limit for different factors for a city

Factor for a city [-]	Optimal speed limit [km/h]
1	85 (see figure 4.18)
2	87
3	89
4	90
5	90
…	90

It turns out that the range of the optimal speed limit is between 85 km/h and 90 km/h, no matter what factor for a city is chosen. It seems that the factor for a city has no significant influence on the optimal speed limit. In this case it is decided to use an optimal speed limit of 90 km/h.

Road user perspective

In figure 4.19, the optimal speed limit is indicated with a red dot: **121 km/h**.

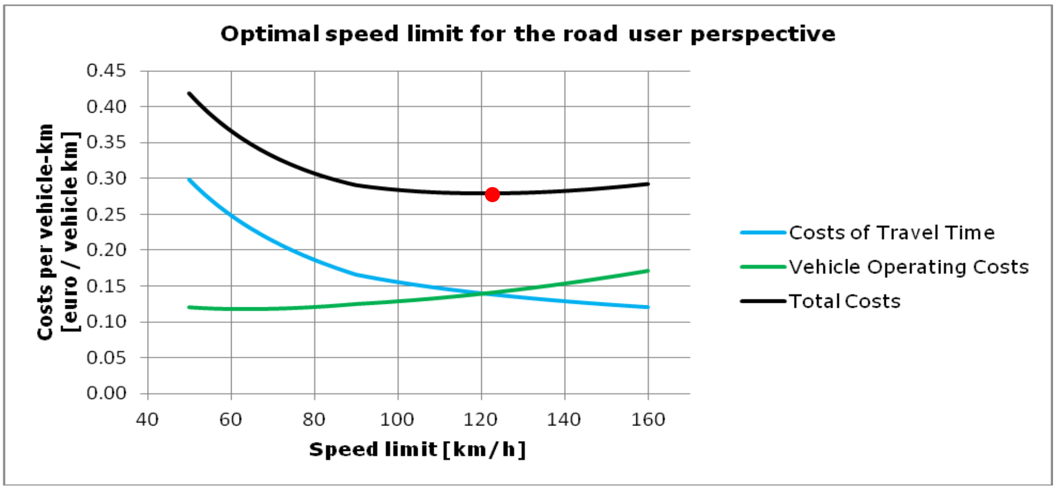

Figure 4.19: Optimal speed limit for the road user perspective

4.7.4 Results of step 1 and step 2

Step 1 and step 2 provide the following results:

- Step 1: upper bound: 120 / 130 km/h
- Step 2:
  - Road authority perspective: 90 km/h
  - Road user perspective: 121 km/h
- For both perspectives, the determined optimal speed limit is lower than the determined upper bound. So, these optimal speed limits are used in step 3: comparison with the current speed limit.

4.7.5 Step 3: comparison, resulting in an advice for the A20R

According to table 4.2, the current speed limit for this road section is 80 km/h. Next, the comparison is performed for both perspectives.

Road authority perspective

Comparison: 90 km/h > 80 km/h.

- Permanent result: result 1: Increase to the optimal speed limit.
- Dynamic result: advice: apply the homogenization approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Road user perspective

Comparison: 121 km/h > 80 km/h.

- Permanent result: result 1: Increase to the optimal speed limit.
- Dynamic result: advice: apply the breakdown prevention approach in case the critical region is reached. However, further research is needed to determine the intensity at the (new) optimal speed limit and thus whether or not the critical region is reached.

Overview of the results

In table 4.22, an overview of the results for this case study is summarized.

Table 4.22: Overview of the results of the A20R

Road authority perspective		**Road user perspective**	
Step 1	120 / 130 km/h	*Step 1*	120 / 130 km/h
Step 2	90 km/h	*Step 2*	121 km/h
Optimal speed limit	90 km/h	*Optimal speed limit*	121 km/h
Current speed limit	80 km/h	*Current speed limit*	80 km/h
Permanent result	Increase	*Permanent result*	Increase
Dynamic result	Further research	*Dynamic result*	Further research
Advice: ➔ Permanent: increase to optimal speed limit; ➔ Dynamic: further research to critical region, if yes: apply homogenization approach.		*Advice:* ➔ Permanent: increase to optimal speed limit; ➔ Dynamic: further research to critical region, if yes: apply breakdown prevention approach.	

4.8 Conclusion

In this chapter the developed assessment framework was applied to six road sections in the Dutch motorway network. The choice for these road sections was based on the formulated motto in chapter 2: *faster if possible, slower when* necessary. Or in other words: road sections where it may be expected that a higher speed limit (either dynamic or static) should be applied. The current speed limits seem to be experienced as being too low and thus are tested in the assessment framework. After performing the case study, it is possible to assess the current speed policy on Dutch motorways.

In table 4.23 the results of the six case studies are shown. The current speed limit is mentioned as well. The optimal speed limit is divided into the road authority perspective and the road user perspective.

Table 4.23: Comparison between current speed limits and the optimal speed limits

Road section	Current speed limit [km/h]	Optimal speed limit [km/h]	
		Road authority	Road user
A2R: Junction Holendrecht → Maarssen	100	90	121
A2R: Junction Everdingen → Junction Deil	130	112	121
A4R	100	94	121
A13R	100	see chapter 5[21]	121
A16R	130	112	121
A20R	80	90	121

The results displayed in table 4.23 are used in chapter 5 to evaluate the current speed policy on Dutch motorways. Also conclusions concerning the steps in the developed assessment framework are shown in chapter 5. The usefulness of the assessment framework in practice becomes clear. In chapter 6 conclusions and recommendations for further research according to the developed assessment framework are given.

[21] The optimal speed limit for the A13R depends of the factor for a city in case of the road authority perspective. How this works is explained in chapter 5.

5 Evaluation of the Assessment Framework

This chapter evaluates the assessment framework. The usefulness of the three steps in the assessment framework in practice is discussed. The results found in the case study are used in this evaluation. Furthermore, the results of the case study are used to assess the current speed policy in the Netherlands as well.

For the evaluation of the assessment framework, step 1, step 2 and step 3 are evaluated in section 5.1, section 5.2 and in section 5.3 respectively. For step 3, a distinction is made between the permanent and dynamic results. In section 5.3 the current speed policy in het Netherlands is evaluated as well. Finally, this chapter ends with a conclusion.

5.1 Evaluation of step 1: the engineering philosophy

In this section, step 1 of the assessment framework is evaluated. In step 1, road layout characteristics are used to determine a speed limit that is still safe under the prevailing conditions. The critical road design elements are evaluated in section 5.1.1. In section 5.1.2 the flow charts are evaluated. And the functioning of the upper bound in the assessment framework is evaluated in section 5.1.3.

5.1.1 Critical road design elements

The road layout characteristics are represented by six critical road design elements (see table 3.1). These six critical road design elements are a summary of 14 critical road design elements, provided by Van Delden and Broeren (2011). The case study shows that all critical road design elements can be found in one of the six critical road design elements.

5.1.2 Flow charts

The relation between the critical road design elements and the speed limit is set up by means of flow charts. In these flow charts, the speed limit that is possible on that road section due to the road layout can be determined. In the case study the critical road design elements are investigated. When all dimensions of these critical road design elements are gathered, it turns out that the flow charts provide an upper bound in a very easy and quick way.

5.1.3 Upper bound

Currently, a lot of (re)construction work is carried out on the Dutch motorway network. This might result in an upper bound of 100 km/h (or lower) due to the old situation. The situation after the construction work might provide an upper bound of 120 / 130 km/h. However, the case study shows that only in case of a movable bridge (on the A4R) and due to the narrow lanes (on the A13R) an upper bound of 100 km/h is found. There are no other road design elements which result in an upper bound of 100 km/h. For both the A4R and the A13R it is imaginable that the road user will accept that a lower speed limit is applied due to the (narrower) road layout.

5.2 Evaluation of step 2: the economic optimization philosophy

This section evaluates step 2 of the assessment framework. In step 2, the optimal speed limit is determined for a road section, with respect to the determined upper bound in step 1. The determined optimal speed limit is safe on the road section due to the road layout. First, the applied perspectives for this research are evaluated in section 5.2.1. Section 5.2.2 describes how the significant factors work in the determination of the optimal speed limit. In section 5.2.3 the factor for a city is described. Section 5.2.4 explains how the optimal speed limit is determined with respect to the upper bound determined in step 1.

5.2.1 Perspectives

In chapter 2 is explained that for this research the road authority perspective and the road user perspective are chosen. Each perspective has its own objective. The road user considers only costs of travel time and vehicle operating costs, while the road authority considers more significant factor (road accident costs, costs of traffic noise and costs of air pollution). The case study shows for each road section that when the road user is chosen a higher optimal speed limit is determined than when the road authority is chosen. This also follows from the considered perspectives per perspective. The road accident costs, costs of traffic noise and the costs of air pollution are higher at higher speeds, so these factors lead to a lower optimal speed limit.

Furthermore, the case study shows that in case the road user perspective is chosen an optimal speed limit is determined of 121 km/h. This optimal speed limit applies for each road section. It seems to be that the road user has a desired speed of 121 km/h, no matter on what road section he/she is. Looking to the considered significant factors for the road user (costs of travel time and vehicle operating costs) only the truck percentage is variable for different road sections. This means that the truck percentage has no influence on the optimal speed limit for the road user. This optimal speed limit only depends on the fixed data for each road section.

5.2.2 Significant factors

The significant factors are expressed in a formula which represents the relation between the speed limit and the cost / vehicle kilometer. In the case study these formulas are summed up. This summation leads to an overall function where clearly an minimum in the costs / vehicle kilometer can be found. The case studies show that the costs of traffic noise are very small in comparison to the other factors. The influence on the optimal speed limit by this factor is nil. In chapter 2 is explained that this is known as Pareto optimal results. There is not one solution which optimizes all targets on a linear line at the same time. The costs are the same at each optimal speed limit

For the road accident costs the same applies in case there are only a few accidents on a road section. When many accidents occur at the current speed limit (and thus many accidents at the optimal speed limit as well as is determined with the Power functions), it turns out that the road accident costs increases significantly at high speeds. For the A2R: Junction Holendrecht → Maarssen, the A4R and the A20R, this is the case. The plots show that at high speeds the road accidents costs become larger. For the three case study an optimal speed limit of plus minus 90 km/h.

5.2.3 Factor for a city

For the costs of traffic noise and the costs of air pollution a factor for a city is used. This factor is applied because the effects of these factors are larger at urbanized areas (near cities). In the case study, there are two road sections classified as road sections situated in urbanized area: the A13R and the A20R. For the A20R, it turns out that the factor for a city has no influence on the optimal speed limit. For each value the optimal speed limit is around 90 km/h. This is the case because of the minimal costs of air pollution at 90 km/h.

For the A13R the road accident costs are zero, so the optimal speed limit for the A13R is higher for a factor for a city of 1 (115 km/h) than the optimal speed limit of the A20R (85 km/h). For the A13R the optimal speed decreases for each increase of the factor for a city with 1, till a maximum of 6 for the factor of a city. Just like the A20R the minimal costs of air pollution is reached at a speed limit of 90 km/h. This means that the optimal speed limit for the A13R decreases till 90 km/h as well.

5.2.4 Determination of the optimal speed limit

In step 2 an optimal speed limit is determined for a road section. This speed limit is used to compare with the current speed limit. In step 1 the upper bound is determined. The optimal speed limit is applied in the comparison to the current speed limit without problems as long as the optimal speed limit is smaller than the upper bound. The case study shows that for most of the critical road design elements an upper bound of 120 / 130 km/h is determined. Only due to the movable bridge on the A4R and the small lanes on the A13R, a lower upper bound is applied. In section 5.1 3 it is already explained how to deal with the fact that the optimal speed limit is above the upper bound. The case study provides no problems on this. A relatively low upper bound does not 'limit' the optimal speed limit undesired.

5.3 Evaluation of step 3: comparison

This section evaluates step 3 of the developed assessment framework. In this step the comparison between the current speed limit and the determined optimal speed limit carried out. In section 5.3.1, the permanent results are evaluated. The dynamic results are considered in section 5.3.2. Finally, section 5.3.3 evaluates the advice that is given concerning the current speed policy in the Netherlands.

5.3.1 Permanent results

When the optimal speed limit is compared to the current speed limit, there are three permanent (during all hours of the day) results possible: the determined optimal speed limit is higher than the current speed limit, the determined optimal speed limit is lower than the current speed limit or both are equal. The case study shows that when the road authority perspective is chosen the permanent result is equal to decreasing to the optimal speed limit for four road sections. For the A20R and the A13R a different permanent result is determined. For these two road sections the result depends of the factor for a city. However, for the A20R an optimal speed limit of 90 km/h is determined, so an increase to the optimal speed limit should be applied.

For the road user other permanent results are determined. For four road sections the current speed limit should be increased to the optimal speed limit of 121 km/h. On two road sections (the A2R: Junction Everdingen → Junction Deil and the A16R, where a speed limit of 130 km/h is implemented), the speed limit is advised to decrease to the optimal speed limit. 130 km/h is implemented to satisfy the wishes and expectations of the road users. However, the road user perspective considers also the vehicle operating costs. These costs are higher at higher speeds and lead to a relatively lower optimal speed limit than 130 km/h.

5.3.2 Dynamic results

The dynamic results are connected to the permanent results. This means that, depending of the permanent results, a dynamic result is advised. In case of the decrease to the optimal speed limit, it must be investigated whether or not this decrease is into the critical region of the fundamental diagram. The same applies for the increase to the optimal speed limit. For these two dynamic results, further research is necessary whether or not the critical region is reached at the (new) optimal speed limit.

Only when there is no change in speed limit, it can be investigated whether or not a dynamic speed limit can improve the traffic flow. This was only the case for the A13R. It turns out that the volumes at the current speed limit will cause a v/c-ratio higher than 0,8 and thus shock waves (which results in stop-and-go waves) will occur. At the peak hours of the day the value 0,8 is exceeded, so during these hours the speed limit should be reduced to improve the traffic flow. Further research is needed to what dynamic speed limit is necessary.

5.3.3 Advice

When the current speed limits are compared to the determined optimal speed limits, it is possible to formulate an advice for each road section. This can only be done for the permanent results. Further research is needed to the dynamic results.

For the six case studies, a distinction can be made into three categories (when looking to the results of the case study):

1. *A2R: Junction Holendrecht → Maarssen* and *A4R*
   The current speed limit is 100 km/h.
   - Road authority perspective: the current speed limit is decreased to around 90 km/h;
   - Road user perspective: the current speed limit is increased to 121 km/h.
2. *A2R: Junction Everdingen→ Junction Deil* and *A16R*
   The current speed limit is 130 km/h.
   - Road authority perspective: the current speed limit is decreased to 112 km/h;
   - Road user perspective: the current speed limit is decreased to 121 km/h.
3. *A13R* and *A20R*
   The current speed limit is 80 / 100 km/h (depending of the factor for a city).
   - Road authority perspective: the current speed limit is decreased to 80 / 100 km/h, depending of the factor for a city;
   - Road user perspective: the current speed limit is increased to 121 km/h.

For the road authority perspective it can be seen that the current speed limit is decreased to the optimal speed limit for all case studies (only for the A13R where the factor for a city the result is uncertain). It is reasonable to assume that in the determination of the optimal speed limit factors are considered (i.e. environmental issues) which causes a lower speed limit. For the road user perspective it turns out that only for the road sections where 130 km/h as current speed limit is applied, a lower speed limit of 121 km/h is determined. For the other road sections the current speed limit should be increased to the optimal speed limit of 121 km/h.

5.4 Conclusion

This chapter evaluates the developed assessment framework. In this evaluation the results determined in the case study for the six road sections are used to evaluate the three steps of the assessment framework. An advice about the current speed policy on Dutch motorways is added as well.

Step 1

The evaluation shows that the developed assessment framework provides a good working methodology for determining an optimal speed limit for a road section. In step 1 the road layout characteristics are considered. For a road section, it is investigated what critical road design elements are present. Due to this presence, an upper bound in the assessment framework is determined. The case study shows that this upper bound functions as a realistic upper bound for the optimal speed limit.

Step 2

In step 2 the optimal speed limit is determined for the two perspectives (the road authority and the road user). For the road user the optimal speed limit does not vary for different road sections. A road user has a certain speed limit that they want to apply. Instead, the road authority differs in the optimal speed limits for different road sections. In this perspective, more significant factors are considered, which lead to a lower optimal speed limit than when the road user is chosen as perspective. Furthermore, in step 2 the factor for a city needs to be mentioned. The factor for a city takes care of the fact that costs of traffic noise and air pollution contain a higher weight near urbanized areas. Due to the factor for a city, the optimal speed limit changes. So it is important to investigate the height of this factor.

Results of step 1 and step 2

As long as the optimal speed limit is below the upper bound found in step 1, the optimal speed limit is used in the comparison. When the optimal speed limit exceeds the upper bound, there are several measures available (for instance lowering the speed limit on the normative critical road design element). The case study shows this gives no problems and thus the optimal speed limit is not limited unnecessary by the upper bound.

Step 3

In the comparison between the current speed limit and the optimal speed limit, there are three permanent results: increase to optimal speed limit, decrease to the optimal speed limit or no change in the current speed limit. The case study shows that depending of the permanent result an dynamic result is considered to improve the traffic flow. However, further research is needed to the intensity on the road at the (new) optimal speed limit.

Usefulness of the assessment framework

Finally, after applying the six case studies into the developed assessment framework, one can conclude that depending of the chosen perspective the current speed limit should be in- or decreased. In general, the road authority wants to decrease the current speed limit, and the road user wants to increase the current speed limit. With these results, the usefulness of the developed assessment framework is proven, because these results are expected for both perspectives. However, there are several aspects which need further research (for instance the factor for a city or the dynamic speed limits). These recommendations are explained in the next final chapter.

6 Conclusions and recommendations

In this final chapter the conclusions and recommendations of this thesis are given. Section 6.1 starts with presenting the findings from each chapter in this report. This is done by answering the sub questions presented in chapter 1. Section 6.2 contains the conclusions of the results of the assessment framework. The recommendations for practice and the recommendations for further research are given in section 6.3 and section 6.4 respectively.

6.1 Findings

In chapter 1 the *main research question* is formulated as follows:

How does an assessment framework, regardless of the chosen perspective, look like, for determining the optimal speed limit (either permanent or dynamic) for a motorway section in the Netherlands, taking into account local conditions and targets?

The main research question is answered by first answering the sub questions mentioned in chapter 1:

1. *What philosophies are available for an assessment framework and what are the differences between them? What perspectives are available in such a philosophy?*
   A philosophy is an approach for determining and setting the speed limit. The five major applied philosophies are:
   - Engineering philosophy;
   - Driver speed choice philosophy;
   - Economic optimization philosophy;
   - Harm minimization philosophy;
   - Expert system philosophy.

   The differences between these philosophies are especially found in the applied factors for determining the speed limit. Each philosophy uses its own factors for the determination of the speed limit. Note that often similar factors are applied in different philosophies.

   In each philosophy a different perspective is chosen. Each perspective has its own viewpoint in the determination of a speed limit. Examples of these perspectives are:
   - The road authority;
   - The road user;
   - The taxpayer;
   - The residents along the road.

For this research only the road authority perspective and the road user perspective are relevant.

2. *What are the significant factors that influence the speed limit and do these factors affect the speed limit?*
   The significant factors that influence the speed limit are the factors dependent on the chosen perspective. For this research only the road authority perspective and the road user perspective are relevant. These perspectives consider the following significant factors:
   1. Travel time;
   2. Vehicle operating costs;
   3. Road accidents;
   4. Traffic noise;
   5. Air pollution.

   These significant factors are applied in an economic optimization philosophy, where the optimal speed limit (speed limit at the lowest total cost) is determined as a function of the total cost of the significant factors. The significant factors affect the speed limit. Applying the significant factors in the economic optimization philosophy results in different optimal speed limits.

3. *How can dynamic speed limits improve traffic flow conditions, traffic safety issues and air quality?*
   In Dynamax it is tested whether or not dynamic speed limits can improve flow conditions, traffic safety issues and air quality. The results are:
   - Traffic flow conditions: solving shock waves by reducing the speed limit, using:
     - Breakdown prevention approach (SPECIALIST-algorithm);
     - Homogenization approach.

     These approaches are advised to be implemented by using either intensity triggers or fixed time slots.
   - Traffic flow conditions: increasing the speed limit in case of low intensities (off-peak hours, for instance late in the evening).
   - Traffic safety issues: decreasing the speed limit in rainy conditions.
   - Air quality: decreasing the speed limit when the concentration of particulate matter (PM_{10}) almost reaches the critical value.

4. *What structure is appropriate for an assessment framework and how does it work?*
   The developed assessment framework consists of three steps. Step 1 and step 2 result in an optimal speed limit, taking the roadway geometry into account:

- **Step 1: the engineering philosophy**. In this step, the roadway geometry is considered when determining the maximum possible speed limit. This speed limit functions as the upper bound in the assessment framework.
- **Step 2: the economic optimization philosophy**. In this step, the optimal speed limit is determined. This is the speed limit with the lowest costs for society. At this determination the significant factors are considered. The significant factors are the factors dependent of the chosen perspective: the road authority or the road user.

  As long as the optimal speed limit is below the upper bound determined in step 1, the optimal speed limit is used. When the optimal speed exceeds the upper bound, there are three possibilities:
    - Choose the boundaries of the road section differently, for instance in the normative road design element;
    - Lower the speed limit locally, for instance at the normative road design element;
    - Apply engineering measures in order to allow a higher speed limit that is still safe (however, it is assumed that engineering measures are not desired in this research).

After step 1 and step 2, step 3 is carried out, where the determined optimal speed limit is compared to the current speed limit, which results in an advice for the user of the assessment framework:

- **Step 3: the comparison → advice**. In the last step of the assessment framework, the determined optimal speed limit is compared to the current speed limit. In this comparison, three permanent results – which are applied during all hours of the day – are possible:
    - Result 1: optimal speed limit < current speed limit;
    - Result 2: optimal speed limit = current speed limit;
    - Result 3: optimal speed limit > current speed limit.

  At the chosen permanent result, the project Dynamax is applied. Dynamax provides dynamic speed limits depending on traffic flow, weather conditions or air quality.

  For traffic flow, the applied dynamic speed limits leads to better traffic flow conditions. Depending on these traffic flow conditions (the volume/capacity-ratio, abbreviated to the v/c-ratio), a dynamic speed limit is applied. During peak hours, when the traffic flow becomes sensitive to small disturbances that lead to breakdowns in the traffic flow, a lower speed limit functions as a proper measure to deal with breakdowns. There are two main measures available to deal with shock waves:

- *The breakdown prevention approach*: reduction of the mean speed at under critical densities. When the mean speed is reduced in advance, the inflow of vehicles becomes lower than the outflow which leads to the shock wave disappearing;
- *Homogenization approach*: homogenization of speeds. This approach cannot suppress or resolve existing shock waves. It can only increase the time to a breakdown, because the speed differences are made smaller. Smaller speed differences leads to a safer traffic situation.

The user of the assessment framework chooses the preferred measure: either solving the shock waves or homogenizing the traffic flow. There are two practical measures that are advisable to use:

- Fixed time slots;
- Intensity triggers.

5. *Which criteria are needed to select a relevant road section for testing the assessment framework in a case study and how are these criteria applied in the assessment framework?*

   In principle each road section can be applied in the assessment framework. There is not specific data needed to select a relevant road section. The road sections applied in the case studies are chosen based on the expectation that a higher speed limit is used. This choice is made due to the applied motto: *faster if possible, slower when necessary*, provided by the Dutch government.

   When the data belonging to the criteria is gathered, it can be completed into the lists set up in chapter 3. These lists are used in the determination of the optimal speed limit. The list for the engineering philosophy (step 1) is used to determine the upper bound on basis of flow charts. And the lists for the economic optimization philosophy (step 2) is completed in Microsoft Excel, where the formulas of the five significant factors are used to determine the optimal speed limit with the lowest cost for society.

6. *How useful is an assessment framework for determining the optimal speed limit for the Dutch motorway network?*

   After performing the case study, it can be concluded that the assessment framework indicates that depending of the chosen perspective the current speed limit should be in- or decreased. In general, the road authority wants to decrease the current speed limit, and the road user wants to increase the current speed limit. With these results, the usefulness of the developed assessment framework is proven, because these results are expected for both perspectives.

6.2 Conclusions

In this section conclusions are drawn for the three steps in the assessment framework, respectively in section 6.2.1, section 6.2.2 and section 6.2.3. In these conclusions, the evaluations of the application of the three steps in the case study are used.

6.2.1 Conclusions for step 1: the engineering philosophy

In the engineering philosophy road layout characteristics are used to determine the speed limit that is safe under the prevailing conditions. In the state of the art chapter is stated that currently in the Netherlands engineering measures are applied to provide a road layout that minimizes the number of traffic injuries. On basis of the road layout a safe speed limit is set.

Upper bound

It turns out that the engineering philosophy provides a speed limit that functions as upper bound in the assessment framework. Due to this upper bound the determined optimal speed limit is possible due to the road layout. In the evaluation is found that for almost all critical road design elements in the case studies an upper bound of 120 / 130 km/h is determined. This implies that currently the road layout in the Dutch motorway network is in general appropriate to apply a speed limit of 120 / 130 km/h. This is concluded because in the case study many critical road design elements are assessed which all resulted in an upper bound of 120 / 130 km/h. Only for two critical road design elements an upper bound of 100 km/h is determined: the movable bridge in the A4R and the narrow lanes on the A13R. From the evaluation can be concluded that the upper bound does not 'limit' the optimal speed limit unnecessary. When for instance a critical road design element is very local situated in a road section (movable bridge) and it allows a relatively low upper bound, then the speed limit is reduced at this critical road design element. For the remainder of the road section the higher upper bound applies.

6.2.2 Conclusions for step 2: the economic optimization philosophy

In the state of the art chapter is stated that to deal with the unavailability of an integral approach, the economic optimization philosophy is a proper way to deal with this. In this way, significant factors can be taken into account by determining the optimal speed limit. The significant factors are the factors depending of the chosen perspective. In this research, the road authority perspective and the road user perspective is chosen.

Road user perspective

In the evaluation the results of the case study are evaluated for both perspectives. For the road user perspective the optimal speed limit is equal to 121 km/h for each road section. The road user only considers the costs of travel time and the vehicle operating costs. In these two significant factors only the truck percentage vary between different road sections. It is logical that a road user have a certain desired speed to travel with (in this case 121 km/h). The road user does not care about environmental issues. Only fixed data for every road section influences the optimal speed limit of the road user. This fixed data are the VoT-values both for passenger cars and trucks and parameters of the vehicle fleet to determine the vehicle operating costs.

Road authority perspective

For the road authority perspective different optimal speed limits are determined for different road sections. It turns out that each significant factor has a different influence on the optimal speed limit. The road accident costs influences the speed limit when many accidents occur on a road section. For the A2R: Junction Holendrecht → Maarssen, the A4R and the A20R, this is the case. The plots in the case study show that at high speeds the road accidents costs become larger. For the three case study an optimal speed limit of plus minus 90 km/h. This is logical, because when many accidents occur on a road section, a relatively lower speed limit is more safe.

Factor for a city

Furthermore, the influence on the optimal speed limit of the costs of traffic noise is nil. In the case study is found that for each road section these costs are almost equal to zero. For the costs of air pollution, the factor for a city determines how the optimal speed limit is influenced. The factor for a city is applied to the A13R and the A20R. In the A20R, the road accidents costs are relatively significant. Due to this, the influence of the factor for a city can be ignored for the A20R. For the A13R, the factor for a city determines the optimal speed limit. The minimum of the costs of air pollution is 90 km/h (at this speed limit vehicle drive at the optimum speed related to air pollution), so the higher the factor for a city is, the more the speed limit convergences to 90 km/h. This is also found in the evaluation in section 5.2.3.

6.2.3 Conclusions for step 3: the comparison

In step 3 the current speed limit is compared with the determined optimal speed limit. This comparison leads to a permanent result and dynamic result.

Permanent result

The case study shows that when the road authority perspective is chosen the permanent result is equal to decreasing to the optimal speed limit for four road sections. For the A20R and the A13R a different permanent result is determined. For these two road sections the result depends of the factor for a city. However, for the A20R an optimal speed limit of 90 km/h is determined, so an increase to the optimal speed limit should be applied.

In general, the permanent results of the case study shows that current speed limits are chosen to high when the road authority perspective is chosen. For the road user perspective, the current speed limits are chosen too low. Furthermore, 130 km/h is not desired to use according to the case study. The maximum speed limit determined in the assessment framework is 121 km/h.

Dynamic result

For the dynamic result further research is needed whether or not the critical region is reached in case of a speed limit decrease or a speed limit increase. In case of no change in the current speed limit, the v/c-ratio is determined. When this v/c-ratio exceeds 0,8, shock waves will occur and a choice needs to be made between the breakdown prevention approach and the homogenization approach. Only for the A13R, shock waves occur. During the peak hours of the day, a dynamic speed limit will improve the traffic flow.

6.3 Recommendations for practice

In this section recommendations for practice are described. These recommendations are about practical issues in the assessment framework, which are found in the case study. In the remainder of this section, recommendations for each step in the assessment framework are described in section 6.3.1, section 6.3.2 and 6.3.3 respectively.

6.3.1 Recommendations for practice for step 1

When step 1 is performed, data for the critical road design elements are needed. In this research, Google Earth is used to obtain this data. However, when all road layout characteristics (for instance on- and off ramps or weaving lanes) of a road section including the dimensions are known in advance, it safes time to determine the upper bound. Besides that, when a road section is reconstructed, the new dimensions can be adapted in an easy way, which might result in a new upper bound for a road section.

6.3.2 Recommendations for practice for step 2

For the factor for a city it is recommended to classify different classes for urbanized areas (light urbanized, mediate urbanized, heavy urbanized). For the A13R, a range of 1 to 6 is found for the factor for a city, with an optimal speed limit for each factor for a city. In this way, for different urbanized areas an optimal speed limit can be determined, possibly dynamic.

6.3.3 Recommendations for practice for step 3

Further research is needed to the implementation of the optimal speed limit. When the current speed limits needs to be changed (either permanent or dynamic), it is important to investigate how this new speed limit can be implemented and to make known the optimal speed limit (either permanent or dynamic) towards the road user.

As is shown in the case study, the optimal speed limits are determined per 1 km/h. It might give problems on how to implement a speed limit like this in practice.

6.4 Recommendations for further research

In this section recommendations for further research are described. For each step, recommendations for further research are given, in section 6.4.1, section 6.4.2 and 6.4.3 respectively.

6.4.1 Recommendations for further research for step 1

It is recommended to investigate whether the values derived from AVV (2007) are still appropriate to use. For instance, on the A13R an upper bound of 100 km/h is applied due to the narrow lanes. Currently, there are more and more techniques available that protect vehicles to cross the white line between the lanes (cameras, sensors). A higher upper bound than 100 km/h is maybe possible during off peak hours.

6.4.2 Recommendations for further research for step 2

For further research, it is recommended to investigate the formulas used in the determination of the optimal speed limit. For this thesis, some assumptions are made. For instance, the vehicle fleet in Great Britain is assumed to be the same as the Netherlands. And the determination of the costs per vehicle kilometer might be too rough chosen. It is recommended to investigate how the costs can be converted from the whole network to one road section (or vehicle kilometer).

6.4.3 Recommendations for further research for step 3

Because it is beyond the scope of this research how dynamic speed limits works in practice, it is recommended to investigate how dynamic speed limits can be used to improve the traffic flow. As is mentioned in the scope of the research in chapter, further research is needed to determine for instance during what times of the day dynamic speed limits are needed or what value the dynamic speed limits should have. Also more research is needed to the critical region, for instance under which circumstances is the critical region reached?

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Appendix A The letter 'Rollout of the nation-wide speed increase'

In this appendix the letter 'Rollout of the nation-wide speed increase' ('Landelijke uitrol snelheidsverhoging') sent to the Dutch parliament on November 28th, 2011, by the minister of Infrastructure and Environment mrs. drs. M.H. Schultz van Haegen, is shown. Unfortunately this letter is in Dutch.

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Datum 28 november 2011
Betreft Landelijke uitrol snelheidsverhoging

Geachte voorzitter,

In mijn brief van 11 februari jl.[1] heb ik een experiment aangekondigd met een (dynamische) maximumsnelheid van 130 km/h op 8 trajecten. Dat experiment is succesvol verlopen. Daarom verhoog ik per 1 september 2012 de algemene maximumsnelheid op autosnelwegen in Nederland naar 130 km/h. Daarnaast verhoog ik de maximumsnelheid op vier van de vijf 80 km zones bij de grote steden per 1 juli 2012 weer naar 100 km/h.

Mijn uitgangspunt is "harder waar het kan, langzamer waar het moet". Kortweg "130, tenzij": overal waar dat mogelijk is, gaat de maximumsnelheid naar 130 km/h. Kan 130 km/h niet de hele dag, dan via een dynamische maximumsnelheid voor een gedeelte daarvan. Dit geldt bijvoorbeeld voor het grootste deel van de A2 tussen Amsterdam en Den Bosch. De hogere maximumsnelheid sluit beter aan bij de beleving van de automobilist en leidt jaarlijks tot aanzienlijke reistijdbaten. Als er een lagere snelheid geldt, dan is dat altijd met een reden: het blijven binnen de randvoorwaarden voor milieu of verkeersveiligheid.

Per 1 september 2012 geldt de maximumsnelheid van 130 km/h in elk geval op bijna 60% van de autosnelwegen de hele dag of een deel van de dag. Voor nog eens 19% van de autosnelwegen onderzoek ik de mogelijkheden nog verder. Het eindbeeld is weergegeven op het bijgevoegde kaartje.

In stappen naar het eindbeeld
Per 1 september 2012 treedt de aanpassing van het Reglement Verkeersregels en Verkeerstekens (RVV 1990) in werking. Daarmee wordt 130 km/h uit uitgangspunt voor autosnelwegen. Op dat moment gaat de maximumsnelheid gedurende de hele dag omhoog op ruim 900 km van de autosnelwegen (39%). Dit zijn de groene trajecten op de kaart. Tegelijk kan op nog eens bijna 500 km (19%) autosnelweg via een dynamisch regime in de avond en de nacht (19.00-06.00 uur) 130 km/h worden gereden (blauwe trajecten).

[1] Tweede Kamer, Kamerstukken vergaderjaar 2010-2011, 32646 nr. 1.

Op nog eens ruim 450 km van de autosnelwegen (nog eens 19%), gelegen langs Natura2000 gebieden en Beschermde natuurmonumenten (gele trajecten op de kaart), wil ik de maximumsnelheid ook verhogen naar 130 km/h. Een voorbeeld van een traject naast een Natura2000 gebied is het noordelijk deel van de A2 tussen knooppunt Holendrecht en Vinkeveen. Voor deze gebieden vindt de komende maanden nog een beoordeling van de effecten op de beschermde natuur plaats. Hierover informeer ik u in het voorjaar van 2012. Dan is ook duidelijk of er meerkosten aan verbonden zijn. Ik streef ernaar ook op deze trajecten de snelheid per 1 september 2012 te verhogen.

Op wegen waar de maximumsnelheid niet de hele dag naar 130 km/h kan, wordt de lagere snelheid aangegeven met verkeersborden "120" of "100". Een dynamische maximumsnelheid wordt via onderborden met tijdvensters aangegeven. De totale kosten voor nieuwe verkeersborden bedragen €5 mln.

Op twee belangrijke snelwegen in de Randstad, te weten de A4 Burgerveen – Delft-Zuid en de A12 Den Haag – Utrecht kies ik voor een dynamisch snelheidsregime met een ruimer tijdvenster. Voor het einde van 2014 wil ik op deze trajecten 130 km/h niet alleen in de avond en de nacht, maar ook overdag buiten de spitsen mogelijk maken. Ik investeer daarom in extra schermen voor de luchtkwaliteit en pas de signalering aan (ca. €7 mln.) om de dynamische maximumsnelheid duidelijk aan te geven voor de automobilist.

80 km zones
Mede door succesvol (bron)beleid is de luchtkwaliteit in Nederland de afgelopen jaren verbeterd, ook langs de autosnelwegen. Uit de uitgevoerde onderzoeken is gebleken dat de luchtkwaliteit ook op en langs de ringwegen van de grote steden is verbeterd, en wel zodanig dat er binnen de normen ruimte is ontstaan voor een snelheidsverhoging. Daarnaast is uit eerdere evaluatie gebleken dat de doorstroming op enkele 80 km zones slechter geworden is. Daarom verhoog ik de maximumsnelheid op de 80 km zones met ingang van 1 juli 2012 weer naar 100 km/h gedurende de gehele dag. Uitzondering hierop vormt de 80 km zone op de A20 bij Rotterdam; ik wil de resultaten van het nog lopende experiment afwachten alvorens een definitief besluit te nemen over dit traject. Hierover zal ik u begin volgend jaar nader informeren.

Experiment en onderzoek
De afgelopen maanden heb ik de mogelijkheden voor de snelheidsverhoging uitvoerig onderzocht. Voor de belangrijkste uitkomsten van het experiment en de uitgevoerde onderzoeken verwijs ik u naar de bijgevoegde eindrapportage van Rijkswaterstaat[2].

Het eindbeeld in 2015 voldoet aan de wettelijke normen voor luchtkwaliteit (Wet milieubeheer) Om het eindbeeld binnen de kaders van het NSL in te passen, investeer ik de komend jaren €35 mln. in schermen voor de luchtkwaliteit[3].

Voor geluid is vanaf 2012 de Wet Swung van toepassing. Hierin wordt gewerkt met geluidproductieplafonds. Door de snelheidsverhoging wordt de werkruimte

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2 "Titel: Onderzoek invoering 130 km/h. Samenvattende analyse experiment en uitwerking voorstel landelijke snelheidsverhoging", Rijkswaterstaat/DVS (november 2011).

3 Daarvan stond € 10 mln. reeds geprogrammeerd in het NSL.

onder de plafonds eerder gevuld dan wanneer het alleen om autonome groei zou gaan. Dit betekent dat eerder geïnvesteerd moet worden om maatregelen te nemen die ertoe leiden dat voor een periode van 15 jaar weer binnen het plafond gebleven wordt. Bij deze eerdere investeringen als gevolg van autonome ontwikkelingen en snelheidsverhoging gaat het in deze kabinetsperiode om een bedrag van €42-57 mln. Deze investeringen waren al voor latere jaren becijferd, maar hoeven in die latere jaren niet meer gedaan te worden om tot en met 2030 binnen de geluidproductieplafonds van de wet SWUNG te blijven.

Het eindbeeld in 2015 is eveneens in overeenstemming met de beleidsmatige doelstellingen voor verkeersveiligheid, natuur en klimaat[4].

Verkeersveiligheid
In eerder overleg over de snelheidsverhoging, heeft uw Kamer terecht veel aandacht gevraagd voor de verkeersveiligheid. Zoals ik steeds heb aangegeven, houd ik onverkort vast aan de nationale doelstellingen om de aantallen verkeersslachtoffers terug te dringen. De ontwikkeling van de aantallen dodelijke slachtoffers en ernstig gewonden op het hoofdwegennet ligt op dit moment op koers in het licht van de afgesproken reducties voor 2020.

In het kader van het experiment is een analyse uitgevoerd van de ontwikkeling van een aantal verkeerskundige indicatoren. De gemiddelde snelheid neemt iets toe. Dit geldt ook voor de onderlinge snelheidsverschillen. Op de 8 trajecten is in de loop van het experiment geen opvallende ontwikkeling in het aantal ongevallen naar voren gekomen.
Zonder aanvullende maatregelen zou het eindbeeld naar verwachting leiden tot een effect van ordegrootte 3 tot 7 doden en 17 tot 34 ernstig gewonden extra per jaar op het hoofdwegennet. Om de dalende trend in de aantallen doden en ernstig gewonden vast te houden richting 2020, kom ik met een pakket van maatregelen voor de verkeersveiligheid op het hoofdwegennet. In het licht van de doelstellingen voor 2020 ga ik daarbij verder dan noodzakelijk om het effect van de snelheidsverhoging te compenseren.

Autosnelwegen die conform de richtlijnen voor 120 km/h zijn ontworpen, bieden voldoende kwaliteit om het verkeer bij 130 km/h comfortabel en veilig af te wikkelen. Ik heb per traject een inventarisatie uitgevoerd naar de uitwerking van het wegontwerp en de ongevalrisico's. Op basis van deze analyse investeer ik de komende jaren waar nodig in verbeteringen in het wegontwerp. Op wegen waar een verhoogd ongevalrisico geldt, verminder ik dit risico door de infrastructuur verder te verbeteren, bijvoorbeeld door het verlengen van in/uitvoegstroken en weefvakken, het vergroten van de obstakelvrije ruimte en het afschermen van obstakels langs autosnelwegen[5]. In totaal gaat het om een additionele investering van €45 mln. in de jaren 2012-2014.
Deze investeringen komen bovenop de €54 mln. die ik via het Programma Meer Veilig 2 deze kabinetsperiode al investeer in infrastructurele aanpassingen voor de verbetering van de verkeersveiligheid op het hoofdwegennet. Om het positieve effect van Meer Veilig 2 kracht bij te zetten, reserveer ik nu reeds €40 mln. voor de verlenging ervan in de periode 2015-2018 (Meer Veilig 3).
In totaal investeer ik hiermee tot 2018 €139 mln. in het nog veiliger maken van het hoofdwegennet. Met deze investeringen verwacht ik de komende jaren een

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4 Tweede Kamer, Kamerstukken vergaderjaar 2010-2011, 32 646 nr. 3 herdruk.
5 Voor een nadere beschrijving van de maatregelen: zie bijgevoegde eindrapportage.

slachtofferreductie te kunnen realiseren in de ordegrootte van 7 tot 11 doden en 47 tot 78 ernstig gewonden per jaar op het hoofdwegennet.

De handhaving van de maximumsnelheid is van groot belang voor de verkeersveiligheid. De minister van Veiligheid en Justitie zorgt daarom met ingang van 1 januari 2012 voor een scherpere handhaving van de maximumsnelheid op 130 wegen en voor hogere boetes op forse snelheidsovertredingen. Bovendien zetten de minister van Veiligheid en Justitie en ik, naast de reguliere verkeershandhaving, de komende jaren in op extra handhaving met behulp van trajectcontrolesystemen, onder meer op een aantal 130-wegen. Begin 2012 wordt een trajectcontrolesysteem geplaatst op de A17/A58 tussen Roosendaal en Bergen op Zoom. In de tweede helft van 2012 wordt de nieuwe trajectcontrole op de A2 tussen Amsterdam en Utrecht operationeel. Voor het einde van deze kabinetsperiode volgen in ieder geval nog twee nieuwe trajectcontroles.

Communicatie
Er gaat veel veranderen op het vlak van snelheden. Op veel trajecten gaat de maximumsnelheid omhoog. Aangezien 130 km/h de norm wordt, komen er nieuwe verkeersborden met "120" op de wegen waar de huidige maximumsnelheid blijft gelden. Bovendien voer ik voor het eerst op grote schaal dynamische maximumsnelheden in. Voor het dynamiseren van de snelheid gebruik ik onderborden en de signalering, zodat ter plekke op de weg volstrekt duidelijk is welke maximumsnelheid geldt. Ik vind het belangrijk dat de automobilist het snelhedenbeleid kan begrijpen. Mijn speciale aandacht gaat daarom uit naar een goede communicatie richting de weggebruiker over het nieuwe beleid.

Wat gebeurt er nog tot 1 september 2012?
Tot 1 september blijft het regime van (dynamisch) 130 km/h van kracht op de 8 trajecten van het experiment (11% van de autosnelwegen). Verder neem ik de praktische voorbereidingen voor de landelijke uitrol ter hand. Zo rond ik de aanpassing af van het RVV 1990, na de advisering door de Raad van State. Voor wegen waarop 130 km/h niet of niet de hele dag mogelijk is, bereid ik de komende maanden een of meerdere verkeersbesluiten voor. Daarin regel ik de lagere maximumsnelheden en/of het tijdvenster. Voor 19% van de autosnelwegen onderzoek ik de effecten van een snelheidsverhoging op naastgelegen natuurgebieden. Rijkswaterstaat zorgt verder voor de detailuitwerking, aanbesteding en plaatsing van de benodigde verkeersborden (2012) en de maatregelen voor verkeersveiligheid en luchtkwaliteit (2012 en verder). Tenslotte zorg ik voor een tijdige en goede communicatie over het snelhedenbeleid richting de weggebruiker. Het is mijn ambitie om, indien dit mogelijk blijkt, het moment van de landelijke uitrol nog naar voren te halen.

Hoogachtend,

DE MINISTER VAN INFRASTRUCTUUR EN MILIEU,

mw. drs. M.H. Schultz van Haegen

Appendix B Results of the study of Elvik (2002)

Elvik (2002) performed a study to the optimal speed limits on public roads in Norway and Sweden. The optimal speed limit is the speed limit that aims to minimize the total costs to society of transport. In the determination of the optimal speed limit five factors were considered: travel time, vehicle operating costs, road accidents, traffic noise, and air pollution. In this appendix only the results for Sweden are presented, because this country is used in this thesis to clarify the economic optimization philosophy for the Dutch situation. Figure B.1 shows the optimal speed limits for Sweden for the four chosen perspectives.

			Optimal speed limits according to the 4 perspectives			
Road type	Current mean travel speed	Current speed limit	Societal	Road user	Taxpayer	Residential
Motorway	109	110	110	120	120	110
Rural highway	95	90	80	100	120	80

Figure B.1: Optimal speed limits in Sweden (Elvik, 2002)

The results are surprising, because for the societal perspective is expected that the optimal speed limit will be lower than the current speed limit on motorways. However, those speed limits are equal. A lower optimal speed limit is expected, because for the considered factors only the travel time has lower costs a high speeds (see figure B.2). As a consequence, a lower optimal speed limit will be derived by summing up all the costs for the considered factors.

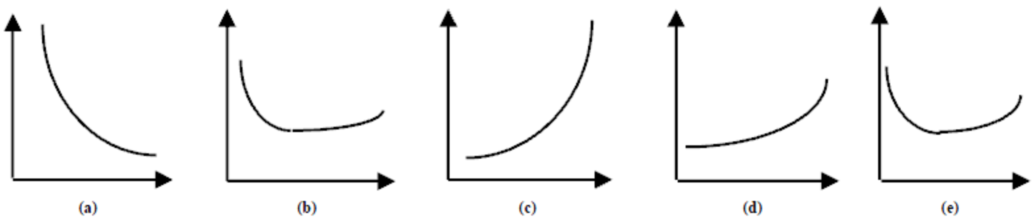


Figure B.2: Typical relationships between speeds (x-axis) and costs per vehicle-kilometer traveled (y-axis) for (a) travel time, (b) vehicle operation, (c) accidents, (d) traffic noise and (e) air pollution (Elvik, 2002)

Appendix C Critical road design elements

In this appendix the critical road design elements provided by Van Delden and Broeren (2011) are explained, including a photo impression. These critical road design elements are researched for investigating the possibilities of implementing a speed limit of 130 km/h.

Table C.1: Critical road design elements (Van Delden and Broeren, 2011)

Critical road design element	Short description
1. Tunnels	A fully closed construction with l ≥ 250 m. 
2. Movable bridges	A bridge which is opened on behalf of the passage of a ship, and which leads to a complete stop of the traffic. 
3. Discontinuities behind each other	A disturbance in the course of the road. There are two types of discontinuities: convergence points (on ramps, joining roads) and divergence points (off ramps, splits). Weaving lanes are compositions of convergence- and divergence points. 

Table C.2 continued: Critical road design elements (Van Delden and Broeren, 2011)

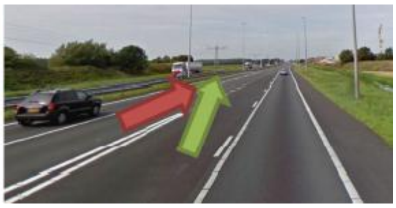
4. Weaving lanes	A roadway section of limited length on the right side of the main road in between a convergence- and a divergence point, which is intended to weave. 
5. On- and off ramps	An on ramp is a lane for finding a gap on the main road (acceleration). An off ramp is a lane for leaving the main road (deceleration).  
6. Tapers	A special configuration of two-lane on ramps, off ramps, joining roads and splits.  
7. Horizontal curves	A curve with a certain radius in the horizontal alignment. 
8. Vertical curves	Vertical curves are applied in order to overcome height differences. There are two types of vertical curves: foot curves and top curves. For instance, foot curves are applied in tunnels, and top curves are applied at movable bridges. 

Table C.3 continued: Critical road design elements (Van Delden and Broeren, 2011)

9. The canting in the road	The canting in the road in order to drain the water towards the road side. This ensures that no aquaplaning can occur.
10. The cross section left	The cross section left consists of the left lane (blue arrow in the picture below), the redressing lane (orange arrow) and the object distance (red arrow). The redressing lane takes care of the possibility to make corrections on the course of the vehicle. The object distance is the distance between the inside of the border line and the object along the road. 
11. The cross section right	The cross section right consists of the emergency lane (blue arrow in the picture below) and the escaping space (red arrow). The escaping space is the space needed to quit a vehicle on one side. 
12. Obstacle free space	The space along the road where no objects may be located. 
13. Rush hour- and plus lanes	At plus lanes an extra lane on the left is added to the main road, which is often narrowed. At rush hour lanes the emergency lane on the right is used as an extra lane.  
14. The traffic composition	The traffic composition is defined on basis of two grounds: the volume/capacity-ratio (which is an indicator for the quality of the traffic flow) and the percentage of trucks. 

Appendix D Power model

Source: (Nilsson, 2004)

Change in traffic safety situation if mean (median) speed is changed from v_0 to v_1

Accidents (y)	Injured (z)
Fatal accident	Fatalities
$y_1 = \left(\frac{v_1}{v_0}\right)^4 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^4 y_0 + \left(\frac{v_1}{v_0}\right)^8 (z_0 - y_0)$
Fatal accidents and serious injury accidents	Fatalities and severely injured
$y_1 = \left(\frac{v_1}{v_0}\right)^3 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^3 y_0 + \left(\frac{v_1}{v_0}\right)^6 (z_0 - y_0)$
All injury accidents	All injured (incl. fatalities)
$y_1 = \left(\frac{v_1}{v_0}\right)^2 y_0$	$z_1 = \left(\frac{v_1}{v_0}\right)^2 y_0 + \left(\frac{v_1}{v_0}\right)^4 (z_0 - y_0)$

Appendix E Impression of the road sections for the case study

In this appendix, impressions of the road sections for the case study are shown. For each road section, a photo is depicted, including the current speed limit [km/h].

A2R: Junction Holendrecht → Maarssen

A2R: Junction Everdingen → Junction Deil

A4R: Junction Burgerveen → Leidschendam

A13R: Berkel en Rodenrijs → Junction Kleinpolderplein

A16R: Junction Klaverpolder → Junction Princeville

A20R: Junction Kleinpolderplein → Junction Terbregseplein

Appendix F Data for the case study

In this appendix, the data is displayed that is needed in step 1 of the assessment framework for the six road sections selected in the case study respectively. In order to collect the data for step 1, the data is completed in the list set up in table 3.6 in chapter 3. The data is obtained using the program Google Earth.

Furthermore, only for the first case study (A2R: Junction Holendrecht → Maarssen), the collected data for step 2 is displayed. This data is completed in the list set up in table 3.7 in chapter 3. For the rest of the case studies, the data for step 2 is explained in chapter 4. This is done because of unnecessary repetitions of table 3.7.

F.1 Data for the A2R: Junction Holendrecht → Maarssen

Data for the engineering philosophy

1. Tunnels / Movable bridges → Is present? → **NO**						
2. Discontinuities (weaving lanes) behind each other → Is present? → **YES**						
Layout	~~Symmetric~~/Asymmetric					
Asymmetric						
Number of lanes main road	> 4	*Length L1 [m]*	1300			
3. On- and off ramps → Is present? → **YES**						
On ramps	*Length L1 [m]*	250	*Length L2 [m]*	100		
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	100	*Length L3 [m]*	x
On ramps	*Length L1 [m]*	250	*Length L2 [m]*	100		
Off ramps	*Length L1 [m]*	170	*Length L2 [m]*	110	*Length L3 [m]*	x
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	110		
4. Tapers → Is present? → **YES**						
Layout	~~Two lanes on ramp~~/Two lanes off ramp					
Two lanes off ramp	*Length L1 [m]*	210	*Length L2 [m]*	210		
5. Horizontal-/Vertical curves → Is present? → **NO**						
6. Cross section left/right (including obstacle free space)						
Passenger cars						
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*			
Driving	Driving	Driving	3,5			
Trucks						
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*			
Driving	Driving	Driving	3,5			
Obstacle free space	*Width B1 [m]*	x	*Width B2 [m]*	x		

Data for the economic optimization philosophy

1. Cost of travel time		
VoT-value for passenger cars (all motives) for the year 2010 [euro/h]	10,67	*(Witteveen+Bos, 2011)*
VoT-value for trucks (road transport) for the year 2010 [euro/h]	45,78	*(Witteveen+Bos, 2011)*
Truck percentage [%]	10,0	

2. Vehicle operating costs				
Parameters for the vehicle fleet in 2002 [L/km] *(TAG, 2011)*				
	a	*b*	*c*	*d*
Average passenger car	0,96	0,05	$-1{,}30*10^{-4}$	$2{,}54*10^{-6}$
Average truck	1,16	0,06	$-4{,}50*10^{-4}$	$8{,}64*10^{-6}$

	Euro 95	*Diesel*	
Price per L at March 2012 [euro/L]	1,813	1,499	*(Autoweek, 2012)*
Truck percentage [%]	10,0		

3. Road accident costs		
Price per fatality [euro/person]	2.690.108	*(Witteveen+Bos, 2011)*
Price per severely injured [euro/person]	276.568	*(Witteveen+Bos, 2011)*

	Number of accidents
Fatal accidents	1
Severely injured	10

Current speed limit v0 [km/h]	100	*Length of road section [km]*	18,7
Truck percentage [%]	*10,0*	*Total length of Dutch motorway network [km]*	2500 *(Rijkswaterstaat, 2012a)*
Total number of vehicle km for passenger cars and trucks on Dutch motorways [km]	$46 * 10^9$	*(Flikkema, 2003)*	

4. Costs of traffic noise			
Mean intensity of passenger cars per hour [veh/h]	5422	*Length of road section [km]*	18,7
Mean intensity of trucks per hour [veh/h]	588	*Factor for city [-]*	1
Price of noise per dB(A) per person [euro/dB(A)/person]	27,97	*(Witteveen+Bos, 2011)*	
Total number of vehicle km for passenger cars and trucks on Dutch motorways [km]	$46 * 10^9$	*(Flikkema, 2003)*	
Total length of Dutch motorway network [km]	2500	*(Rijkswaterstaat, 2012a)*	
Total number of people affected by traffic noise [number]	238.000	*(Rijkswaterstaat, 2012b)*	

(pink)	Means: fixed data	(yellow)	Means: variable data

5. Costs of air pollution					
Price per kg PM_{10} (for motorways) [euro/kg]	376,91	*(Witteveen+Bos, 2011)*			
Price per kg NO_2 (for motorways) [euro/kg]	15,08	*(Witteveen+Bos, 2011)*			
Factor for city [-]	*1*				
Emission rates for PM_{10} and NO_2 [kg/km] *(Drewes, 2006) and (De Lange et al., 2011)*					
Emission rates for PM_{10} for cars [kg/km]			*Emission rates for PM_{10} for trucks [kg/km]*		
50 km/h	$3{,}3 * 10^{-5}$		50 km/h	$8{,}0 * 10^{-5}$	
80 km/h	$3{,}3 * 10^{-5}$		60 km/h	$7{,}5 * 10^{-5}$	
100 km/h	$3{,}8 * 10^{-5}$		70 km/h	$7{,}0 * 10^{-5}$	
120 km/h	$3{,}9 * 10^{-5}$		80 km/h	$6{,}0 * 10^{-5}$	
130 km/h	$4{,}0 * 10^{-5}$		90 km/h	$5{,}2 * 10^{-5}$	
Emission rates for NO_2 for cars [kg/km]			*Emission rates for NO_2 for trucks [kg/km]*		
50 km/h	$1{,}8 * 10^{-4}$		50 km/h	$17{,}50 * 10^{-4}$	
80 km/h	$2{,}2 * 10^{-4}$		60 km/h	$16{,}00 * 10^{-4}$	
100 km/h	$2{,}8 * 10^{-4}$		70 km/h	$13{,}00 * 10^{-4}$	
120 km/h	$4{,}2 * 10^{-4}$		80 km/h	$11{,}25 * 10^{-4}$	
130 km/h	$5{,}0 * 10^{-4}$		90 km/h	$11{,}20 * 10^{-4}$	
(pink)	Means: fixed data		(yellow)	Means: variable data	

F.2 Data for the A2R: Junction Everdingen → Junction Deil

1. Tunnels / Movable bridges → Is present? → **NO**					
2. Discontinuities (weaving lanes) behind each other → Is present? → **YES**					
Layout	Symmetric/~~Asymmetric~~				
Symmetric					
Number of lanes main road	4	*Number of lanes entering road*	x	*Length L1 [m]*	650
Number of lanes main road	4	*Number of lanes entering road*	x	*Length L1 [m]*	630
3. On- and off ramps → Is present? → **YES**					
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	110	*Length L3 [m]* x
On ramps	*Length L1 [m]*	250	*Length L2 [m]*	100	
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	110	*Length L3 [m]* x
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	100	
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	110	*Length L3 [m]* x
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	100	
Off ramps	*Length L1 [m]*	170	*Length L2 [m]*	110	*Length L3 [m]* x
4. Tapers → Is present? → **YES**					
Layout	Two lanes on ramp/Two lanes off ramp				
Two lanes on ramp	*Length L1 [m]*	300			
Two lanes off ramp	*Length L1 [m]*	220	*Length L2 [m]*	230	
5. Horizontal-/Vertical curves → Is present? → **NO**					

6. Cross section left/right (including obstacle free space)					
Passenger cars					
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*		
Driving	Driving	Driving	3,4		
Trucks					
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*		
Driving	Driving	Driving	3,4		
Obstacle free space	*Width B1 [m]*	x	*Width B2 [m]*	x	

F.3 Data for the A4R: Junction Burgerveen → Leidschendam

1. ~~Tunnels~~ / Movable bridges → Is present? → **YES**			
Movable bridges			
Vertical curves	*Cross section left/right*	*Slope*	
See no. 5	See no. 6	Not considered	

2. Discontinuities (weaving lanes) behind each other → Is present? → **YES**					
Layout	Symmetric/~~Asymmetric~~				
Symmetric					
Number of lanes main road	2	*Number of lanes entering road*	1	*Length L1 [m]*	690

3. On- and off ramps → Is present? → **YES**						
On ramps	*Length L1 [m]*	280	*Length L2 [m]*	100		
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	100	*Length L3 [m]*	x
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	110		
Off ramps	*Length L1 [m]*	170	*Length L2 [m]*	100	*Length L3 [m]*	x
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	110		
Off ramps	*Length L1 [m]*	170	*Length L2 [m]*	100	*Length L3 [m]*	x

4. Tapers → Is present? → **YES**				
Layout	Two lanes on ramp/Two lanes off ramp			
Two lanes on ramp	*Length L1 [m]*	∞		
Two lanes off ramp	*Length L1 [m]*	300	*Length L2 [m]*	300

5. Horizontal-/Vertical curves → Is present? → **NO**		
Vertical curves	Foot curve at objects: length R [m]	x
	Top curve: length R [m]	∞

6. Cross section left/right (including obstacle free space)			
Passenger cars			
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*
Driving	Redressing	Driving	3,4
Trucks			
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*
Driving	Driving	Escaping	3,4
Obstacle free space	*Width B1 [m]* x	*Width B2 [m]*	x

F.4 Data for the A13R: Berkel en Rodenrijs → Junction Kleinpolderplein

1. Tunnels / Movable bridges → Is present? → **NO**					
2. Discontinuities (weaving lanes) behind each other → Is present? → **NO**					
3. On- and off ramps → Is present? → **YES**					
<u>On ramps</u>	*Length L1 [m]*	440	*Length L2 [m]*	100	
4. Tapers → Is present? → **YES**					
<u>Layout</u>	~~Two lanes on ramp~~/Two lanes off ramp				
<u>Two lanes off ramp</u>	*Length L1 [m]*	250	*Length L2 [m]*	210	
5. Horizontal-/Vertical curves → Is present? → **NO**					
6. Cross section left/right (including obstacle free space)					
<u>Passenger cars</u>					
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*		
Driving	Driving	Escaping	3,3		
<u>Trucks</u>					
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*		
Driving	Driving	Escaping	3,3		
<u>Obstacle free space</u>	*Width B1 [m]*	x	*Width B2 [m]*	x	

F.5 Data for the A16R: Junction Klaverpolder → Junction Princeville

1. Tunnels / Movable bridges → Is present? → **NO**							
2. Discontinuities (weaving lanes) behind each other → Is present? → **YES**							
Layout	Symmetric/~~Asymmetric~~						
Symmetric							
Number of lanes main road	3	*Number of lanes entering road*	1	*Length L1 [m]*	880		
Number of lanes main road	3	*Number of lanes entering road*	1	*Length L1 [m]*	890		
3. On- and off ramps → Is present?							
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	100			
Off ramps	*Length L1 [m]*	150	*Length L2 [m]*	110	*Length L3 [m]*	x	
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	110			
Off ramps	*Length L1 [m]*	160	*Length L2 [m]*	110	*Length L3 [m]*	x	
On ramps	*Length L1 [m]*	260	*Length L2 [m]*	110			
4. Tapers → Is present?							
Layout	~~Two lanes on ramp~~/Two lanes off ramp						
Two lanes off ramp	*Length L1 [m]*	260	*Length L2 [m]*	250			
5. Horizontal-/Vertical curves → Is present? → **NO**							
6. Cross section left/right (including obstacle free space)							
Passenger cars							
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*				
Driving	Driving	Driving	3,4				
Trucks							
Function lane	*Function lane on left*	*Function lane on right*	*Width of lane L [m]*				
Driving	Driving	Escaping	3,4				
Obstacle free space	*Width B1 [m]*	x	*Width B2 [m]*	x			

F.6 Data for the A20R: Junction Kleinpolderplein → Junction Terbregseplein

<table>
<tr><td colspan="8">1. Tunnels / Movable bridges → Is present? → NO</td></tr>
<tr><td colspan="8">2. Discontinuities (weaving lanes) behind each other → Is present? → NO</td></tr>
<tr><td colspan="8">3. On- and off ramps → Is present? → YES</td></tr>
<tr><td>Off ramps</td><td>Length L1 [m]</td><td>480</td><td>Length L2 [m]</td><td>110</td><td>Length L3 [m]</td><td>x</td><td></td></tr>
<tr><td>On ramps</td><td>Length L1 [m]</td><td>260</td><td>Length L2 [m]</td><td>100</td><td></td><td></td><td></td></tr>
<tr><td>Off ramps</td><td>Length L1 [m]</td><td>230</td><td>Length L2 [m]</td><td>90</td><td>Length L3 [m]</td><td>x</td><td></td></tr>
<tr><td colspan="8">4. Tapers → Is present? → YES</td></tr>
<tr><td>Layout</td><td colspan="4">Two lanes on ramp/Two lanes off ramp</td><td colspan="3"></td></tr>
<tr><td>Two lanes on ramp</td><td>Length L1 [m]</td><td>300</td><td colspan="5"></td></tr>
<tr><td>Two lanes off ramp</td><td>Length L1 [m]</td><td>400</td><td></td><td>300</td><td colspan="3"></td></tr>
<tr><td colspan="8">5. Horizontal-/Vertical curves → Is present? → NO</td></tr>
<tr><td colspan="8">6. Cross section left/right (including obstacle free space)</td></tr>
<tr><td colspan="8">Passenger cars</td></tr>
<tr><td colspan="2">Function lane</td><td colspan="2">Function lane on left</td><td colspan="2">Function lane on right</td><td colspan="2">Width of lane L [m]</td></tr>
<tr><td colspan="2">Driving</td><td colspan="2">Driving</td><td colspan="2">Escaping</td><td colspan="2">3,4</td></tr>
<tr><td colspan="8">Trucks</td></tr>
<tr><td colspan="2">Function lane</td><td colspan="2">Function lane on left</td><td colspan="2">Function lane on right</td><td colspan="2">Width of lane L [m]</td></tr>
<tr><td colspan="2">Driving</td><td colspan="2">Driving</td><td colspan="2">Escaping</td><td colspan="2">3,4</td></tr>
<tr><td>Obstacle free space</td><td>Width B1 [m]</td><td>x</td><td>Width B2 [m]</td><td>x</td><td colspan="3"></td></tr>
</table>

Appendix G V/c-ratio's for the A13R

Source: Regiolab Delft. Regiolab Delft is a laboratory for regional traffic monitoring. Traffic data is obtained from systems and integrated in a traffic information system. This information is used to analyze a region under different conditions (website: http://www.citg.tudelft.nl/en/about-faculty/departments/transport-and-planning/research /facilities/software/regiolab-delft/)

Date	Time	Hectometer poles						
		16.5	*16.7*	*17.1*	*17.4*	*17.8*	*18.2*	*18.5*
3/20/2012	6:00 AM	0.4	0.5	0.2	0.6	0.7	0.9	0.8
	6:30 AM	0.6	0.8	0.3	0.8	1.0	1.2	1.2
	7:00 AM	0.7	1.0	0.4	1.0	1.1	1.4	1.3
	7:30 AM	0.6	0.8	0.3	0.9	1.0	1.2	1.2
	8:00 AM	0.7	0.8	0.3	0.9	0.9	1.2	1.2
	8:30 AM	0.5	0.7	0.3	0.8	0.9	1.2	1.2
	9:00 AM	0.6	0.7	0.3	0.8	0.9	1.2	1.1
	9:30 AM	X	X	X	X	X	X	X
	10:00 AM	X	X	X	X	X	X	X
	10:30 AM	0.5	0.5	0.2	0.8	0.9	1.1	1.0
	11:00 AM	0.6	0.5	0.2	0.8	0.9	1.1	1.1
	11:30 AM	0.6	0.5	0.2	0.8	0.9	1.1	1.1
	12:00 PM	0.6	0.6	0.2	0.8	0.9	1.2	1.1
	12:30 PM	0.6	0.6	0.2	0.8	1.0	1.2	1.2
	1:00 PM	0.6	0.6	0.2	0.8	0.9	1.2	1.2
	1:30 PM	0.6	0.6	0.2	0.8	1.0	1.2	1.0
	2:00 PM	0.6	0.6	0.2	0.8	0.9	1.2	1.1
	2:30 PM	0.6	0.8	0.3	0.8	1.0	1.2	1.2
	3:00 PM	0.6	0.8	0.3	0.9	1.0	1.2	1.1
	3:30 PM	0.6	0.8	0.3	0.8	0.8	1.0	1.0
	4:00 PM	0.5	0.6	0.3	0.6	0.7	0.8	0.7
	4:30 PM	0.5	0.6	0.3	0.7	0.8	1.0	0.9
	5:00 PM	0.5	0.6	0.3	0.6	0.7	0.9	0.9
	5:30 PM	0.5	0.5	0.3	0.6	0.8	1.0	0.9
	6:00 PM	0.5	0.7	0.3	0.7	0.8	1.0	1.1
	6:30 PM	0.5	0.7	0.3	0.8	0.9	1.1	1.1
	7:00 PM	0.5	0.5	0.2	0.7	0.8	1.1	1.1
	7:30 PM	0.5	0.4	0.1	0.6	0.7	0.9	0.8
	8:00 PM	0.5	0.3	0.1	0.6	0.6	0.8	0.8

Date	Time	Hectometer poles						
		16.5	*16.7*	*17.1*	*17.4*	*17.8*	*18.2*	*18.5*
3/21/2012	6:00 AM	0.3	0.6	0.3	0.3	0.5	0.7	0.7
	6:30 AM	0.6	0.7	0.6	0.4	0.6	0.9	1.0
	7:00 AM	0.8	0.9	0.7	0.5	0.7	1.1	1.1
	7:30 AM	0.7	0.7	0.6	0.5	0.7	1.0	1.0
	8:00 AM	0.7	0.7	0.6	0.5	0.7	1.0	1.0
	8:30 AM	0.6	0.6	0.5	0.5	0.7	1.0	1.0
	9:00 AM	0.7	0.7	0.5	0.5	0.7	0.9	0.9
	9:30 AM	X	X	X	X	X	X	X
	10:00 AM	X	X	X	X	X	X	X
	10:30 AM	0.4	0.7	0.4	0.4	0.6	0.8	0.8
	11:00 AM	0.4	0.7	0.4	0.4	0.6	0.8	0.9
	11:30 AM	0.4	0.7	0.4	0.4	0.6	0.9	0.9
	12:00 PM	0.4	0.7	0.4	0.4	0.6	0.9	0.9
	12:30 PM	0.5	0.7	0.5	0.5	0.6	0.9	0.9
	1:00 PM	0.5	0.7	0.4	0.4	0.6	0.9	0.9
	1:30 PM	0.5	0.7	0.4	0.5	0.7	0.9	0.8
	2:00 PM	0.5	0.7	0.5	0.5	0.6	0.9	0.9
	2:30 PM	0.6	0.8	0.6	0.5	0.7	0.9	1.0
	3:00 PM	0.7	0.8	0.6	0.5	0.7	1.0	0.9
	3:30 PM	0.6	0.7	0.5	0.5	0.7	0.9	0.9
	4:00 PM	0.5	0.6	0.4	0.4	0.6	0.8	0.7
	4:30 PM	0.5	0.5	0.5	0.5	0.7	0.9	0.9
	5:00 PM	0.6	0.6	0.4	0.4	0.6	0.8	0.2
	5:30 PM	0.5	0.5	0.4	0.4	0.6	0.9	0.8
	6:00 PM	0.5	0.6	0.5	0.5	0.7	0.9	0.9
	6:30 PM	0.6	0.6	0.5	0.5	0.7	0.9	0.9
	7:00 PM	0.4	0.6	0.4	0.4	0.6	0.8	0.8
	7:30 PM	0.3	0.5	0.3	0.4	0.5	0.7	0.7
	8:00 PM	0.2	0.5	0.3	0.4	0.5	0.7	0.7

Date	Time	Hectometer poles						
		16.5	*16.7*	*17.1*	*17.4*	*17.8*	*18.2*	*18.5*
3/22/2012	6:00 AM	0.5	0.3	0.4	0.4	0.4	0.5	0.4
	6:30 AM	0.8	0.5	0.5	0.9	0.9	1.0	0.8
	7:00 AM	1.0	0.5	0.6	1.1	1.2	1.4	1.2
	7:30 AM	0.8	0.5	0.6	1.0	1.0	1.2	1.1
	8:00 AM	0.9	0.5	0.6	1.0	1.0	1.2	0.8
	8:30 AM	0.7	0.5	0.5	1.0	1.0	1.1	1.0
	9:00 AM	0.8	0.5	0.5	0.9	0.9	1.1	1.0
	9:30 AM	X	X	X	X	X	X	X
	10:00 AM	X	X	X	X	X	X	X
	10:30 AM	0.7	0.5	0.5	0.5	0.5	0.6	0.5
	11:00 AM	0.7	0.5	0.5	0.5	0.5	0.6	0.5
	11:30 AM	0.6	0.5	0.5	0.5	0.5	0.6	0.5
	12:00 PM	0.7	0.5	0.5	0.5	0.6	0.6	0.5
	12:30 PM	0.7	0.5	0.5	0.6	0.7	0.8	0.7
	1:00 PM	0.8	0.5	0.5	0.6	0.7	0.8	0.7
	1:30 PM	0.7	0.5	0.5	0.6	0.7	0.9	0.9
	2:00 PM	0.7	0.5	0.5	0.6	0.6	0.8	0.7
	2:30 PM	0.8	0.5	0.5	0.8	0.8	1.0	0.8
	3:00 PM	0.9	0.5	0.6	0.9	0.9	1.1	1.0
	3:30 PM	0.8	0.5	0.5	0.9	0.9	1.1	1.0
	4:00 PM	0.6	0.4	0.4	0.7	0.7	0.9	0.8
	4:30 PM	0.6	0.4	0.4	0.8	0.9	1.1	1.0
	5:00 PM	0.7	0.5	0.4	0.7	0.7	0.9	1.0
	5:30 PM	0.6	0.4	0.4	0.8	0.8	1.0	0.9
	6:00 PM	0.6	0.5	0.5	0.8	0.8	1.0	0.9
	6:30 PM	0.7	0.5	0.5	0.9	0.9	1.1	1.0
	7:00 PM	0.6	0.5	0.4	0.5	0.6	0.8	0.6
	7:30 PM	0.5	0.4	0.4	0.3	0.4	0.5	0.4
	8:00 PM	0.5	0.4	0.4	0.2	0.3	0.3	0.3