

Het verkeerskundig  
laboratorium  
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ITS EDU LAB

# HOT lanes

*Implementation considerations and assessment for  
the Netherlands*

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March 2013



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ITS Edulab is cooperation between  
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## Colophon

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## Summary

The road network in the Netherlands can be considered as saturated with considerable levels of congestion. To meet the rising problems, policies are developed to increase road capacity at several places and to introduce a general congestion charge to discourage road use during peak hours. Not so long ago, mobility policies focused mainly on reducing travel times. But we have recently come to realise that travelling time reliability is at least as important to travellers, hauliers and shippers. The importance of travelling time reliability for passenger and goods traffic has been acknowledged by government and local authorities.

The answer to these problems presented itself in the U.S. due to circumstances in regards to the poor performance displayed by the previously developed dedicated carpool lanes (High Occupancy Vehicle lanes - HOV). By allowing also the solo drivers to use the lanes conditioned by the payment of a toll, the High Occupancy Toll (HOT) lanes were developed. The concept could present itself as a solution for further advancements regarding road pricing in the Netherlands. This presents the necessity of quick and comprehensive methodology that incorporates all the aspects and considerations, derived from the lessons learned so far, that lead to a potentially successful implementation.

By addressing major aspects that include several influencing factors on the operations' outcome, as commonly found across most of the existing projects through the literature review, a methodology is developed. Comprised of two major phases, the methodology includes all the necessary elements ranging from initial planning and the corresponding goals and objectives up to the implementation setup that provide insight on the interaction of design aspects and performance indicators.

The first phase provides the steps for screening, ranking and selecting the suitable location and the corresponding conditions for the concept to be feasible. This is achieved with the used of criteria and specific indicators that ensure the fact that the chosen location enhances the potential of the concept.

The second phase is more extensive as it includes all the possible design and operations options into the development of scenarios that are evaluated and adapted with the use of a modelling procedure that provides the necessary results. Besides the final evaluation, the modelling procedure provides guidance towards an optimal setup while highlighting the trade-offs between choices.

The methodology is applied to specific cases in order to assess and clarify usability aspects that dictate its efficiency. Several locations are analysed based on criteria such as congestion, reliability, demand and physical attributes and subsequently ranked with the use of determined weights.

A specific location is then picked for the application of Phase 2. An adapted modelling framework is devised around a chosen existing traffic simulation model. The inclusion of several user groups is arranged (income classes) and the addition of a mode choice model for the carpooling is made. Another addition is the algorithm developed for the determination and iteration of toll values. For the inclusion of the previously mentioned aspects in the modelling procedure, several modifications had to be performed within the model. Due to unpredicted issues of compatibility, the model evaluation results of the scenarios could not be used to gain insight and subsequently determine a best implementation setup.

Although no specific evaluation has been conducted, the methodology is considered to be able to produce a potentially successful implementation setup for a HOT-lane concept. In certain areas the included flexibility of the procedures proved beneficial to the usability, while as, for example, the modelling framework is proved to be a downfall.

The methodology has proven to be comprehensive enough to cover most of the aspects related to the implementation and offer sufficient flexibility for adaptation according to specific purposes and needs.

Further research and attention need to be considered with regards to the modelling framework. Due to the extensive behavioural aspects that can be included, adapting or even developing a traffic simulation model is a challenge. In terms of future consideration of the concept for the Netherlands, HOT-lanes should be put in relation or combination with existing dedicated managed lanes such as the rush-hour or truck only lanes.

A pilot study involving a HOT-lane concept can be feasible as it could provide valuable insight also for other traffic management developments.

# Preface

This report marks the end of Master in Transport, Logistics and Infrastructure at the Delft University of Technology. This research was conducted with the support of the ITS Edulab, a collaboration between Rijkswaterstraat – Centre of Transport and Navigation branch and Delft University of Technology.

During my graduation at the ITS Edulab, I was given the chance to conduct research on a topic that was of my interest and also current in the Traffic Management field, for which I would like to thank Serge Hogendoorn and Henk Taale for his promptitude as a response.

Furthermore I would like to thank Adam Pel, for his relentless support, understanding, and insightful recommendations offered consistently during the whole period of my graduation. In the same lines I would like to mention Henk Taale again for his dedication of time to provide the necessary modifications and for solving issues with regards to the traffic simulation model.

A sincere thank you to Jan Anne Annema that was able to provide the right inspiration on occasions when things were not going well. Also I would like to express my gratitude to Ronald van Katwijk for hanging on the committee and provide practical advice, despite the rare occasions that we were able to meet.

The extensive time spent at the office flew by due to the great companionship of my fellow graduating colleagues, for which I'd like to thank them, but also for the openly advice which proved to be essential at times.

Finally I would like to thank my family for their unlimited support and understanding that got me through the tougher periods and to the "finish" line.



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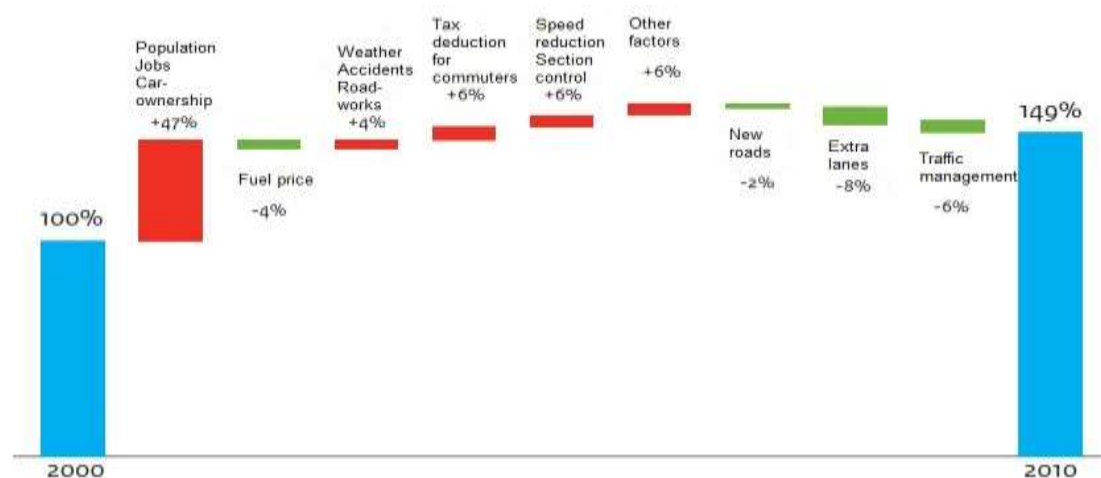
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# 1 Introduction

For the last 10-15 years, traffic management measures tend to fall nicely in place on The Netherlands' road network. Although the "Better use" policy measures manage to reduce congestion and reduce time losses, one of the most coveted measures that can add to the efforts is still missing from the extensive array and that is road pricing. Considering the current situation and traffic environment, road pricing can be introduced in the form of the HOT-lane concept developed in the USA. Providing both options (toll and free) on the same carriage-way is viewed as a concept that brings the benefits of road pricing policies (without big impact on the user's choices) while still preserving the user's current options. This prompts the need for an efficient way to identify and assess the possibilities and the effects of such an implementation in the Netherlands.

Mobility challenges include dealing with an increase in travel demand, growth in congestion, the need to improve safety, and the limited resources to address these challenges. With 16.6 million inhabitants, a surface area of just over 33,000 square kilometres and approximately 9 million vehicles, the Netherlands is densely populated and very mobile. The primary road network, with a total length of around 5,800 kilometres, is highly utilised and this leads to an average of 200 kilometres of traffic jams per working day (KiM, 2011). From 2000 to 2010, travel time losses due to traffic jams and heavy traffic congestion on the main road network increased by 49 percent, as it can be observed in Figure 1.1. This figure would have likely been 15 percent higher in 2010, had new traffic lanes, road expansions and traffic management regulations not been implemented. There is no longer a stable relationship between travel time loss and traffic volumes, because traffic volumes on the main road network have reached maximum capacity at more locations and times of day, as especially witnessed in recent years. Small, local changes have led to greater fluctuations in travel time loss.



**Figure 1.1 Evolution of lost travel time on Netherlands' main roads 2000-2010 (KiM, 2011)**

Increased mobility comes with the risk of unintended negative effects in the area of congestion, pollution and road casualties. The road users do not consider (mobility) in their decision making which choice poses the least risk to others in terms of accidents, pollution and travel time delay. Table 1.1 gives an overview of the various items which determine the total congestion costs.

**Table 1.1 Total congestion costs on main roads in the Netherlands (in billion euros) (KiM, 2011)**

	2000	2009	2010
Costs average travel time losses	0,6	1,0	1,1
Corresponding diversion costs	0,6	1,0	1,1
Costs of unreliable travel times	0,2	0,4	0,4
Corresponding diversion costs	0,1	0,2	0,2
Additional fuel costs	0,01-0,02	0,02-0,03	0,02-0,04
Total direct costs	1,6	2,6	2,8
Indirect costs	0,0-0,5	0,0-0,8	0,0-0,9
<b>Total cost</b>	<b>1,6-2,0</b>	<b>2,6-3,4</b>	<b>2,8-3,7</b>

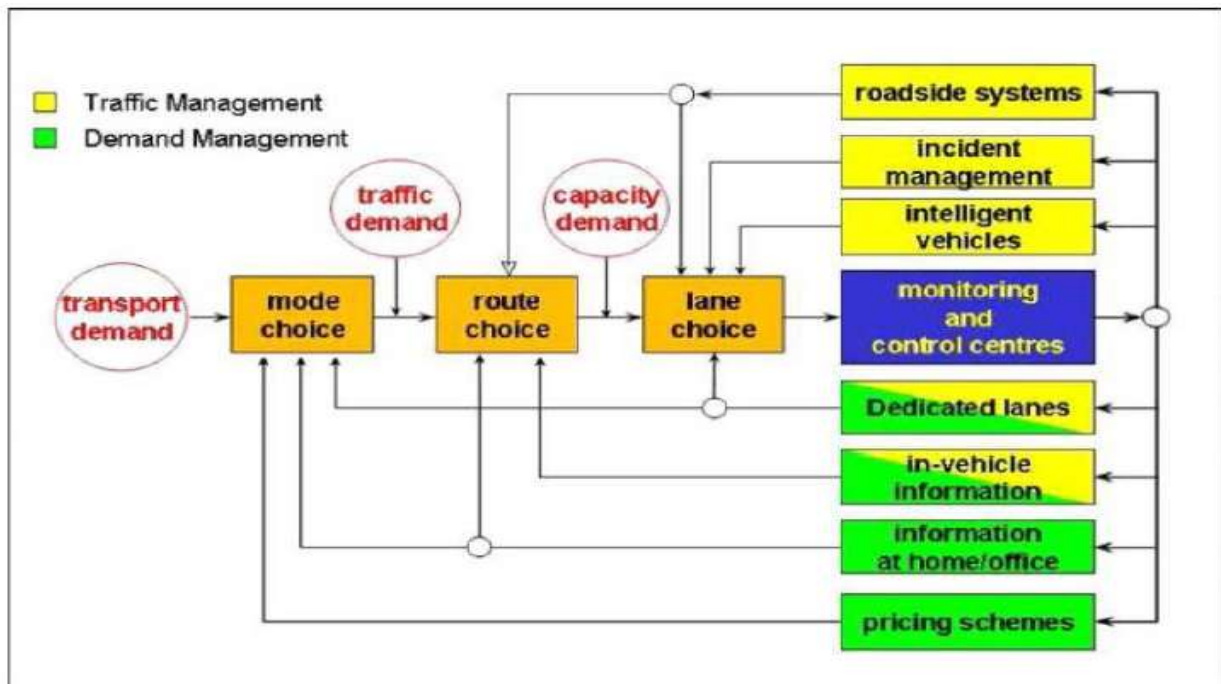
Many measures have been taken over the last three decades to ensure this high level of mobility, and many more are needed as traffic is expected to grow between 10 and 35% between now and 2023 (KiM, 2011).

### Traffic management environment

All across Europe, countries have limited resources to address the growing travel demand and congestion problems they face. Thus, cost-effective use of limited funds is important and typically present in governmental policy. In the Netherlands, for example, the governmental mobility policy has a three-element approach of improving the infrastructure, improving road use, and improving and streamlining internal procedures (Kooten & Adams, 2011). These policy objectives point to the need to make the best use of the existing infrastructure and focus on infrastructure improvements on new connections, widening, and extra or designated lanes. Essentially, all of the efforts undertaken to improve use of the existing roadway through traffic management work to meet the goals set to improve mobility, accessibility and reliability.

Although usually traffic management is commonly used to refer to the generally applicable measures in relations to most of the available ITS infrastructure, it is not the only approach toward solving congestion and mobility problems. While the traffic management employs ways of influencing both the traffic supply and demand of the network, transportation demand management (TDM) include more "soft" measures directly at the demand side through planning. TDM measures have the characteristic of having an impact on the generation and / or attraction of trips and trip-attributes (e.g. mode) from one place to another in a certain time period. They potentially influence human (mode, departure time, and / or route) choice behaviour. Figure 1.2

illustrates that the distinction between demand and traffic management is not very well identified as there are interlaying areas.

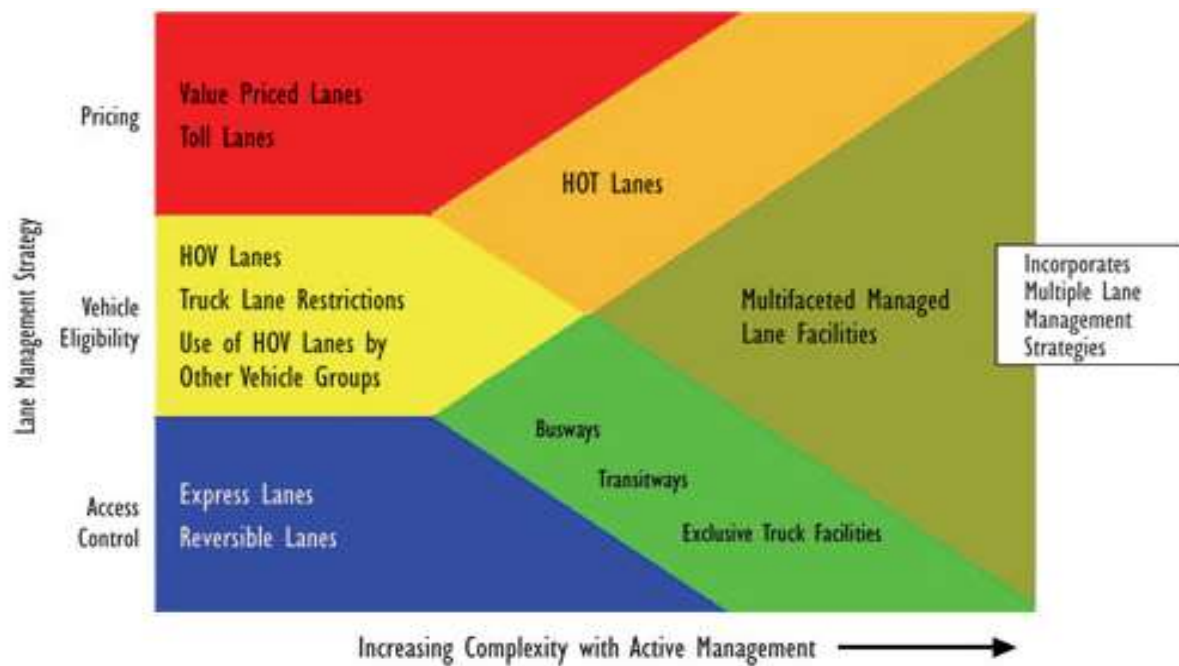


**Figure 1.2 Functional classification of ITS based on control (Middelham, 2006)**

This research is focusing on the “Dedicated lanes” (referred also as “Managed lanes” according to American terminology) and pricing schemes.

### **The concept of High Occupancy Toll (HOT) lanes**

The subject of this thesis addresses a specific form of a dedicated lane named “High occupancy toll lane”, as it can be seen in Figure 1.3. It has evolved mainly in the USA, by taking advantage of available unused capacity in the previously developed carpool lanes or High Occupancy Vehicles lanes by allowing vehicles that do not meet the minimum occupancy requirement to pay a toll for access to the lane(s). The price can be set in a regular toll schedule, it can change by time of day or day of the week, or it can change dynamically in response to the current level of congestion. HOT lanes use both vehicle eligibility and pricing to regulate demand.



**Figure 1.3 Managed Lane Applications (Federal Highway Administration, 2008)**

Thus HOT lanes improve travel options, provide reliable travel times, generate revenue, and increase the overall efficiency of capacity use. As it can also be observed in Figure 1.3, HOT lanes use both vehicle eligibility and pricing to regulate demand. These lanes usually offer travellers reduced travel times that are more reliable, thus encouraging them to carpool. In turn, this can increase the people-moving capacity of the travel corridor.

In several cases, the HOT lane has been constructed as a barrier-separated lane (or segment of road) through the median of an existing highway (Federal Highway Administration (FHWA), 2004). It therefore offers road users the choice of using the possibly more congested „free“ or general purpose lanes which have no restriction on access or the HOT lanes depending on vehicle occupancy or willingness to pay. It has also taken the form of a flat rate toll as well as a variable toll depending on time of day, vehicle occupancy or level of congestion on the „free“ lanes (Federal Highway Administration (FHWA), 2008a).

Access requirements and rate structures for HOT lanes vary by facility. In some cases, only single-occupant vehicles (SOVs) are charged a toll to access the facility while in other cases, more stringent vehicle occupancy requirements must be satisfied to permit access by tolling. Some facilities charge constant rates to toll paying motorists while others charge variable rates designed to maintain free flowing conditions.

HOT lanes may be created by either converting existing HOV to HOT, building new lanes and make them HOT, or converting an existing GP lane to HOT.

The conversion of an existing GP lane to an HOT-lane has the potential to create winners and losers. Drivers in lanes that were previously toll free will now have to be squeezed into the remaining non-tolled lanes if they do not want to pay the toll. Flow in the priced lane will be faster and more reliable, and potentially even higher than before (since stop-and-go conditions pass fewer cars per hour than freely flowing traffic). People willing to pay will benefit. Those that are not willing may not. The overall benefit/cost may be positive, but one group may benefit at the dis-benefit of another (Cambridge Systematics, 2007).

Another issue that requires policy attention is the use of revenues generated by the special toll lanes in excess of conversion and operating costs. The toll receipts can be used to fund new public transport service in the corridor and provide an alternative to paying a toll.

Several aspects of the HOT-lane concept were presented. The facility was described as restricting access to non-qualifying user groups, through more open or more closed type of separation from the "free" general purpose lanes. The restriction or access is provided through the use of electronic toll free-flow techniques. Through various types of pricing schemes the facility is managed in order to maintain a required level of service. The prices may vary with congestion levels and/or time of day. For the type of implementation (use of already available road way space, either a general purpose or shoulder lane) considered several concerns were also mentioned.

### **Opportunity for implementation**

The Dutch economy has traditionally been relatively dependent on trade, transport and logistics services, which was encouraged by the country's strategic geographic location. Therefore, perhaps even more so than in other countries, accessibility is considered as an important condition for further economic growth and development, much of which can be expected to take place in previously mentioned industries.

Travel times and travel time reliability are components of accessibility in traffic engineering sense. In this chapter we restrict ourselves to the accessibility to the road network. That means improving accessibility in practice often reduces travel time losses due to congestion and delays.

The HOT-lanes concept has been proven at some extent to have positive outcome in dealing with congestion, with the use of pricing. Road pricing has been proposed as a potentially powerful travel demand management (TDM) strategy capable of significantly influencing travel demand characteristics through the network.

Probably more than in most other EU-countries (with the exception of Scandinavian countries), the implementation of road pricing type of instruments has been considered seriously by successive Dutch Ministers of Transport over the last 15 years or so. The Netherlands has a long experience in developing new road pricing proposals to reduce the increasing levels of congestion. Accordingly,

four types of road pricing have been considered in The Netherlands: peak hour permits ('spitsvignet'), toll plaza's ('tolpleinen'), electronic peak hour cordon charging ('kilometer-heffing'), and, most recently, generally applied kilometre charges. None of these cases led so far to implementation (Verhoef & Ubbels, 2006). Currently the direction of road pricing follows the lines of providing people monetary incentives not to drive during the peak represented by the initiative projects such as "spitscoren", covering a corridor, and "spitsvrij", covering an area.

Road pricing is seen as offering interesting possibilities, but so far the major political hurdles have proven too difficult. One possible explanation is that complex decision-making must be handled by one government, while the implementation and management depends on the policies of the next government administration. As much broader deployable solutions have so far been proven politically infeasible it may be appropriate to explore in short-term whether a limited pricing measure such as high occupancy toll (HOT) lanes can be effective in the Netherlands.

The infrastructure is already present to manage and operate the lanes in corridors where dynamic traffic management has already been implemented. The addition of a managed lane strategy can be easily supported and optimized since these corridors are suitable and users are already familiar with dynamic operating conditions that reflect congestion levels. The governments' commitment to infrastructure investment and technology in managing congestion provides great opportunities for more regulated lanes. Furthermore, implementation of speed harmonization and temporary shoulder use represent key predecessors for managed lanes, as they reinforce the efficient use and optimization of the existing network (Mirshahi, et al., 2007).

The temporary use of the shoulder sets the stage for the flexible use of the road way space. The use of managed lanes can address bottleneck problems, vehicle restrictions, and the potential benefits of pricing and occupancy-based strategies.

The Netherlands seem to have a policy culture which is often relatively open to new, innovative and sometimes experimental policy concepts. This, together with what has been presented so far, points to a genuine opportunity and feasibility for the concept of HOT-lanes to be introduced in the Netherlands, even if just as an intermediate step towards more extensive road pricing policies for the future.

## 1.1 Research Approach

This section presents the reasoning and process to be followed for achieving the set goal.

### 1.1.1 Problem definition

Dynamic road pricing is potentially a powerful tool to influence demand, but it is also politically sensitive, as mentioned in the previous section. Road pricing can offer extended possibilities to traffic management. It is therefore necessary to explore what other less far-reaching possibilities are there to implement road pricing as a traffic management option. This brings the perspective of a measure such as HOT lanes that can be implemented successfully in the Netherlands. The HOT-lanes concept has spread in the US since its first implementation, encouraged by the success of several projects, and also evolved in various forms that provided the flexibility needed for achieving success.

HOT-lanes have, where evaluated, helped reduce congestion. However, it is difficult to draw overall conclusions about their effectiveness because only in half of the projects now open to traffic in the US have been evaluated. Other results, where available, are mixed, as different measures to assess performance have been used and little has been done to compare performance across projects. Where congestion pricing projects have also added lanes, the results of pricing have not been distinguished from the results of adding capacity. A more complete understanding on how to address the potential benefits and effects of the implementation of HOT-lanes is needed.

Therefore, if the implementation of such a concept can be successful in the current traffic situation and environment of the Netherlands, is definitely uncertain. Considering that the conversion of an existing “free” lane to a tolled one has been rarely tried, a thorough analysis has to be undergone by addressing suitability issues throughout the implementation phase and the evaluation of its effects. The need for a methodology that can effectively put to use the lessons learned, and provide a quick overview of the possibilities, presents itself. This can be regarded as a gap between policy and policy-supporting models, which can provide a solution to properly use the refinements and findings on HOT-lanes for the quick assessment of a possible implementation in the Netherlands.

#### **Problem statement:**

*The valuation of tolled lanes in the United States is for an important part based on the valuation of congestion relief and travel time reliability. For the Netherlands the concept can prove to be an effective traffic management instrument that can further improve the accessibility (reduce travel time losses and travel time unreliability) while making an important step towards general road pricing. Currently there is no proper method that incorporates all the key factors and lessons learned into a quick, effective evaluation of implementation of the HOT-lanes concept.*

### 1.1.2 Research Objective

Based on the previously defined problem statement the corresponding research objective is to define the methodological steps required for an effective implementation of a HOT-lane concept in the Netherlands as a traffic management measure. The steps cover the process from initial planning, as consideration of a HOT-lane implementation, throughout possible locations and defining an operational setup. They will also include analysis techniques and adaptation of an existing traffic simulation model making it capable of estimating the effects of such an implementation.

#### Main research question:

*[What are the methodological steps needed for defining and evaluating a potential implementation of a HOT-lane in the Netherlands and what are they comprised of?]*

To help answer the main research question, the following sub-questions were devised:

- *What is the state of current practice regarding HOT-lanes?*
- *What are the main aspects and their influencing factors that need to be addressed?*
- *What are the considerations of previous research in terms of implementation planning?*
- *What is the appropriate structure for incorporating the implementation considerations and the design aspects into the methodology?*
- *How are the various aspects with their influence and interaction represented through phases and procedural steps?*
- *How is the potentially successful implementation setup determined and evaluated?*
- *What are the practical considerations when applying the methodology to specific case studies?*
- *How useful is the methodology when addressing a possible implementation of the HOT-lane concept?*

### 1.1.3 Research scope

Although the implementation of the HOT-lanes is treated as a whole, not all details and aspects are addressed in details. Due to the nature of the research's objective that emphasizes on a quick and efficient manner of bridging the gap between policy and policy-supporting tools of evaluation, only the main influencing factors are identified and addressed.



Therefore from a planning perspective only the identification of the suitable goals and objectives of the implementation is addressed without going beforehand into depth in terms of acceptability and equity issues. The latter mentioned will be taken into consideration as far as influencing design factors, but no further.

The design aspects that will be addressed will only be limited to conceptual elements that influence the performance of the HOT-lane. The technology and other technical physical elements will not be treated in detail although they will be briefly mentioned for providing perspective on the whole project. Finally the implementation's evaluation will be using modelling techniques that only address the overall performance, on a macroscopic level, of the facility and include options and details that allow the tailoring and assessment of the policy and its underlying concepts. The inclusion of the different aspects that the traffic model needs to represent will resort to basic modelling techniques without appealing to more specialised and state of the art methods.

The output of the simulation is used to assess the performance of the facility, but also providing the data for comprising a basic cost-benefit analysis of the implementation.

#### **1.1.4 Research relevance**

The research relevance addresses both scientific purposes as well as providing practical assistance in terms of sketch-planning for the policies that consider an implementation of the concept.

**The scientific relevance** refers to the technicalities of including in the modelling procedures the latest findings in from previous research in the same framework. Although treated separately extensively aspects such as the modelling of travel time variances that expresses the value of travel time reliability, departure time choice or elastic demand, there was no inclusion into the same methodology of most of the aspects. Although this is not achieved per se, it is taken into consideration and the opportunity is offered by including the connections that allow their interaction.

Policy development until now has referred to a multitude of aspects that describe the operations of a HOT-lane, such as vehicle occupancy, separation, access, pricing schemes, etc. These are usually treated specifically in turns while the influence of the others is considered fixed.

Although other typical studies have included the evaluation of certain predetermined policy combinations, such as (Loudon, 2009) that used sketch-planning methods to assess managed lane options such as HOV, HOT, and truck-only lanes, the methods didn't consider other potential variations, e.g. start-end access vs. multiple access vs. unlimited access.

Eisele et al. (2006) built a decision-support tool for the conversion from HOV to HOT. Similar to solving a multi-attribute decision making problem, three categories with 22 attributes are scored.

Based on default or user-defined weights, HOV/HOT conversion is suggested if the total score exceeds a specific threshold. The main concern in applying the tool rests in the validity of the weights as well as in the subjective scoring of the attributes.

**The practical relevance** relies on the ability to intuitively be able to develop the best implementation setups. It is within these lines that this research aims at comprising a methodology that can aid the policy makers in what can be called the sketch-planning of an implementation of a HOT-lane concept.

An aspect that needs pointed out is that most of the developed studies and methods, although more or less generally applicable are to be used on predetermined specific cases (locations). Considering that most of the projects currently in practice have characteristics that are the result of the context and conditions of the area/location where the implementation was executed/investigated, the importance of how are those predetermined specific cases identified and assessed presents itself.

Several guides were developed over the years, by the Federal Highway Department from the U.S. (Federal Highway Administration (FHWA), 2003; Federal Highway Administration (FHWA), 2008a), guides that are very comprehensive, but offer no quick method nor step like procedure that can ensure a quick and efficient way of consideration and evaluation of implementing the concept.

#### **1.1.5 Structure of the report**

Figure 1.4 outlines the structure of the report in correlation with the sub-research questions that help to reach the conclusion of the proposed main research question for this thesis.

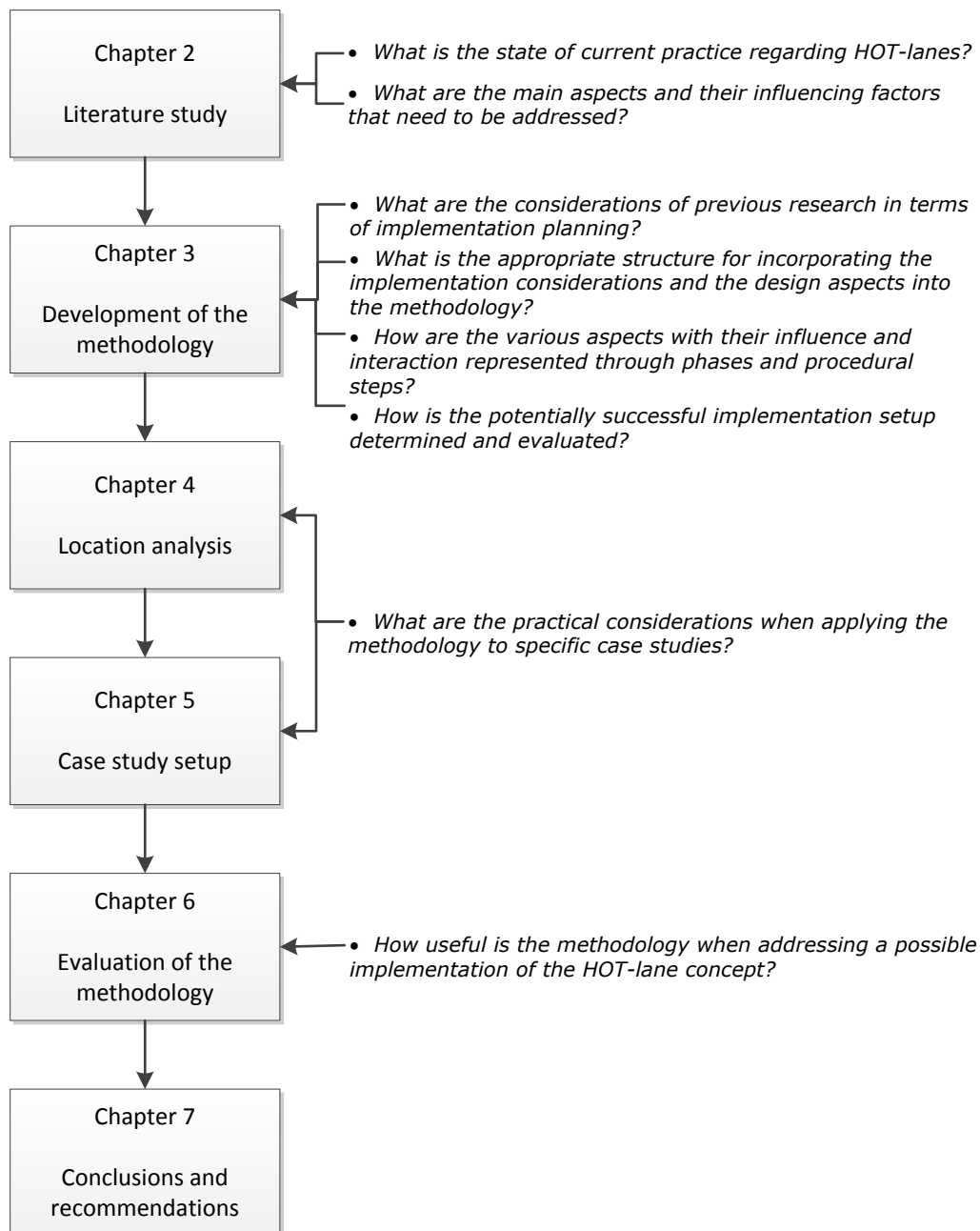
Chapter 2 includes the representation of current practice of the HOT-lane concept in the U.S. while evidencing the major aspects that are considered to contribute to the success or failure of such an implementation. Through the addressing of certain varying elements from the projects' characteristics several influencing factors are summarized.

Chapter 3 is the most important part of the report due to its incorporation of all the phases of the methodology. It represents specific aspects included in detailed steps and their correlation within the whole methodology. Starting from the assessment of suitable locations for a potentially successful implementation through rating with the use of specially considered criteria, scenarios are developed for a specific case and evaluated with the application of a traffic modelling framework.

The next two chapters, 4 and 5 respectively, portray the application of the methodology on actual specific cases in order to exemplify and clarify how the methodology can be used. From this

application and assessment is made in chapter 6 to determine the efficiency and practicality of the proposed methodology.

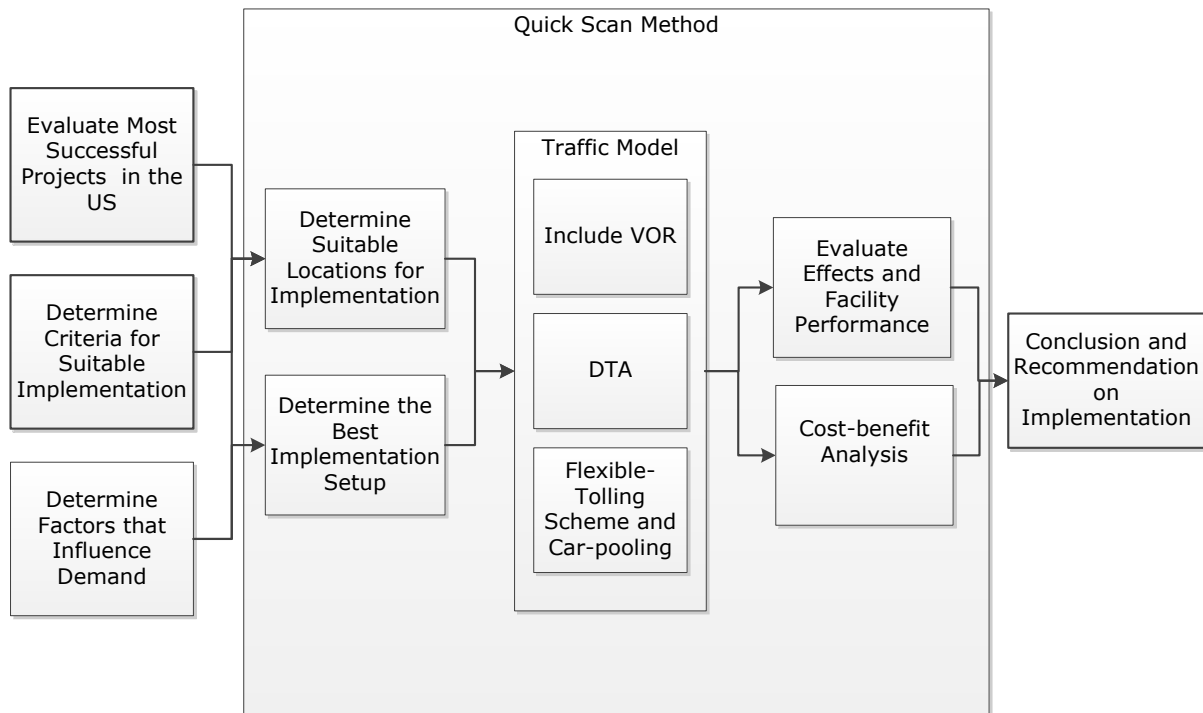
Last, but not least, conclusions are drawn on if the main research question was answered and what findings and recommendations are drawn from the process.



**Figure 1.4 Report structure**

### 1.1.6 Research Methodology

Based on the research objective and the research questions a research model is constructed as it can be seen in Figure 1.5.



**Figure 1.5 Research Model**

The methodology proposed addresses the consideration of a HOT-lane implementation in two phases. The first is concerning the soft measures that have to be considered in terms of planning and making sure that the necessary conditions are met in making the first phase assuring the potential success of the implementation. The conditions already pre-consider effects of the design aspects that can pose important issues later on.

This leads to the second phase where the design and operations aspects that dictate the setup to be implemented. Specific design options are considered part of the various scenarios for implementation. In order to assess the different possible setups, a model and a modelling framework are defined. In this project, an existing model is chosen to which elements considered important for the evaluation of the implementation are added. The goal is not to develop a procedure or include detail of elements that require extensive modifications in order to keep the method as approachable as possible in due time. The modelling procedure will also provide insights in the extent of the correlation between the different design aspects leading to further considerations of the methodology's procedure.

## 2 Literature study

This chapter represents the first part of this research and includes the necessary initial knowledge for achieving the proposed objective. From general elements and characteristics of the preliminary setup considerations of the implementation of a HOT-lane to detailed analysis of the extensive history of practice from the USA can be found in this chapter. The numerous successful implementations of such a concept and how these translate into the design and setup of such a facility are discussed. The initial considerations are made that provide the direction for the development of the methodology.

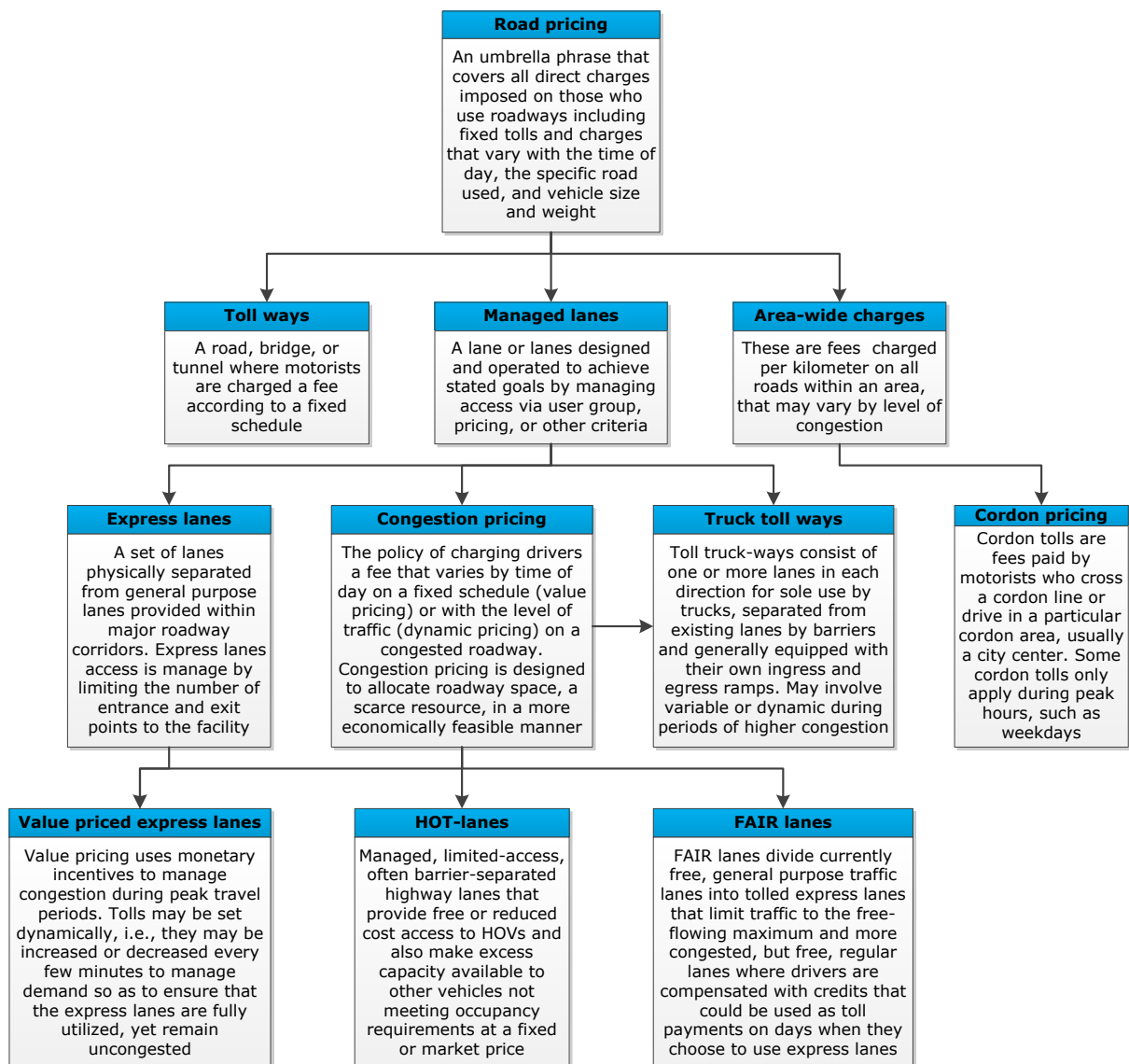
### 2.1 Reasoning behind the concept

Road transport is known to generate considerable external costs, particularly in the form of congestion, accidents and noise. Governments may use different types of measures to deal with these problems, pricing being one of them. Most countries use a number of straight-forward pricing mechanisms, such as fuel taxes, registration fees and parking charges. For the purposes of this study, the term "road pricing" only considers forms of direct highway user charges, including fixed tolling and variable pricing.

Road pricing has been proposed as a potentially powerful travel demand management (TDM) strategy capable of significantly influencing travel demand characteristics through the network. Generally, the policy objectives of road pricing can be summarized as follows: managing demand, optimizing congestion level, reducing environmental impacts, maximizing social welfare gains, raising revenues to cover maintenance and construction costs, etc. Road pricing is considered to be a very effective instrument for welfare maximisation and reducing the societal damage of mobility.

The words "tolling," "pricing," "value pricing," "congestion pricing" and others are used without true understanding of their meaning. Tolling is a broad term that refers to any kind of direct user fee on highway transportation. Pricing, on the other hand, refers specifically to using the amount of the toll price to achieve some other objective, usually congestion relief or reliable traffic flow.

**Figure 2.1** shows the relationship between different approaches to road pricing, including both tolling and managed lanes.



**Figure 2.1 Road pricing typology** (AECOM Consult, 2006)

HOT lanes are an example of the concept of value pricing, which involves charging an optional toll to allow access to a restricted traffic facility such as an HOV lane (Stockton, Edmonson, Hughes, Hickman, Puckett, & Q. Brown, 2000).

They were originally preceded by HOV lanes which were not successful resulting in underutilised lanes thus emerging as a solution for the demand consisting of drivers of SOVs that were willing to pay for a faster trip but did not have the required number of occupants (Kim, 2002).

HOT lanes combine pricing strategies and occupancy restrictions to manage the number of vehicles using the facility. HOT lanes typically provide free access to qualifying HOVs, and allow vehicles that do not meet the occupancy levels required for free travel, the option of paying a toll to gain

access to the HOV lanes (Perez & Sciara, 2003). The price may be set in a regular toll schedule, it may change by time of day or day of the week, or it may change dynamically in response to the current level of congestion. Thus, the lanes are “managed” through pricing to maintain free flow conditions even during rush hours. The appeal of the concept can be reduce to the following:

- It expands mobility options in congested urban areas by providing an opportunity for reliable travel times to users prepared to pay for this service;
- It generates a new source of revenue which can be used to pay for transportation improvements, including enhanced transit service; and
- Utilizing available and unused capacity (carpool lanes in the US and hard shoulders in the Netherlands)

Economists have focused on the potential ability for road pricing to improve the efficiency of road networks by causing motorists to internalize the externalities they impose on other motorists and the public at large. The delay costs imposed on others from a vehicle’s contribution to congestion is the primary external cost discussed in the congestion pricing literature. However, other external costs such as those associated with accidents, emissions, and noise can be incorporated into congestion pricing. Small et al. (2006) have noted that HOT lanes have the potential to improve the efficiency of urban highways by making better use of underutilized carpool lanes and providing faster and more reliable travel to those who value it most. Economists generally believe that congestion pricing has the potential to alleviate congestion on roadways in an economically efficient way. Those who value a fast and reliable trip will pay for the option. Drivers who place a lower value on time will choose to stay in the un-priced and potentially more congested roadways. Thus, paying a toll that reflects a driver’s value of time and covers external costs can potentially reduce congestion and the demand for road space at peak periods.

The operations of HOT-lanes employ several mechanisms under a management strategy used to control the flows, such as the following:

- Occupancy requirements (legacy of HOV lanes with HOVs defined by the number of person carried) that qualify the HOVs that can use the facility at no or reduced cost
- Pricing system – the tolling scheme may be fixed, varying by time of day, or dynamic, varying in response to real-time traffic conditions. In either case, higher tolls are charged during peak demand periods
- Toll collection - HOT lanes rely on electronic payment systems
- Vehicle classes – the policy may be related to vehicle type depending on local transportation goals (low-emission vehicles, motorcycles, emergency vehicles, public transport vehicles, taxis, and/or trucks may benefit from preferential attention as the carpools)

- Access points – as HOT lane facilities are in somehow separated from the general purpose lanes, the access to the lane may be provided at intermittent points, but in many cases there may be only single entry and exit points

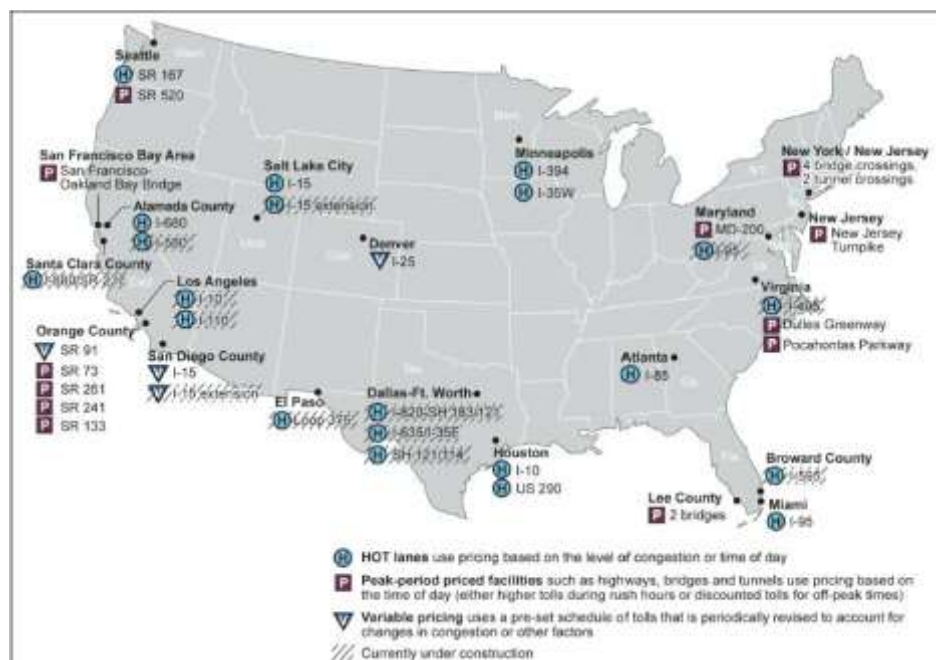
Although the history of HOT lanes appears to have led to some standardization regarding physical configuration and operation of these facilities it should also be noted that they can be and actually are different, as it can be observed in the presentation of several representative project from the following section.

## 2.2 HOT-lane projects – description and performance

HOT lanes exist, in multiple forms, in nine US major urban areas, and more are proposed. Because of the many appealing features of HOT lanes, there are numerous examples of their use.

All congestion pricing projects in the United States have used either High Occupancy Toll (HOT) lanes or peak-period pricing on already tolled facilities. (U.S. Government Accountability Office, 2012).

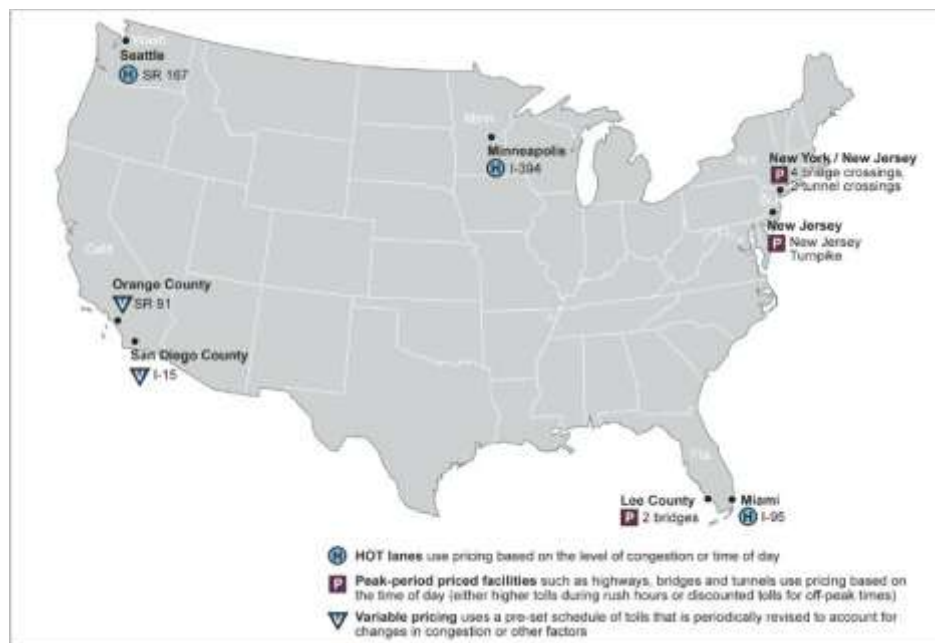
Since the first U.S. congestion pricing project was implemented in Orange County, California, in 1995, 19 project sponsors have initiated 41 pricing projects on highways, bridges, and tunnels. Of the 41 pricing projects, 30 are completed and open to traffic. The 30 opened projects include 12 HOT lane projects and 18 peak-period priced facilities, as it can be observed in **Figure 2.2**.



**Figure 2.2 Congestion Pricing Projects in Operation or Under Construction** (U.S. Government Accountability Office, 2012)



Of the project sponsors that have operational congestion pricing, 8 have a current and completed evaluation of at least one of their projects. These eight evaluations assess five HOT lane projects and nine peak-period pricing projects, as shown in **Figure 2.3**.



**Figure 2.3 Projects That Have Current and Completed Evaluations of Congestion Pricing Projects**  
(U.S. Government Accountability Office, 2012)

As this project focuses on the implementation of HOT-lanes, projects that involve corridors are to be taken into account, which are briefly discussed below, thus excluding the peak-period priced facilities that are used on bridges, tunnels and short sections of highway.

### **State Route 91 (Orange County, California)**

The California State Route (SR) 91 HOT lanes project is the nation's first experiment with value pricing. The SR-91 Express Lane facility was constructed as part of a private, for profit toll road venture authorized by the California Legislature in 1989. These HOT lanes were built in one of the most congested corridors of California, with typical peak-period delays of 30–40 minutes. However, the Orange County Transportation Authority subsequently took control of the facility after its first three years of operation. The project's realisation goals:

- promote California's ridesharing policy and
- return a profit to the investors.

The toll lanes are located in the freeway median between Anaheim and Riverside Counties, and the facility provides two extra lanes in each direction.

While all vehicles are charged a toll during peak periods on the 10-mile State Route 91 Express Lane facility, vehicles with three or more occupants receive a 50% discount on the toll charge. The toll varies by time of day and day of the week according to a fixed schedule. The tolls are set using level of service (LOS) considerations (travel time savings to users compared to users of the parallel free route). A LOS "C" is the chosen criterion for toll rate setting. There is no objective of optimizing system transportation costs or any other criteria. Hence, the facility is not a strict congestion pricing experiment as economists originally advocated.

All tolls are collected electronically by Automatic Vehicle Identification (AVI).

### **Interstate 15 (San Diego, California)**

San Diego Association of Governments (SANDAG) is the lead agency on this project in cooperation with California Department of Transportation (Caltrans), which owns and operates the HOV lanes and the freeway facilities. The other participants are Metropolitan Transit Development Board (MTDB) and California Highway Patrol (CHP). CHP is responsible for enforcement.

The project goals are to:

- maximize use of the existing I-15 HOV lanes
- test whether allowing solo drivers to use the facility's excess capacity can relieve congestion on general-purpose lanes
- improve air quality
- fund new transit and HOV improvements in the I-15 corridor

The I-15 HOT lanes consist of two reversible lanes that are approximately eight miles in length. Construction is underway to extend the facility and add two additional HOT lanes. Currently, the toll for SOVs varies dynamically with congestion in the HOT lanes and is updated every six minutes. Message signs near the access point to the HOT lanes indicate the charge, which typically varies between \$0.50 and \$4.00, although it may be as high as \$8.00 in periods of high demand. Carpools with two or more passengers can use the I-15 HOT lanes for free.

### **Interstate 394 (Minneapolis, Minnesota)**

The I-394 MnPASS facility allows vehicles with two or more persons to travel free while SOVs may access the HOT lanes if they pay a toll. The facility is dynamically priced. A three-mile stretch of it consists of two reversible lanes that accommodate peak direction traffic, while the remainder consists of one lane in each direction.

The HOT lane innovations that were firstly used in Minnesota I-394 facility comprise of two major characteristics: tolling is performed on lanes which are not separated with barriers from general

purpose lanes in 8-mile section of total 11-mile long facility and dynamic pricing is applied on multiple sections with multiple entry and exit points (Halvarson, Nookala, & Buckeye, 2006).

The implementation considered a HOT lane system that met five project objectives (Cambridge Systematics, 2006a):

- Improve the efficiency of I-394 by increasing the number of people and vehicles using the HOV lanes
- Maintain free-flow speeds for transit and carpools in the express (HOV) lanes
- Use excess revenues, if available, to make transit and highway improvements in the I-394 corridor
- Use electronic toll collection (i.e., tags/transponders and readers) which do not require toll booths
- Employ new Intelligent Transportation System (ITS) technologies, such as dynamic pricing and in-vehicle electronic enforcement

### **State Route 167 (Seattle, Washington)**

The SR-167 HOT lane facility opened in 2008 and is located near Seattle, Washington. The SR-167 HOT lanes allow vehicles with two or more occupants (HOV 2+) to use it free while SOV must pay a toll to access the lanes. The facility is dynamically priced every five minutes using real-time traffic data on speed and volumes, with tolls varying between \$0.50 and \$9.00. Motorists who wish not to use the HOT lane can use two parallel GP lanes that operate in each direction.

### **Evaluation of performance**

Evaluations of 14 congestion pricing projects in the United States have generally shown reduced congestion, although other results are mixed, and not all possible relevant effects have been assessed (U.S. Government Accountability Office, 2012).

Some HOT lane projects have added new lanes and thus, for these projects, the effects of pricing on performance have not been distinguished from the effects of the added lane. In addition, although the number of cars using HOT lanes has risen, there were fewer people in the cars due to the increase SOVs or a decrease in car-poolers. Other effects of congestion pricing projects, such as equity income impacts, have not always been evaluated.

### **Travel Time and Speed**

The increased capacity from adding two new toll lanes, in each direction, substantially reduced peak period freeway congestion on *SR 91*, giving short-term travel time benefits to all commuters in the corridor. In the six months after opening of the express lanes, the typical PM peak trip delay

on the freeway fell from 30-40 minutes to less than 10 minutes per trip. A year later the PM peak trip delay had increased by about 5 minutes to the 12-13 minute range, reflecting both time shifts in travel demand and the effect of the underlying long-term traffic growth trend. A small travel time improvement of about 6 minutes per trip was observed on one of the parallel arterials (Sullivan & Harake, 1998).

In the case of the *I-95 Express Lanes*, the data shows that the travel time of vehicles in the HOV lanes decreased from 25 minutes to 8 minutes after the Express Lanes. The posted speed for the facility is 55 MPH, which equates to 8.0 minutes of travel time in each direction. The actual average peak period travel time through the 7.33-mile corridor is 6.9 minutes in the South-Bound EL and 7.7 minutes in the North-Bound EL. An important project benefit is the reliability of reduction in travel time delay. Under worst congestion conditions, FasTrak users can save up to 20 minutes avoiding delay on the *I-15* main lanes and on the on-ramp to the main lanes (Supernak J. , 2005).

Despite the observed increases in traffic volume in the *I-394 MnPASS* lanes, travel speeds in the lane have not been negatively impacted as most locations experienced no change or a slight increase in travel speed. Speeds in the general purpose lanes were observed to experience a slight increase following the implementation of MnPASS for all locations tested when compared with similar periods from previous years. Although statistically significant, caution should be applied in attributing all of the speed increase to the MnPASS implementation. In many locations, the speed increase in the general purpose lane was accompanied by a slight decrease in volumes that may also partially be responsible for the speed increase. Further analysis of the speed changes observed in the general purpose lanes on I-394 revealed that the relative increase in travel speed in the general purpose lanes (compared with speeds in previous years) is even greater on days with higher volumes, or days when there were incidents occurring in the corridor (compared with similar incident days from the before period). This observed impact suggests that MnPASS is helping to mitigate the negative impacts on the worst travel days, and is effectively reducing speed and travel time variability in the corridor (Cambridge Systematics Inc., 2006).

In the case of the *SR 167* the southbound peak-hour speeds in the general purpose lane increased 19 percent compared to 2007; while northbound speeds increased 3 percent. Speeds in the HOT lanes remained at the posted speed limit of 60 mph. The second year average weekday southbound peak-hour travel time was 11 minutes with 15 minutes at the 95<sup>th</sup> percentile travel time. The same peak-hour travel time in year one was 12 minutes with 19 minutes at the 95<sup>th</sup> percentile travel time (Washington State Department of Transportation, 2010).

## Throughput

Comparing 2008 and 2009, the person throughput during the PM peak hour (4 PM-5 PM) in HOV/HOT lanes and GPLs increased by 23 percent and 8 percent respectively. The person throughput in Express Lanes increased even when the average vehicle occupancy dropped due to SOVs being allowed in Express Lanes. Overall, the person throughput increased by 12 percent in the facility after the Express Lanes implementation (Federal Department of Transportation, 2011). Total person throughput on the Express Lanes increased 42% in both the a.m. and p.m. peak periods between 2008 and 2010. The largest source of that increase came from toll paying SOVs. The other source was transit.

The total average daily throughput on *SR 91* increased 14% in the first year following the capacity increase resulting from opening the toll lanes. This increase of about 28,000 vehicles per day is approximately equal to the amount that average weekday express lane traffic grew during the same time period. It was judged that just less than 60% of the first year growth in average daily throughput is traffic induced by improved travel conditions (Sullivan E. , 1998).

During the evaluation period from 1996 to 1999, it was concluded that the Express Lanes did not result in any measurable impact on traffic congestion on the *I-15* GPLs. Traffic volumes on the *I-15* corridor increased over time due to Express Lanes as well as due to external factors such as housing growth in the corridor and rerouting of traffic from *I-5*. As the project progressed, utilization of the Express Lanes was steadily improving (Supernak J. , 2005).

The 2004 data was obtained from MnPASS technical evaluation report (Cambridge Systematics Inc., 2006) and 2007 data was obtained from the quarterly reports (MnDOT, 2008) issued by MnPASS. It was observed that the person throughput in AM and PM peaks increased after the Express Lanes. Also, in PM peak the person throughput increased with a decrease in the percentage for vehicles. The findings indicate that in almost all the cases, the person throughput is not negatively impacted due to HOT lane operations. As one of the objectives of *I-394* Express Lanes is to increase the number of people using the HOV lanes, the above findings indicate that Express Lanes are achieving this objective. Also, considering the peak hour traffic of Express Lanes in 2008 (MnDOT, 2008), the Express Lanes still have enough of their capacity available to maintain the free flow (assuming 1500 vph to be the capacity of each lane for maintaining the free flow).

During the second year of operations, the average daily traffic volumes on *SR 167* recovered to pre-opening volumes in 2007. The daily volumes in the first year of operations decreased slightly, most likely in response to the sudden increase in gas prices and deteriorating economy. The peak-hour, peak-direction traffic volumes increased compared to 2007 levels. On average HOT lane volumes have increased by 12 percent and general purpose lane volumes increased 2 – 3 percent (Washington State Department of Transportation, 2010).

## **Off-peak travel**

To evaluate two of the five HOT lane projects—I-15 in San Diego and SR 91 in Orange County—project sponsors surveyed drivers to determine whether they changed their trips to travel at off-peak times (Supernak, et al., 2002; Sullivan E. , 2000). According to the I-15 survey results, some traffic shifted from the middle of the peak rush hour to the “peak-shoulder” times—the times directly before and after peak periods. However, the sponsors did not explain why this shift occurred. Sponsors of peak-period pricing projects conducted more robust studies of off-peak travel because it was a more explicit goal of their projects.

These studies showed some success in reducing congestion during peak times. The evaluation reported more significant improvements in the morning before the peak periods than after the peak periods at the end of the day, which the evaluation attributed to drivers finding it easier to arrive at work early than to arrive at work later. A majority of drivers had little flexibility to change their schedule to travel at off-peak times. Furthermore, drivers said that the toll difference of \$1 was not great enough to influence them to change their travel time although there were users that could alter their travel departure times between 30 minutes and 2 hours.

## **2.3 Other aspects and considerations**

The effects of a HOT-lane implementation go beyond the picture painted by the performance indicators presented in the previous subchapter. There are a multitude of underlying factors together with the aspects they influence that dictate the success of such a project.

Most of the survey responses found in most studies regarding HOT-lanes facilities indicated that there had been some degree of resistance to congestion pricing and/or managed lanes within the areas where they were implemented. The reasons for the opposition included resistance to tolling what many in the public consider should be a free service already paid for by gas taxes or other taxes. Some resistance has also been based on a concern that the tolling favours higher income travellers who are better able to pay for the use of the lanes with the higher level of service. Yet others were concerned about geographic equity when highway facilities within a region are not uniformly tolled.

### **2.3.1 Safety and access points**

Another identified major element is safety and its close relation with access points. These have influence throughout the process, from evaluation to design considerations. An analysis is performed for each of the selected projects.

Auto motorist groups have expressed concerns over the safety implications of traffic weaving that occurs at the beginning and end of HOT lanes or express lanes, where tolled lanes and general purpose lanes merge.

**SR-91** - An interesting occurrence was observed in a 1996 survey (Sullivan E. , 1998) which showed the perceived level of increased safety with the Express Lanes. When respondents were asked different reasons for using the Express Lanes other than the travel time savings, 40 percent of them mentioned driving comfort and the perception of greater safety in the lanes. The accident rate for the section of SR 91 containing the Express Lanes decreased significantly after the Express Lanes opened. This most likely reflected the reduced peak period congestion (Sullivan E. , 1998). The Express Lanes have no intermediate exits or entrances.

**I-95** - Compared to the previous existing situation of the HOV lanes which could be accessed from anywhere, the Express Lanes have no intermediate access and can be accessed only at the two ends (Florida Department of Transportation, 2009). In a 2009 survey of South Florida commuters (South Florida Commuter Services, 2009), there were comments from the respondents on the design of Express Lanes complaining about the narrow lanes being unsafe, cars driving over the plastic poles to access the Express Lanes, and suggesting a barrier separation. In addition to this, there were responses complaining about the safety of the express lanes with people cutting in and out of the Express Lanes and no shoulder to pull over in case of emergency. It has to be noted that Express Lanes were converted from one HOV lane to two Express Lanes and during this process the shoulder was reduced and lanes were narrowed. However, the perception of increased safety was indicated by the respondents as one of the reasons for using the Express Lanes.

**I-15** - Most of the Express lane users felt safer in the Express Lanes than in the GPLs. In a survey conducted in 1997, 83 percent of I-15 users considered the I-15 Express Lanes to be safer than the adjacent GPLs (Wilbur Smith Associates, 2002). This difference in safety was perceived most by Express lane users, including both car-poolers (84 percent) and ExpressPass users (90 percent). The evaluation (Supernak, et al., 2002) considered the decreasing carpool volume on I-15 GPLs (from 1996 through 1999) as outcome of several factors including rising levels of economic prosperity and frustration over lack of access to the Express Lanes, with only one entrance and one exit. The above evidence regarding the safety and access aspects of concrete barrier separation indicate that there is a trade-off between perceived safety and access convenience.

**I-394** - There are 11 access points for the I-395 MnPASS project, five in the eastbound and six in the westbound. The access points are approximately 400 to 1200 metres in length. The access points include visual enforcement of occupancy levels and electronic toll tag readers (Turnbull, 2005). Since, there was no previous experience of operating a HOT lane only with double white line separations from the GPLs, authorities were concerned regarding the enforcement of the separation mechanism, excessive weaving between lanes at the entry and exit points, space for drivers to get into or out of the facility, and if the separation mechanism would result in more

accidents (Munnich & Buckeye, 2007). A panel survey conducted six months after the Express Lanes started; the safety issue did not surface among the survey responses. Accidents on I-394 have declined 12 percent. Entering and exiting the facility lanes has not been a significant problem, and drivers have generally respected the double-white lines (Munnich & Buckeye, 2007).

**SR167** - With the HOT lane concept, motorists can enter and exit the HOT lanes at designated access points providing more predictable entry and exit manoeuvres. Drivers can enter at the beginning of the HOT lanes and at several 1 km access zones. There are six northbound and four southbound access zones marked with single dashed lines. Other than at entry/exit points, the HOT lanes are separated from GPLs by double white lines which are illegal to cross and a buffer was added for increased safety. To provide the shoulder and buffer, the corridor was re-striped and the GPLs were narrowed (Washington State Department of Transportation, 2010).

Although in a survey (Washington State Department of Transportation, 2010) more than one-third of the respondents agreed with the statement that HOT lanes improved roadway and safety, in another study (Washington State Department of Transportation, 2009) there were complaints about getting cut off as they exit the HOT lanes. Participants were also concerned regarding the speed difference between the HOT and GPLs. There were also complaints about insufficient time to exit the freeway after crossing the dotted white lines, not enough space to enter/exit at the dotted white lines, and not enough places where the dotted white lines can be crossed. However the general believe remained that the SR 167 HOT lanes are not impacting the safety in the corridor, but no conclusions regarding the safety impact of HOT lanes have been made yet due to insufficient data (Washington State Department of Transportation, 2010).

### **2.3.2 Car-pooling**

Carpooling is considered an interesting Transport Demand Management (TDM) tool that has produced some reduction in the number of SOV trips in the past, mainly when applied to employment centres where persons have their companies in common (Bianco, 2000). The other alternative is household carpooling which has proven to be quite inefficient in decreasing work related trips (Morency, 2007). An increase in scale of participation, from companies to large-scale systems, has always been the objective of public policy making. Unfortunately research has shown that this is difficult to achieve due to the high probability of sharing the ride with a non-acquaintance (Duecker, Bair, & Levin, 1977).

Empty seats in single occupancy vehicles are a potential resource for expanding commuter capacity without increasing the number of vehicles on the roadways. Since in the US the HOV lanes suffer a large loss in vehicle-carrying capacity and offer small travel time savings in comparison with GP lanes, the most important justification for HOV facilities is that they increase person-carrying capacity by encouraging carpooling. It has been hypothesized that for some travellers the attraction of HOV lanes overcomes the inconvenience of carpooling.



A study found in 2001 that, 83% of carpools for home-based work trips had people from the same household (McGuckin, Srinivasan, & Murakami, 2005). In conclusion, it appears that carpooling is declining and carpool formation for work trips depends almost entirely on the work locations of members of the same household. Despite the decline in carpooling, the belief remains that time savings offer a carpooling incentive.

For example, in a 2001 survey from Los Angeles, 57% believed that 'travel-time savings' is a common motivation for carpooling; and 82% of respondents who actually carpooled identified time savings as their main reason for carpooling (PB Study Team, 2002). The classical carpooling has a low flexibility, particularly in handling schedule variations and destinations that persons have (Concas & Winters, 2007).

Although carpooling is no longer the only condition to use the pay lanes, the number of carpooling people at the corridor increased. It was suggested that this is a consequence of the so called insurance effect, what means that people are no longer dependent on a co-driver to gain access what makes it possible to maintain the same departure times during the week. This makes carpooling a more attractive alternative (Baker, 2008).

The results presented in a study indicated that the disutility of forming a carpool was a major influence on HOT lane usage. The results also showed that commuters, participants with college education, those who shared the toll with their carpool partners, and/or those between 25 and 54 years old were likely to make more HOT-lane trips. It was also found that drivers who perceived higher HOT travel time savings, those who travelled on the corridor more frequently, and those who took longer trips were likely to use HOT lanes more often whereas long carpool formation times decreased the likelihood of using HOT lanes. Gender and annual household income were only loosely related to HOT lane usage. Travellers were generally more likely to choose the mode with the least restrictions on vehicle occupancy (Appiah, 2004).

Increasing the amount of time by which travellers are willing to alter their departure times increases the number of people who are able to find someone who also wants to carpool and has the same origin and destination. However, due to the relatively small number of people choosing to share rides, the average travel time for the system does not vary significantly. Increasing the attractiveness of carpooling, although reducing the number of vehicles on the roadway and providing a greater opportunity to find a match, does not necessarily improve the average trip time for the whole system. Carpool formation time - for an average trip length of 45.3 minutes, participants spent 4.3 minutes (9.5 percent of trip length) picking up and dropping off their carpool partners and this emerged as one of the potential barriers to HOT lane usage (Appiah, 2004). The carpool formation times reported in this study were consistent with another study in which it was reported that for an average trip of 47 minutes car-poolers spent 4.8 minutes (10.2 percent of their time) traveling to pick up passengers (Billheimer, 1990).

### 2.3.3 Equity

Road pricing may generate geographic, economic, and competitive inequalities. Both the public and auto motorists have argued that geographic inequalities occur when limited access facilities provide access to some areas and not others (Federal Highway Administration (FHWA), 2003). Congestion pricing has raised equity concerns among the public and elected officials. In general, an analysis of equity issues examines how costs and benefits of projects are distributed among members of society. In the transportation economics literature, four concepts of equity are mentioned (U.S. Government Accountability Office, 2012).

- The extent to which members of the same group are treated equally; for example, whether some people with the same income pay a larger amount in taxes or fees.
- The extent to which those who benefit from a project, such as a new lane, pay for those benefits; for example, is the lane paid for by a toll on users or by a state sales tax paid in part by persons who may not use or benefit from the lane?
- How the costs and benefits of a project are distributed across members of different groups such as high- and low-income people; for example, whether all groups pay in proportion to their income or whether low-income people pay proportionally more of their income for tolls than high-income people.
- The extent to which those who impose social costs bear those costs; for example, whether polluters or drivers on crowded highways pay the full social cost of their driving, or, if a toll causes diversion from the tolled highway to adjacent neighbourhoods, those neighbourhoods incur the costs of pollution and crowding.

Even greater equity concerns could also be raised as decision makers consider introducing tolling and pricing into previously un-tolled facilities. Converting an un-priced lane to a priced one does not have much public or political support.

To these objections, a clear distinction was made between horizontal and vertical equity (Litman, 1999). Horizontal equity considers the extent to which the advantages of a measure are experienced by the one that paid for it. Vertical equity considers the question if people who naturally form the weak groups in society experience an advantage or at least not a disadvantage by a measure.

Both aspects have been analysed for the case of the Californian HOT-lanes (Baker, 2008). The HOT-lane use depends on the valuation of travel time and travel time reliability and for these valuations income is not the most influential variable. This is because the willingness to pay the toll is more a function of the opportunity cost of a missed appointment than the value of time to the motorist. Motorists in the lower income categories may be even more willing to pay the higher toll when needed to assure timely arrival at work or day-care centre to pick up their children given the potential consequences of not arriving on schedule for either purpose. The study states that a

strong improvement of travel time reliability will make a pay lane attractive for road users spread over all income classes.

In terms of the impacts of HOT lanes on low-income communities, research that examined projects such as the SR-91 and the Katy Freeway QuickRide HOT, suggests that income and work flexibility had little or no influence on use of the HOT lanes (Plotnick, Romich, & Thacker, 2009). Other studies also identified equity as not an issue with regard to HOT lanes or at least a manageable one (Mahendra, Grant, Higgins, & Bhatt, 2010).

For instance, the revenue generated can be used to implement a number of measures such as reduce tax levels, improve road facilities, and increase investment in public transport. Such measures might mitigate public concerns about the equity of providing premium express lane service that is used more by higher income travellers than middle and lower income travellers (Appiah, 2004).

To address equity concerns, innovative approaches to pricing can be used to reduce purchasing power differences. Complex derived tolls could incorporate driver income, vehicle type, or fuel efficiency. Transportation agencies in Atlanta, GA have suggested a unique approach involving commuter credits for proposed HOT-lanes along I-85/Northwest Expressway. The program would reward positive driving practices by allowing participants to acquire credits for driving during off-peak hours or in GP-lanes. Credits could then be used for free HOT-lane trips when desired (Rountree & al., 2008).

#### **2.3.4 Acceptability**

Effective outreach is an essential element of HOT lane planning and implementation. Basic public awareness of HOT lanes in general, as well as political and popular support for the particular proposal in question can reduce the efforts to implement HOT projects (Parsons Brinckerhoff, 2003).

The issue of toll revenue allocation can play a crucial role in achieving public acceptance of road pricing initiatives. A 1996 survey determined that for 83 percent of road users, their opinion of transport pricing measures depended on the allocation of revenues generated by that project (Verhoef & Ubbels., 2004). Regardless of the revenue allocation, the transparent accounting of revenue sources and intended allocations of those revenues is likely to have a positive effect on project acceptability and may also increase trust in toll road agencies.

Double taxation was a concern to the general public because they thought it was unfair to pay a toll to use roads that were financed with tax revenues. They were also concerned that the concept would be applied to more roads and highways in the region, which would require them to pay tolls to use other publicly-funded roads (Collier & Goodin, 2002).

Surveys of drivers on highways with HOT lanes find that most users of both free and tolled lanes approve road tolls and that approval ratings increase as drivers become more familiar with the benefits of HOT lanes (Sullivan E. , 1998). In a survey of drivers in the Greater Toronto and Hamilton Area (GTHA), it was found that more than 75 percent of drivers would be willing to pay to avoid congestion during high-urgency trips (Finkleman, 2010).

The least popular road pricing schemes are those that propose to apply tolls to existing toll-free roads because of the perception that such roads were already paid for with motor fuel taxes and should therefore remain “free” (Samuel, 2003). There is significant resistance to adding tolls to existing Interstate highways in the United States, particularly in urbanized areas where these facilities are among the most intensely travelled (Rufolo & Bertini, 2003).

Despite studies that show general satisfaction with managed lanes post-implementation, a certain level of public support is required at earlier stages to ensure that projects are politically feasible. One study noted that public support for managed lanes can be bolstered by marketing individual driver reliability benefits, improvements to the HOV and transit network, and overall system improvements (Plotnick, Romich, & Thacker, 2009). Moreover, the support of high-profile politicians and grass-roots coalitions can help in convincing key decision makers to move-ahead on HOT-lane projects (Finkleman, 2010).

In order for the public, planners, engineers and politicians to embrace pricing, concise information and consensus on project objectives is necessary. A comprehensive list of real and perceived issues should be developed. Through the public outreach efforts to gain support for the HOT conversion project, several lessons were learned on how to present the idea of value pricing to the general public. These lessons included the following (Munnich & Barnes, 2004):

- The public must understand that there are no “free roads”.
- Identify the costs associated with doing nothing.
- It is easier to sell HOT lanes where there is still a choice for non-toll travel.
- Link the benefits directly to the costs (HOT lanes are a commodity).

Additional unintended consequences of tolling are almost certain, but their particular manifestations and scale are difficult to predict and their appearance may vary from case to case. Some of the most common concerns include the following (Cambridge Systematics, 2007):

- Diversion of traffic to non-tolled routes and impacts on neighbourhoods - the risk for road pricing initiatives to adversely affect traffic on local roads is cited by numerous stakeholders as a cause for concern;
- Toll increases that are not offset by benefits, resulting in reduced travel to business establishments (thereby impacting the economy);

- Inadequate public transport service or other modal alternatives create hardships for low-income households;
- Private-sector ownership or effective control of key corridors and accessibility;
- Inadequate consideration of alternatives to tolling, including funding from existing sources or increased taxes, ramp metering, incident management, parking management strategies;
- Reduced safety - in addition, auto motorist groups have expressed concerns over the safety implications of traffic weaving that occurs at the beginning and end of HOT lanes or express lanes, where tolled lanes and general purpose lanes merge.

Related to the previously presented key issues throughout this chapter, a former study (Hamilton, 2006) included the resulting potential success factors through consultation with experts and scheme developers from the road user charging field. The study included various type of road pricing from cordon pricing to HOT-lanes. One of the most obvious results was that HOT lanes may have fewer success factors needed. HOT lanes are reasonably simple and offer a win-win situation in that those who can pay are rewarded with faster journey times as are those who car-pool. But this then frees up more capacity for existing lanes for those who do not choose to pay. The factors in question were pricing appropriately, clear business case and the presence of a political champion.

### **2.3.5 Pricing**

Publicly funded projects are more likely to have demand management and welfare maximization as their primary goals. The selected goals, which in turn will dictate the pricing strategy, will influence revenue generation. The pricing strategy selected may cause a conflict between demand management goals and revenue management goals because, theoretically, there are no optimal market prices that can simultaneously achieve both objectives. In practice, however, the experiences of I-15 lanes and SR-91 lanes in California suggest that it is possible to design prices that bring the apparently conflicting objectives together. One factor that makes this possible is the existence of strong demand within the corridor and high pre-existing levels of congestion.

For a publicly funded project, public acceptability of the project is always critical. It is more critical initially, thus initially it is better to set the prices high enough only to cover basic expenses. This low toll is necessary to create a reliable base of future patronage. This approach should improve diversion behaviour and in the long term will be consistent with both improved mobility and revenue generation assuming other issues related to pricing and revenue use in initial and later years have been dealt with. It is therefore recommended that (Wilbur Smith Associates, 1995):

- Initially low peak and off-peak rates should be imposed. This dual approach is good for public acceptability initially but not good for revenue generation or welfare. This approach is also not good for demand management. These initial low rates can be based on willingness to pay market studies.

- At a later stage, when demand is stimulated and elasticity improves, such projects can implement other pricing techniques to effectively manage demand and at the same time raise revenue. Price setting should also consider the manner and frequency of potential toll rate increases.

A number of different types of pricing strategies could be implemented based on the goals of the project. These include (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000):

- *Break-even* type in which the price is set such that the operating, maintenance, and debt service costs are covered.
- *Second best prices*, which include the true efficiency maximizing price or the profit maximizing prices. This strategy is one that is based on the relation between demand, willingness to pay, and marginal costs of operating the facility. These characteristics have yet to be implemented
- *Market prices* based on a number of other criteria reflecting the different objectives of the agency operating the facility including:
  - prices based on other toll rates already operating within the region
  - prices based on comparable facilities in nearby states after appropriate cost of living adjustments
- Prices based on compatibility with rates on other modes
- Willingness to pay
- Toll sensitivity analysis.

Willingness to pay (WTP) estimates has been used in the past for pricing decisions. The goal is to identify the willingness to pay function or the marginal benefit of travellers. VOT is an implicit parameter in this research and can also be used for toll setting.

The main differentiation between pricing strategies found in practice is they're either static or dynamic.

**Static congestion pricing** refers to a tolling system where toll rates are only changed depending on time of day. The system is static, because the toll rate schedule is not affected by the real-time traffic conditions and usually do not change for a long period of time. The first studies for congestion pricing always considered this "static" type of tolling, mostly focusing on the optimization of toll rates, toll plaza locations or which links to be tolled in a large network. Several different implementation approaches exist for static congestion pricing. Time-of-day pricing method provides lower toll rates during off-peak hours to reduce peak-hour traffic congestion. Toll rates are pre-determined.

**Dynamic congestion pricing** is the tolling system in which real-time traffic conditions are also considered. Several traffic parameters can be considered to determine the toll rate including travel speed, occupancy and traffic delays. These parameters are measured real-time and the toll rates are updated within short time intervals. Users are informed about the current toll rate with the help of variable message signs and they are allowed to make their route choice either using the tolled road to save time, or using an alternative road without a fee.

The problem is that there is still a small amount of uncertainty about prices with dynamic pricing even if there are set maximum limits at different times of the day. In principle, dynamic pricing violates the transparency condition that a good road pricing system should follow (Hau, 1992). Since there are no projects that have implemented both variable time-of-day pricing and dynamic pricing at some stage of the project, there is no evidence to guide decision making. For either of these two strategies to be effective as demand management strategies, we have to assume that travellers are rational and are willing to make the currency cost and congestion (travel time) trade-off decisions between the HOT lane and "free" options.

Since dynamic pricing uses real-time traffic data to derive congestion based tolls, it does seem to suggest that it may be more effective than variable tolls in managing demand. Travel times could improve, as well as reliability. Although the continuously time-varying optimal tolls suggest a fair system for the users, it is also debatable whether smoothly-varying toll rate will be appreciated by drivers (Lindsey & Verhoef, 2000).

As mentioned initially, the pricing scheme depends directly on the project's objective. For an indication of the trade-offs achieved in practice, a listing of the previously analysed projects with their corresponding objectives and pricing schemes applied is in Table 2.1.

**Table 2.1 State of practice on objectives and pricing schemes of managed lanes projects**

<b>Project</b>	<b>Pricing Scheme</b>	<b>Objectives</b>
<b>SR 91 Express</b>	Static tolling– use of predetermined time-varied toll schedules	<ul style="list-style-type: none"> <li>• promote California’s ridesharing policy</li> <li>• return a profit to the investors.</li> </ul>
<b>I-95 Express lane</b>	Dynamic tolling – toll adjustment every 15 min considering traffic flow situation	<ul style="list-style-type: none"> <li>• reduce congestion</li> <li>• improve reliability</li> <li>• encourage ridesharing and transit</li> </ul>
<b>Miami I-15 Express Lanes</b>	Dynamic tolling - toll schedule varies dynamically every 6 minutes depending on the congestion level	<ul style="list-style-type: none"> <li>• test whether it can relieve congestion on general-purpose lanes</li> <li>• improve air quality</li> <li>• fund new transit in the I-15 corridor</li> </ul>
<b>Minneapolis I-394 HOT Lanes</b>	Dynamic tolling – the price per trip fees can be adjusted every 3 minutes; the value of the toll varies with congestion levels and distance travelled	<ul style="list-style-type: none"> <li>• maintain free-flow speeds for transit and carpools</li> <li>• use excess revenues, if available, to make transit and highway improvements</li> <li>• use electronic toll collection</li> <li>• employ new Intelligent Transportation System (ITS) technologies</li> </ul>
<b>SR 167 HOT Lanes</b>	Dynamic tolling - The tolling algorithm which depends on speed, rate of change of the number of cars entering the system calculates toll rates every 5 minutes	<ul style="list-style-type: none"> <li>• testing the HOT lane concept’s ability to maintain the speed and reliability</li> <li>• testing the ability of a HOT lane to generate a stream of revenue that can be used to pay for the operation and maintenance of the facility as well as transportation system improvements</li> </ul>

Although most of the projects seem to implement a dynamic setting on their pricing, there are differences on levels of price and time of pricing. Nevertheless there are considerable differences between the schemes applied because the tolling algorithms are proprietary, thus it is unclear how they work and what they are designed to achieve. However, it is known that their algorithms have minimum and maximum tolls as well as a mechanism to adjust the toll so that specified HOT lane level-of-service requirements are not breached, which is also why the majority are dynamically updated.



## 2.4 Overview

As presented in the previous section, the several projects that illustrate the concept's implementation vary across a number of aspects. For a better overview of the differences/similarities the descriptions of the discussed projects is summarized in the form of Table 2.2.

**Table 2.2 Current practice projects from the US and their characteristics**

	<b>SR-91 (Orange County, CA)</b>	<b>I-15 (San Diego, CA)</b>	<b>I-394 (Minneapolis, MN)</b>	<b>SR-167 (Seattle, WA)</b>
<b>Year opened</b>	1995	1997	2005	2008
<b>Distance (km)</b>	10	8	11	11 SB / 9 NB
<b>Number of GP lanes per direction</b>	4/5	4	2	2
<b>Number of HOT lanes</b>	2 lanes in each direction	2 reversible lanes	1 lane in each direction for 8 mile, 2 reversible for 3 miles	1 lane in each direction
<b>Carpool policy (ride free)</b>	HOV 3+ (only during off-peak)	HOV 2+	HOV 2+	HOV 2+
<b>Pricing scheme</b>	Static Toll Schedule	Dynamically priced	Dynamically priced	Dynamically priced
<b>Operation schedule</b>	24 hours per day/ 7 days per week	12.5 hours/day ; 5 days per week	9 hours/day ; 5 days per week	14 hours/day ; 7 days per week
<b>Annual Gross Revenue (million US dollars)</b>	43.7 (2009)	~1.2 (2007)	~1.0 (2007)	0.3 (2008)

Together with the previously discussed performance indicators, that showed various range of results due to the different characteristics as it appears in the table above, the revenues was added as an overall indicator. The differences in revenue are at least partly due to the treatment of carpool vehicles for the purposes of tolling, as well as the number of priced lanes and pricing level as a result of the development's goals, the level of congestion in the corridor, but also differences in willingness-to-pay of motorists.

HOT lanes are gaining interest as a strategy for meeting multiple performance objectives in congested highway corridors. HOT lanes can provide benefits in reducing travel time, offering travellers viable options to congestion, improving freeway efficiency, increasing the attractiveness of alternative modes, and raising revenue to offset implementation and operating costs. However, the extent to which these benefits can be attained depends on different policies of the HOT lanes.

## **Performance**

Performance wise the research and observations, made after the implementation of the presented projects, show improvements across all the performance indicators at various extents.

- HOT-lanes show they contribute to reduction in delays, the improvement of travel time reliability, with a magnitude that can increase with the worsening of the traffic conditions.
- In terms of throughput, the studies from the U.S. do not provide applicable insight due to the concept's history of evolution and implementation. It can be stated that the overall effects on throughput and occupancy stabilize after first years of implementation.
- Off peak-travel incentives have been proven to be of little or no effect, partly due the small differences in toll value or little flexibility in drivers' schedules. When a shift to off-peak was observed, the period before the morning peak was the preferred choice
- In some situations, revenue was also addressed depending on the importance attributed by the project's initiators.

From the results presented in the performance evaluation, it can be concluded that the HOT-lanes project improved performance in certain corridors according to certain measures, although the measures are usually mixed and varied across all projects.

## **Car-pooling**

It has always been shown that favourable conditions for carpool formation impose a limitation for a further development of the phenomenon. It appears that HOT-lanes provide an extra incentive for carpool formation which, depending on the case, provides a better choice than off-peak travel and helps reduce the magnitude of the impact incurred by the necessary formation time. The important remaining issues regarding carpooling are related to the travellers' characteristics that may indicate a predisposition to consider carpooling. This is yet to be investigated in depth and is considered locally specific (region, country, etc.).

## **Equity**

The focus on equity addresses the effects of the differentiated pricing implied by the HOT-lanes concept, on the different groups and between the members of these groups that can result in inequalities. It is a matter of how the benefits and costs are distributed. It usually comes down to focusing the monetary gains or offer extra support to areas that include low income travellers more such as public transport.

## **Acceptability**

This is generally related to the project's initiator ability to clearly relate the benefits to the public through an open and transparent view of the implementation. Properly addressing the equity issues presented previously and making sure that the project doesn't cause side effects that impact the local communities nor worsens the current traffic conditions in certain cases.

## Pricing

As presented previously in section 2.3.5, as well as summarized in Table 2.2, the preferred pricing strategy is through dynamic tolling. In terms of how dynamic tolling is applied and the tolls determined there can be differences. Although in Table 2.1 juxtaposition is tried between projects' objectives and their use of pricing methods, there is no clear correlation between them. This may have to do with the fact that specific objectives were used and not more general directions.

## Factors to be considered

The multitude of aspects summarized in this overview relates directly to a number of factors, according to previous research, that are to be considered when addressing the implementation of a HOT-lane concept.

According to one of the studies, the decision to use an HOT lane (and the demand for HOT lanes) will be influenced by (Perez & Sciara, 2003):

- Pricing strategy – fixed toll versus variable toll
- Nature or purpose of trip – recreational versus commute
- Availability of alternate travel routes and vehicle operating cost on alternate routes as perceived by user
- Travel time savings offered to HOT users
- Value of time/willingness of motorists to pay for improved travel conditions
- Predictability or reliability of HOT trip compared to alternative free route trip
- Travel patterns (O-D matrix)
- Attractiveness of carpooling

Another study resulted in the following criteria for success when considering the implementation of a HOT-lane (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000):

- Corridor has capacity deficiencies
- Corridor is used by travellers making relatively long trips
- The new lane would develop sufficient demand for it to be considered feasible
- The new lane makes sense in terms of the overall phasing for the regional program
- Transportation alternatives are, will be, or could be available at the time fees are implemented
- Project would be cost effective
- Income revenue exceeds implementation costs

Nevertheless there are also other effects of the implementation that need addressing when considering the implementation of such a concept. These will be addressed further as the analysis

will focus on aspects derived from this overview. The aspects will act as the base of the considerations included in the devising of the methodological steps.

## 2.5 Conclusions

The literature study provides the specific areas where the methodology developed focuses on. As it can be already observed, numerous factors can influence the outcome of the considered implementation.

An element that incorporates a multitude of factors is the **location** of implementation and its **characteristics**.

As a start, the possible **goals and objectives** of such a project need to be identified as they are subsequently correlated to multiple choices in planning and design. This results in a focus on **pricing scheme** options and choice in terms of operations.

Derived from the addressing the equity and acceptability concerns some aspects are taken further into consideration, aspects which lean towards the policy adaptation through design choices such as: **access points and safety**.

They directly impact the convenience (and safety) with which travellers access the HOT lanes, as well as enforcement activity. As the number of access points increases the need of enforcement at those points also increases. Safety issues with HOT lanes depend mostly on the separation mechanism of HOT lanes, and the number of access points. For example, safety issues are fewer with concrete barrier separated HOT lanes with no intermediate access points and will be greater with double-white line separation and many intermediate access points.

## 3 Development of methodology

This chapter includes the principals and reasoning behind the proposed methodology. It approaches the implementation with a general initiation procedure of such a project by describing the general process and combining it with previous proposed methods and lessons derived from practice, as described in section 2, to form the guidelines of the proposed methodology. The methodology's steps and details are further determined and presented in a step wise procedure.

### 3.1 Methodology considerations

As practice has proven in the US, the implementation of HOT-lanes was initially treated similar to as any other traffic management measure for highways. Now that the pricing projects have been in operation for several years the lessons learned and the findings can be incorporated into future implementations. The successful projects represent the joint cooperation of different authorities from the initial stages of project development throughout operations. These projects are large undertakings that required the assistance of several stakeholders. Planning for the managed lanes projects has required input from the different institutions, such as the state department of transportation, the metropolitan planning organization and other local agencies in the case of the U.S. practice.

#### 3.1.1 Previous research

HOT-lane policies may refer to aspects of the operations that can include: vehicle occupancy, vehicles allowance, separation, access, operations schedule, tolls, etc. These policies are commonly categorized as vehicle eligibility, access control, and pricing. Usually the focus is on the effect of a single policy by assuming all other policies as fixed without providing an effective way to comprehensively evaluate joint effects of these policies. For example, Chu et al. (2007) evaluated operational performance of high-occupancy vehicle (HOV) lanes under various vehicle eligibilities; Nesamani et al. (2010) investigated the operational and air quality impacts of allowing hybrid vehicles use of HOV lanes;

Although other typical studies have included the evaluation of certain predetermined policy combinations, such as (Loudon, 2009) that used sketch-planning methods to assess managed lane options such HOV, HOT, and truck-only lanes, the methods didn't consider other potential variations, e.g. start-end access vs. multiple access vs. unlimited access.

Eisele et al. (2006) built a decision-support tool for the conversion from HOV to HOT. Similar to solving a multi-attribute decision making problem, three categories with 22 attributes are scored. Based on default or user-defined weights, HOV/HOT conversion is suggested if the total score

exceeds a specific threshold. The main concern in applying the tool rests in the validity of the weights as well as in the subjective scoring of the attributes.

A review of existing HOT lane facilities suggests that their performance can vary widely, particularly in terms of their abilities to generate revenue (see Table 2.2). Factors that can influence the revenue generated by these facilities include the level of congestion and users' willingness to pay, as well as design features such as the share of capacity that is HOT, the tolls applied, and whether or not the facility is priced dynamically or according to a static toll schedule.

Another aspect that needs pointed out is that most of the developed studies and methods, although more or less generally applicable are to be used on predetermined specific cases (locations). Considering that most of the projects currently in practice have characteristics that are the result of the context and conditions of the area/location where the implementation was executed/investigated, the importance of how are those predetermined specific cases identified and assessed presents itself.

Several guides were developed over the years, by the Federal Highway Department from the U.S. (Federal Highway Administration (FHWA), 2003; Federal Highway Administration (FHWA), 2008a), guides that are very comprehensive, but offer no quick method nor step like procedure that can ensure a quick and efficient way of consideration and evaluation of implementing the concept.

A methodology that is both comprehensive and flexible to include most design variations of the implementation, while including the up-to-date lessons learned and direction in evaluation of such a concept is to be developed. Without aiming at providing a single answer verdict on the investigated cases, the methodology takes advantage of its flexibility in order to provide an overview of the influence that most of aspects considered in the planning procedure have on the potential outcome of the implementation.

### **3.1.2 Stakeholders**

From the overview of aspects such as acceptability and equity, the different perspectives on the concept's effects became evident. An identification of the stakeholders from vehicle users and local community to traffic operators and private parties provides an overlook of the considered stakeholders that can influence the outcome of the implementation.

Government (politicians) – this group of stakeholders are the ones that can both make/brake the project; it can either take the role of project champion as an initiator. Their power is undisputable but their interest is susceptible to social and/or economic circumstances.

Public/Community – their voice can be heard on a number of issues related to equity, adverse impacts, increased costs and use of revenue. Their interest is high and with moderate power.

Vehicle users – their interests align in general with those of the public/community, with differences that raise concerns about taxation, safety, privacy and enforcements, while they may disregard some of the adverse local impacts.

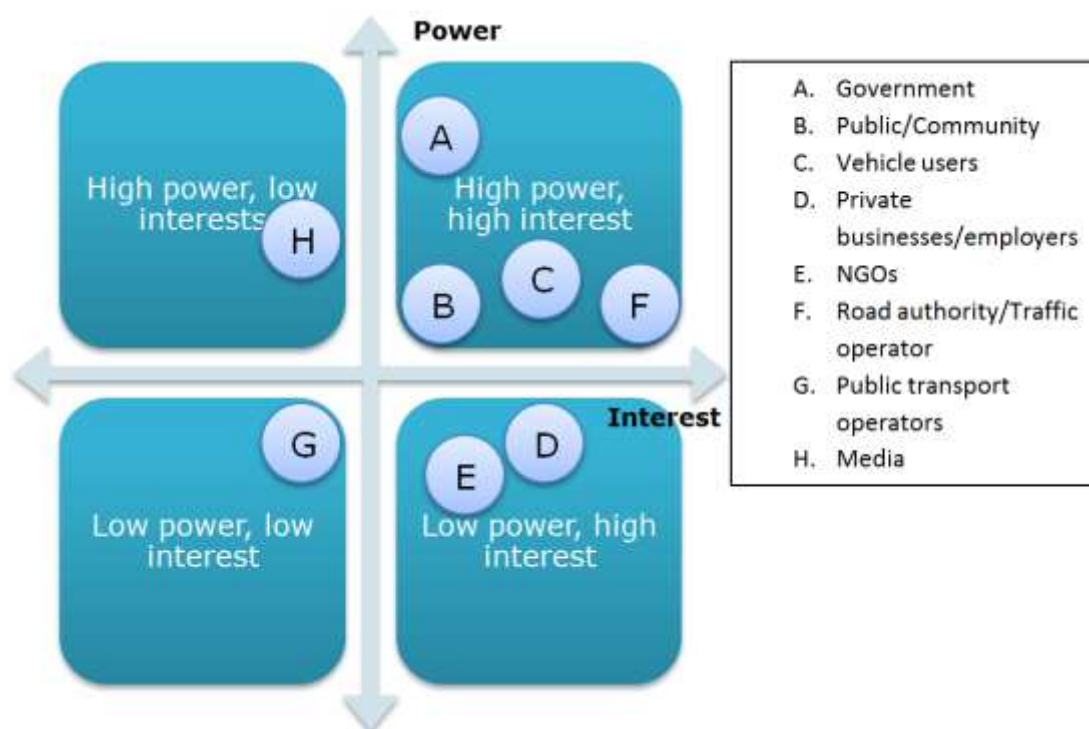
Private businesses/Employers – their interest is quite high as they can have a great benefit from the potential of improving transport operations and reduce delay. Their power is not up par with their interest.

Non-governmental organisations (NGOs) – their interest is quite high when considering the adverse impacts on environment or community and their support can be considered if the negative impacts are reduced to a minimum while the encouragement of carpooling is of positive influence.

Road authority/Traffic operator – this stakeholder can both represent a public authority as well as a private operator/investor. They both can play the role of initiators and/or assume the role of operators depending on the financing scheme applied for the implementation. Their interest is high and their power rather limited by other stakeholders.

Public transport operators – Depending on the objectives of the project, the position taken towards public transport is expressed. This group's interests are dictated by the magnitude of the effects reflected on their operation, depending of the decision taken in the implementation and their association with the project dictated by proximity.

Media – their interest is rather high considering the impacts on the concept's impact on society and their power is high. Their support depends on the well understanding of the project and rationale behind it and whether the project benefits and deserves support from their readers.



**Figure 3.1 Power-Interest diagram of stakeholders**

In Figure 3.1 the discussed stakeholders are presented according to their evaluated levels of interest and power towards the implementation of a HOT-lane. The focus of this research will include the upper right echelon of stakeholders. In accordance the considered goals and objectives within the methodology will include the influencing factors related to this group of stakeholders.

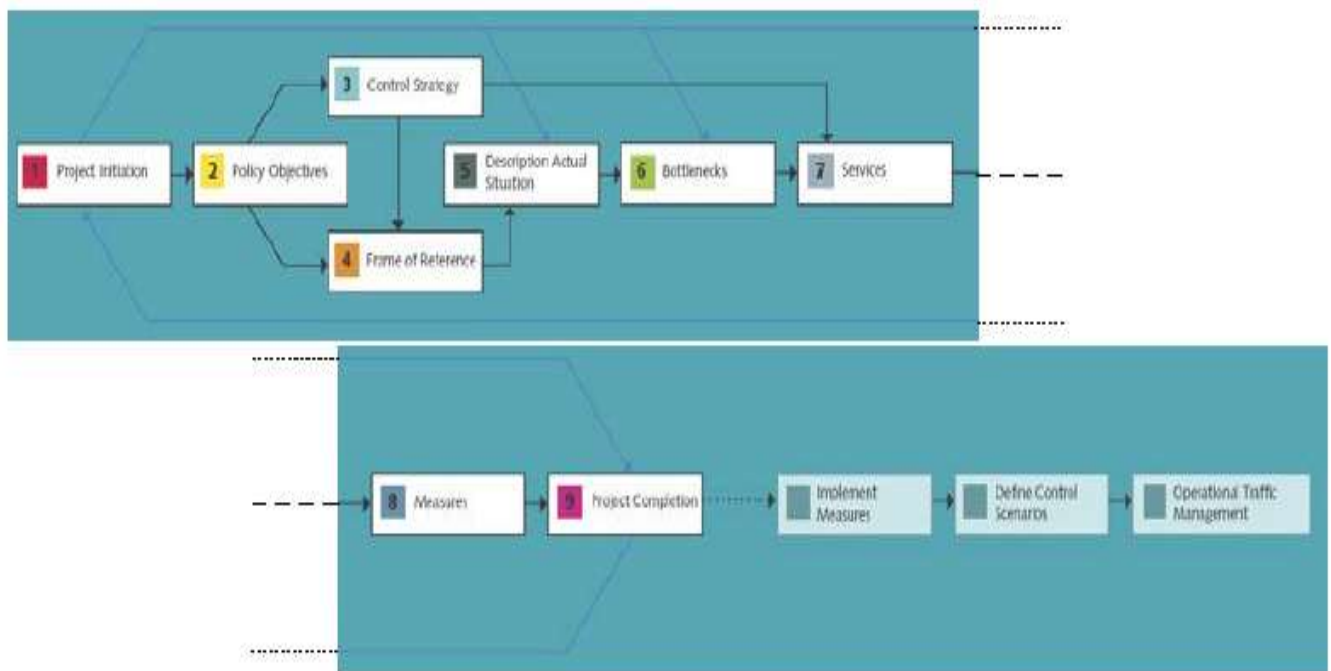
The perspective taken is from the point of view of the initiator and future operator whether they are either public or private entities, even a combination of both (public-private partnership). As this research proposes a generally applicable methodology that facilitates a quick and efficient initial planning and assessment of an implementation possibility, further details on stakeholders' influence on aspects that don't address general considerations and design elements are not to be addressed further on.

### 3.1.3 Planning

The way the development of such projects presents itself, it is in line with the current developments in the case of the sustainable traffic management approach developed by the by the Dutch Ministry of Transport, Public Works and Water management(Rijkswaterstaat). The key to the so-called GGB (Gebiedsgericht benutten which literally means region-specific utilization of road infrastructure) approach is that the various road authorities within a region as well as other stakeholders such as police, emergency services, public transport



operators, and commercial transport companies work together. In a structured process, local and regional traffic problems are dealt with as part of an overall plan. Rather than searching for a single best solution for a stretch of road or for one road authority, the “best” solution for the entire region is sought, which respects everybody’s interests as well as possible. The method consists of nine steps, each of which is comprehensively dealt with within a handbook, as shown below in Figure 3.2.



**Figure 3.2 Step-by-step workplan sustainable regional traffic management (Rijkswaterstraat, 2005)**

The framework starts with what needs to be achieved by translating a common policy into strategies that reflect the common objectives of the different stakeholders (national road authority, municipalities). How the consideration of a HOT-lane fits within these guidelines is addressed through the presentation of the procedure developed in the use for the concept’s implementation. The *strategy* reflects among other things the priorities which are given to certain parts of the network. This strategy is then translated into a *frame of reference*. At the planning level, the current situation in the network is used to identify the main bottlenecks in the network. A comparison of these bottlenecks with the frame of reference is used to determine which ITS/DTM measures are to be deployed to establish the frame of reference (e.g. which measure should be implemented on which location).

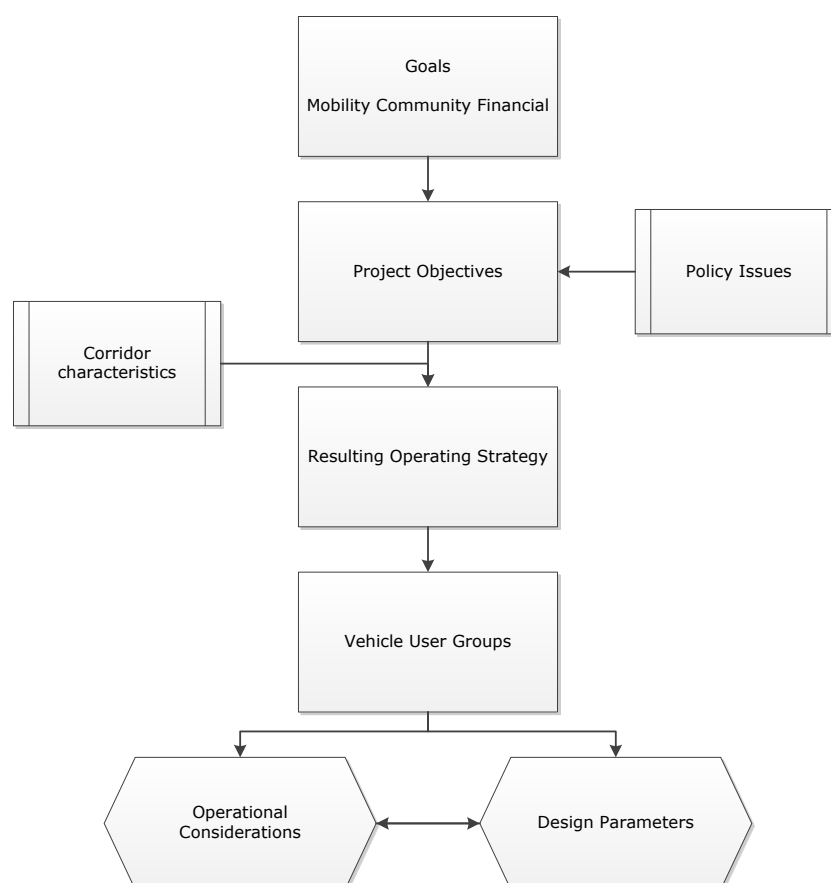
A strategy might focus on decreasing the amount of heavy vehicles for certain origin-destination relations or corridors or on a significant improvement in the accessibility of a certain region by car, by a pricing strategy. These strategies then need to be translated into specific services, for

example, user class-specific rerouting or tolling for certain user classes. Last, but not least, the final step refers to the actual implementation of these control scenarios into concrete measures, also in the light of the available measures in the region.

Within the previously presented guidelines, it is assumed that a HOT-lane concept is the service decided upon to be implemented locally/regionally. Its specific design aspects and operations' characteristics are part of control scenarios devised as specific measures.

These being said, the scope of the developed methodology is to provide policy makers the guidelines and means to sketch-plan (US term for initial development of measures in broad lines) and evaluate potentially successful implementation setups of a HOT-lane.

The US Federal Highway Administration has developed extensive studies that over the years underpinned the detailed milestones involved in the process of a HOT-lane project development. A detailed outlook on what such a method/tool should include is provided by a study performed under the US FHWA which devised a flow chart for the decision support process of a managed lane development. A simplified version of the flow diagram is presented in Figure 3.3.



**Figure 3.3 Simplified Conceptual Decision Process Flow Diagram (Fisher & Goodin, 2005)**

It can be observed that similar to the GGB methodology, the process diagram presented has as starting point the common goals with the corresponding objectives of different stakeholders, although categorized under several applicability areas.

The first half helps to identify and inter-relate the goals and objectives with the corridors influence on the general strategy of the concept. The second part addresses the design of the facility and the future operational effects of the implementation.

The flow chart maps the general project development process with additional elements unique to managed lanes: identification of managed lanes operating strategy and potential user groups. The bottom portion of the simplified flow chart shows that operational considerations and design parameters come into play once the operating strategy and resulting user groups are defined. The lower boxes of the flow diagram relate to development steps that involve the design of the facility and the operational components necessary for implementation.

What is included as policy issues in Figure 3.3 refers to what has been previously addressed in section 2.3 regarding acceptability, equity with the addition of institutional issues. The latter stems from the more problematic inter-agency correlation in planning present in the US. Some of the issues mentioned have been addressed at length in different studies over time and their relevance minimized while others can be mitigated through careful planning and effective public outreach. It can be thus concluded that most of the issues can be addressed through appropriate goal and objectives considerations and suitability. In the Netherlands' case this is assumed to be properly addressed by the GGB+ methodology.

#### **3.1.4 Goals and objectives**

As anticipated early on starting with section 2.3.5 and underlined by the consideration of different stakeholders, presented in 3.1.2, the goals and objectives have determining influence on the project's implementation and they can vary depending on the specific stakeholders' considerations. As established in the previous section, they also play their role early on, being the starting point in the planning procedures.

The overall goals for the implementation of managed lanes can be divided into three distinct groups: mobility goals, community goals, and financial goals. First, the mobility goals of managed lanes are focused upon such wide topics as demand and accessibility. These goals are characterized as mobility goals because they aim to improve the mobility of the facility or system in question. The second category of goals is the community goals. Community goals are generally defined as goals which aim to help maintain or improve the local community based on the interests of its constituents. Financial goals are goals which aim to address the financial involved in

infrastructure expansion with limited funding and the financing methods used for the development of projects (Fisher & Goodin, 2005). Table 3.1 highlights different mobility, community, and financial goals that may be associated with managed lanes.

**Table 3.1 Possible managed lanes goals (Fisher & Goodin, 2005)**

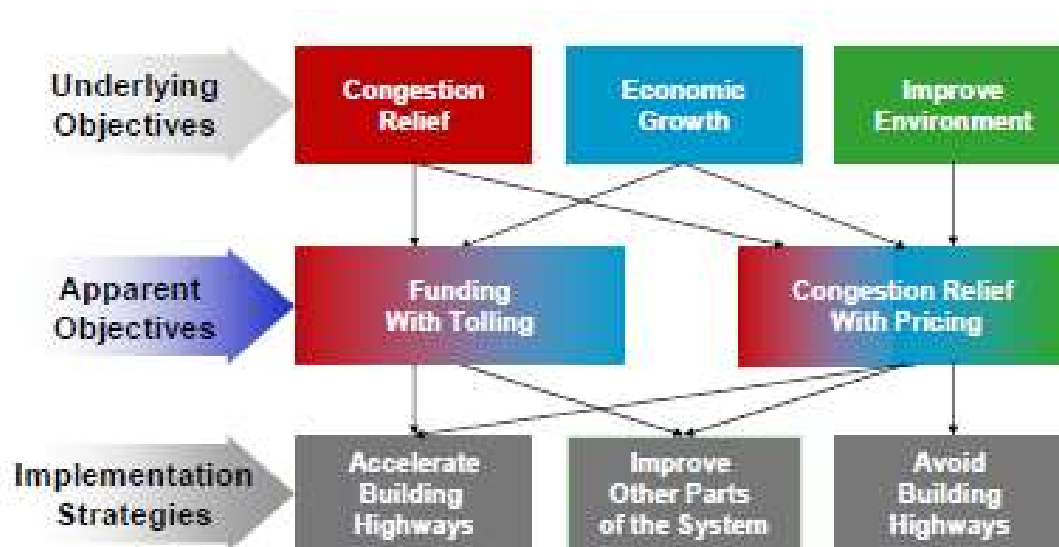
<b>Category of goals</b>	<b>Possible goals</b>
<b>Mobility goals</b>	<ul style="list-style-type: none"> <li>• Provide a transportation system that can handle current and future demand</li> <li>• Increase mobility and accessibility by offering travel options</li> <li>• Provide additional capacity</li> <li>• Optimize existing lanes capacity</li> <li>• Provide congestion relief</li> <li>• Modify travel demand</li> <li>• Enhance alternative modes</li> <li>• Improve accessibility</li> </ul>
<b>Community goals</b>	<ul style="list-style-type: none"> <li>• Improve the safety of corridor travel</li> <li>• Minimize environmental impacts</li> <li>• Preserve neighbourhoods</li> <li>• Maintain an urban form</li> <li>• Maintain land-use patterns</li> </ul>
<b>Financial goals</b>	<ul style="list-style-type: none"> <li>• Develop transportation improvements that are financially self-sustaining</li> </ul>

When considering the HOT-lane concept implementation in the Netherlands, with the current policy environment situation, a few other underlying specific goals can be considered (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000):

- Test/evaluate peak-period pricing strategies
- Phase in congestion pricing
- Provide a new travel alternative–pay to bypass congestion
- Maintain or increase mobility on adjacent free lanes

With the introduction of electronic toll collection the opportunity opened for new concepts in tolling, such as high-occupancy toll (HOT) lanes, express toll lanes, truck only lanes, cordon tolling, and mileage-based pricing. Electronic toll collection has also broadened the potential policy rationale for tolling. Whereas, the historical use of tolling has been to fund high-cost projects, it can now be used to manage congestion on a network with limited capacity.

The universe of objectives for tolling is varied, and not all the stakeholders involved may have the same objectives, as observed in Figure 3.4. People often confuse the underlying objectives for tolling, such as congestion relief, improving the environment, or stimulating economic growth with the more apparent objectives, which might be summed up as funding through tolling or system management through pricing.



**Figure 3.4 Objectives and Strategies of Tolling and Pricing (Cambridge Systematics, 2007)**

The possible financial objectives of tolling, from the previously described perspective, could be (Cambridge Systematics, 2007):

- Fund project's cost – this is feasible since the consideration of converting shoulder lanes into HOT-lanes can be considered with a low cost
- Subsidize other transportation improvements – HOT lane plus toll revenue to subsidize corridor transit can be an effective combination

From an economical objective the point of view the competitiveness of specific industries the introduction of HOT-lanes can induce uncertain benefits, higher value trip would improve time and reliability, but more congestion in GP lanes while exclusion of trucks in HOT could impose higher costs on business. This could turn out as a dis-benefit as the worsening of the conditions in the GP lanes could impact trucking throughput (Cambridge Systematics, 2007).

Congestion relief is both an underlying objective and an apparent objective. Traditionally, congestion relief came from providing new capacity in the form of new highway lanes or through traffic operations improvements. Current practices now try to achieve congestion relief through

time-of-day or dynamic pricing. When stating congestion relief as an objective, three more specific objectives may describe the combination of motivations:

- Demand management
- Reducing recurrent delay
- Improving reliability

For each of these objectives, the following descriptions provide more details to illustrate their relevance in evaluating various tolling applications.

### **Demand Management**

Demand management refers to strategies that reduce the amount of travel, usually by private cars. The rationale for demand management strategies is generally threefold. One is to reduce congestion. Another is to reduce automotive emissions. The third is to reduce energy consumption (and potentially greenhouse gas emissions). Without these three problems related to auto use, one can argue that *more* traffic is an indicator of a robust economy. Nevertheless, congestion offsets economic development by contributing to noise, delay, visual blight, and barriers between neighbourhoods.

The connection between tolling and demand management is that people will alter their travel behaviour when the price changes. Pricing can contribute to what is traditionally called demand management when it affects the *overall amount* of travel, particularly by private automobile, or at least the amount of travel during congested peak travel times.

Pricing is best able to influence overall travel demand when applied to the entire transportation system, as in an area pricing concept, or a concept where all roads are priced by time of day. Pricing on individual roadways such as HOT lanes or a single highway are unlikely to change overall travel demand – rather they are likely to move traffic from one road to another, from one mode to another, or from one origin-destination pair to another.

### **Reduce Recurrent Delay**

Recurrent delay is that which is predictable, and is driven primarily by too much traffic volume trying to squeeze through insufficient roadway capacity (i.e., bottlenecks). This condition is distinct from non-recurrent delay, which is caused by episodic events (e.g., accidents, inclement weather, roadway construction, etc.) that temporarily reduce capacity or degrade operations. There are two ways to look at recurrent delay:

- Travel time (or speed) on a particular road or entire corridor
- Travel time (or speed) on the entire regional transportation system

With pricing projects, the effects on congestion can be more complicated and difficult to predict. Pricing existing facilities can affect trip origins and destinations, intermediate stops (i.e., trip chaining activity), mode of travel, time of departure, or whether the trip is made at all. It is possible that congestion relief in one corridor might be offset by additional congestion in other corridors.

### **Improve Reliability**

The Federal Highway Administration (FHWA) defines reliability as “the consistency or dependability in travel times, as measured from day to day and/or across different times of the day.”

Travel time reliability benefits are often cited in connection with toll lane projects. These special lanes can be priced to keep traffic at the level at which flow and speed are optimized. Therefore, if a traveller has a special need to be somewhere on time (i.e., they value reliability very highly for that trip), then they can pay a toll and ensure a reliable trip.

When considering reliability in the HOT-lane context, it is important to distinguish those choosing to pay the toll (and gaining a reliability benefit) from those who choose not to pay the toll. In situations where an existing general purpose lane is converted to any form of toll lane, non-toll payers are squeezed onto fewer lanes, potentially resulting in higher congestion levels, and therefore worse reliability. The same concern would hold true for proposals to toll existing freeway or roadway capacity. The reliability gains of the winners may be overwhelmed by the reliability losses of the losers.

### **Overview**

As presented in the previous section, there is a multitude of goals under the HOT-lane umbrella. The underlying reasons behind them come from different stakeholders’ perspectives and can result in contradictory objective. Although the flexibility of the concept allow for goals coming from different perspectives to be jointly considered, the result can be more inclined towards one side. For an overview perspective, Table 3.2 includes an extensive variety of fitting goals for HOT-lanes and their associated objectives.

**Table 3.2 Goals and typical project objectives**

<b>Goals</b>	<b>Typical project objectives</b>
Provide a transportation system that can handle current and future demand	Increase vehicle or persons carrying capacity Reduce travel time
Increase mobility and accessibility by offering travel options	Provide travel alternatives Encourage public transport oriented development Fund new transit and managed lane improvements
Provide additional capacity	Increase vehicle or persons carrying capacity
Optimize existing lanes capacity	Increase vehicle or persons carrying capacity
Provide congestion relief	Increase vehicle or persons carrying capacity Reduce travel time Provide travel alternatives Reduce peak period vehicle trips Encourage public transport oriented development
Modify travel demand	Provide travel alternatives Reduce peak period vehicle trips
Enhance alternative modes	Provide travel alternatives Provide intermodal connectivity and accessibility Encourage public transport oriented development
Improve accessibility	Provide intermodal connectivity and accessibility
Test/evaluate peak-period pricing strategies	Monitor and report on operations, congestion, air quality impacts, and public reaction to demonstration projects
Phase in congestion pricing	Implement pricing in a way that minimizes negative public opinion  Increase public familiarity with and acceptance of pricing policies/ technologies
Maintain land-use patterns	Provide intermodal connectivity and accessibility Encourage public transport oriented development
Develop transportation improvements that are financially self-sustaining	Fund new public transport and managed lane improvements  Produce enough revenue to cover operations/maintenance (O/M) and enforcement  Produce enough revenue to cover debt service Private investment profit



From the sum of all the corresponding objectives a few policy objective functions can be deduced, functions that consider the performance measures of the facility, in the form of the following:

- Maximize vehicle throughput
- Minimize total travel time (time, costs, lost)
- Maximize revenue
- Minimize travel time variance
- Maintain level of service

These will play an important role in the stages of the methodology, especially during evaluation and interpretation of different scenarios devised.

## 3.2 Methodology structure

The methodology is made to include the first planning stage considerations such as the goals and objectives and other policy aspects throughout its steps exerting their influence on choices that are to be made. Except these influences carried throughout the whole process, the methodology includes two phases.

The first phase addresses the mentioned factors in section 2.4 that as mentioned in the conclusions of section 2 are related to the location (referred as predetermined specific cases in section 3.1.1). The location relates to a number of factors that can determine the success of an implementation, as mentioned in section 2.4, such as capacity issue of the corridor while the travel patterns should portray that there is sufficient potential demand that responds to the feasibility that the concept is able to provide travel time savings and an improvement of the predictability, thus reliability, of travel time.

The second phase includes both the comprising of different scenarios based on the possibilities of implementation considerations and/or design aspects, which are further evaluated with the help of a traffic simulation model. The model addressed in this research is only given as example and it should provide insight on the aspects that need to be included for a comprehensive evaluation. The representation of the model within the methodology is general, merely as a tool that provides generalized output. The details of what can or should be included in the traffic simulation procedure are addressed in more detail in section 3.4.3. Although the traffic simulation portrays quite a central role, it should act as a module that is easily replaced/updated according to state-of-the-art developments in the field and/or specific necessities of the application of the methodology.

Within the second-phase there is also the evaluation and interpretation of results. Because of the loop created between the implementation simulation procedure and the development of the scenarios that result in an implementation setup, it can be regarded that there are two levels of details when it comes evaluation. One is more preliminary and serves as insight for the

adjustments of scenarios, including some of the model's outputs, while the other transforms the outputs into costs and benefits in more economical sense in order to provide insight in the cost-effectiveness of the project without ignoring the more generalized effects of the implementation (equity, potential acceptability, etc.)

All the discussed phases and elements of the proposed methodology are included in a comprehensive diagram represented in Figure 3.5.

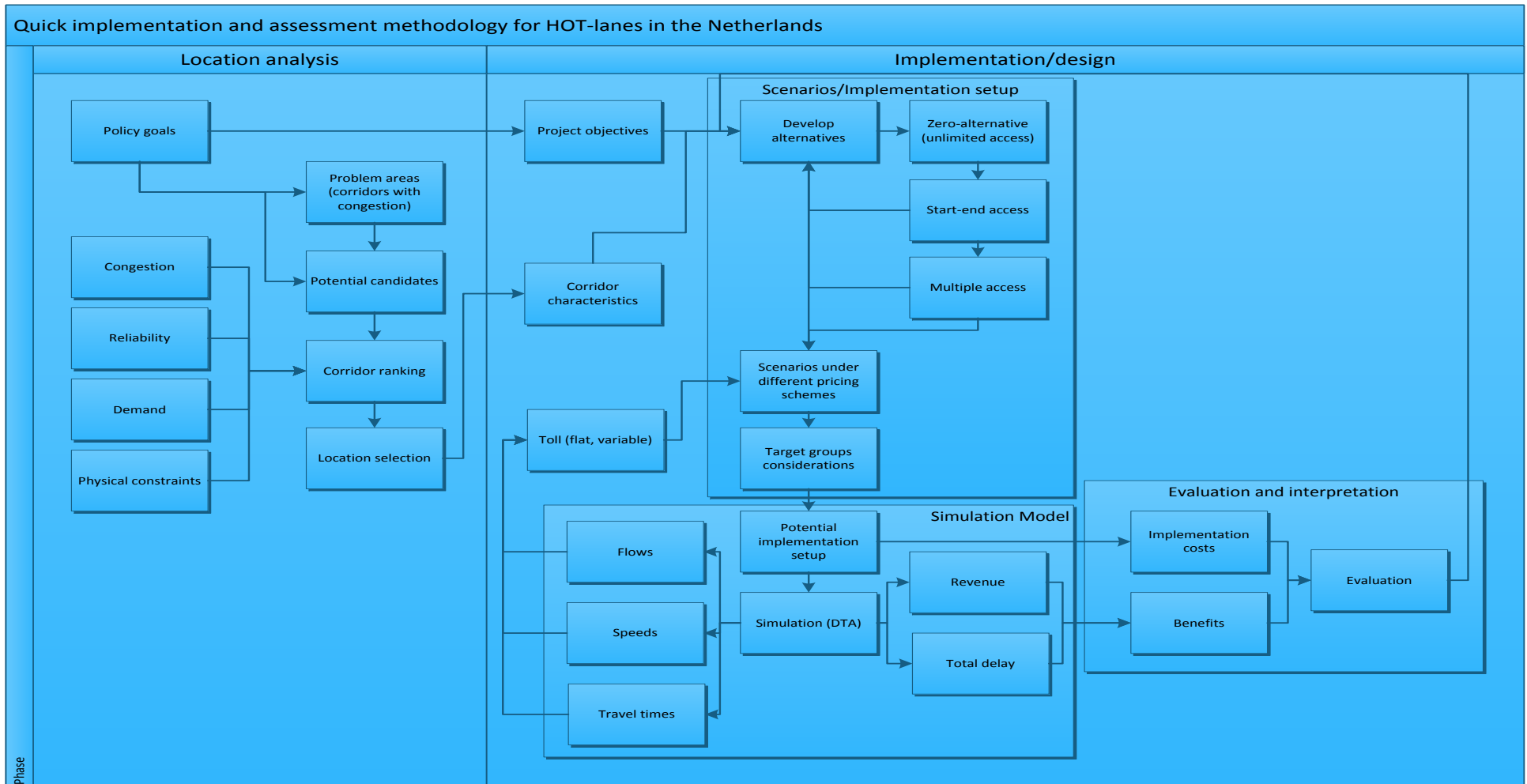


Figure 3.5 Complete overview of the proposed methodology for implementation and assessment of HOT lanes

### 3.3 Phase 1: Locations analysis and selection

The starting point of the methodology presumes that all the possible goals in the case of HOT-lane concept are applicable to a region's strategy. What needs to be identified is which specific locations can benefit from an implementation resulting in a positive effect of such a project to an extent that it can be declared a success.

#### 3.3.1 Corridor characteristics and considerations

As it is presented in the previous section, the goals and objectives have ramification down to the end design decision of the implementation. They also give an indication on the conditions and characteristics that are to be met by the location of implementation, in terms of feasibility. Another aspect that influences the feasibility and potential success of the project is the demand necessary to support such a measure. Several factors that influence demand were presented in section 2.4, from which certain characteristics of the demand are taken into consideration when establishing the criteria dictating the conditions that a location should provide for suitability of implementation and potential success.

There are other considerations, besides goals and strategies, which must be considered before determining the appropriate implementation. Not all of the goals and objectives can adequately define all of the possible real-world environments in which HOT-lanes are to be constructed (Fisher & Goodin, 2005). The mentioned considerations are listed with brief definitions:

- Physical constraints – include cross-section limitations, right-of-way restrictions and access limitations that may impact the type of strategy that can be used
- Price elasticity and willingness to pay – Price elasticity and WTP help portray the role of road pricing in the corridor
- Congestion levels along the corridor or at isolated traffic bottlenecks – these indicate that congestion management strategies, including HOT-lanes, should be considered
- Vehicles demand for the facility – this includes travel patterns that determine the “HOT-lane” market because access will be restricted, vehicle demand in the specific corridor can support a dedicated lane
- Speed differences between HOT lane and the adjacent lanes – this creates safety issues for movements between the two and thus the operational speed of the facility is dependent on the physical separation; it can also create incentives for toll violations also depending on the separation choice and its use in enforcement (Parsons Brinckerhoff, Texas Transportation Institute, 2003)

HOT facilities will likely generate substantial usage and be successful only when recurrent congestion occurs regularly on the adjacent general-purpose lanes (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000).

HOT facilities can be single lane or multiple lanes. Narrower than standard lane widths should only be considered in special circumstances or for short distances. Full-width paved shoulders are preferred on any roadway to accommodate disabled vehicles and to provide additional area for vehicles to manoeuvre or recover. Shoulders should be considered where right-of-way is available or can be acquired at a reasonable cost.

Reduced cross sections for HOV facilities, which can also be applied to HOT facilities, are primarily the result of retrofitting the lanes into the existing highway. No absolute minimum standard has been established for cross section reductions, especially for short sections of roadway. To ensure operational reliability, the width plus the lateral clearance should provide an envelope sufficient for passing a stalled vehicle (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000).

The length of the HOT-lane is primarily dependent on the congestion length on a specific corridor. From the users point of view this is one of the most important design element. The demand for the facility can turn out to be disappointing if the length is too short. This has to do with the fact that the length determines the (perception of) size of the time gains (Scholten, Jankovic, & Uden, 2000). A number of sources that mention the travel time savings in relation to the length of the HOT-lane. Considering a length of 4-7 km and a considerable speed difference of 50 km/h it was concluded that the time gains should be within 5 to 8 minutes (Weggemans, Veling, Tertoolen, & Uden, 1999). Based on the average travel time savings that are derived from the US projects' situation it was concluded that in the morning peak the amounts of time saved will amount to 4 minutes, for a length of 3 km, and 10 minutes for a length of 7km (Sullivan E. , 1998; Schreffler, 1998). Based on the results of the DHV study model (DHV Milieu en Infrastructuur BV, 1997), the travel time savings, for the then proposed test corridors, were substantially smaller: 2-4 minutes.

In the study commissioned by the Ministry of Transport, the calculated cost for construction and operation would only outweigh the (social) benefits only in the case of a travel time saving of at least 10-12 minutes (Ministrie van Verkeer en Waterstaat, 1999).

A thorough understanding of corridor characteristics is crucial to HOT-lane success. In order for pricing to be feasible it must offer a service superior to the adjacent general-purpose lanes. This means there must be serious congestion on a facility without viable alternate routes.

### **3.3.2 Selection criteria**

Right from the planning phase feasibility requirements have been introduced and identified. These involve feasibility criteria that are directly connected to the candidate corridor characteristics. Previous studies have shown a range of criteria that centre on the presence of congestion and the ability to save drivers a minimum number of minutes of travel time, as well as the ability to construct HOT-lanes with a positive balance of costs and benefits.

When the possible goals and objectives were identified, in the section 3.1.4, the most comprehensive and suitable themes for an implementation in the Netherlands included congestion relief, test/evaluate pricing, phase in general road pricing. This points to the search of existing traffic problem areas that fit the implementation of such a policy concept.

When the implementation of the HOT-lane concept is investigated from a national/regional perspective of testing such a road pricing solution, the need for a screening process for suitable corridors becomes evident.

Criteria for success correlated with the possible issues are along the same lines as the feasibility criteria identified previously. Corridor deficiencies in terms of capacity availability for the existing throughput, as well as sufficient demand and characteristics that influence the cost-effectiveness are among the criteria.

In the overview presented in section 2.4, at the end of the analysis on the US projects, several factors that influence demand were summarized. It can be noticed that most of them deal with characteristics of and for the future users of the facility with details on the trips made as well as on the "trip makers".

All of the above presented findings lead to the development of general criteria under different aspects that are to be used in a screening process that provides the specific locations where the success of such an implementation is most probable.

The selected criteria that correspond to the possible goals are to be found all across the following performance measures (in relation to the performance indicators from section 2.2):

- Congestion levels along a corridor or at isolated bottlenecks
- Vehicle demand
- Physical attributes to add a HOT-lane

The possible parameters and thresholds corresponding to each type of criteria are summarized in Table 3.3. The criteria will serve as guidance in the selection and classification of corridors, as these are related to US practice.

**Table 3.3 Corridor screening criteria**

<b>Criteria</b>	<b>Parameters</b>
<b>Presence of congestion</b>	Congestion Travel speeds Vehicle loss hours
	Bottlenecks Travel speeds Vehicle loss hours
<b>HOT demand</b>	Vehicle demand Vehicle volumes Vehicle demand must be capped at max per-lane flow Criteria is either met or not
<b>Physical attributes</b>	Physical ability to convert a lane Resulting volumes cannot exceed 2000 vehicles/hour Reductions in lane, shoulder widths that are acceptable

Due to nature of the scope on national/regional implementation level and this project's limited available time, the screening on the presence of congestion is addressed by using the results of previous studies that dealt with the identification and classification of congested locations in the Netherlands. As a substitute for this traffic performance indicator, the reliability of the corridors is assessed as it is a major component of the benefits of the HOT-lane concept. Details on the reliability criteria are provided in the next subchapters.

The data necessary for the criteria can come from a series of sources such as detector loops traffic data, LMS/NRM data from the traffic models runs, etc.

From the design point of view several pre-screening criteria are used to reduce the number of possible candidates presented in this research project. These are derived from the corridor considerations, but also from the safety and access points' characteristics that can have a greater influence in the Netherlands than the US counter parts. One major difference is the high density highway network present in the Netherlands as well as the high volume traffic present during peak hours. With these in mind, the following pre-screening criteria are taken into consideration:

- Minimum corridor length
- Maximum number of connections point such as intersection and on/off ramps

### **Reliability**

When thinking about travel time reliability in the context of tolling and pricing projects, it is reasonable to conclude that measures that reduce recurring congestion will also be effective at improving reliability.

A particular analytical issue is quantifying the value of reliability and forecasting that reliability. Whereas recurrent delay is mostly predictable based on traffic levels, non-recurrent delay is less predictable, avoiding it being even more valuable to travellers that need to be on time. The accuracy of analytical methods can have a critical role in determining the overall benefits of express toll lanes and the price sensitivity to tolls.

Measures of travel time reliability can be important indicators of traffic system performance, can reveal yearly changes in the conditions, and can supplement existing sources of traveller information. Nearly all projects use straightforward congestion measures to prioritize corridors. In addition to other goals, improving and maintaining a standard of travel time reliability is usually stated as a goal and it is recommended that reliability should be included in transportation planning. Literature suggests that travellers are less concerned with the actual time that their trip takes than the consistency of that time (Lyman & Bertini, 2007).

Using reliability as a performance indicator of traffic conditions is relatively new and only average traffic conditions have in the past usually been communicated to travellers. This though does not capture the experience of travellers, because they are more likely to remember the bad days, when their travel time was affected by unexpected delays. Therefore travellers are not only interested in reducing the travel time, but as well, or even more, interested in reducing unreliability (OECD, 2010a).

There is no consensus on which indicators to use for travel time unreliability. Most unreliability measures used/proposed in practice relate to the day-to-day variation on a particular route, for a particular time (period) of the day, limited to workdays (sometimes by day of the week). Many different indicators have been proposed. These can be divided into various classes. One of the possible classifications can be (van Lint, van Zuylen, & Tu, 2008):

- Statistical range indicators
- Buffer time indicators
- Tardy trip indicators
- Probabilistic indicators
- Skew-width indicators

The following lists some reliability measures that are commonly used:

- 90th or 95th percentile travel time: in other words, out of 100 travel times on a given corridor, the 90th or 95th longest
- Standard deviation of travel time
- Coefficient of variation: computed as standard deviation of travel time divided by mean travel time



- Buffer index: computed as difference between 95th percentile travel time and mean travel time, divided by mean travel time ; the extra time that travellers allocate to travel to make sure they are on time in 95% of the cases ; when the buffer time is assumed to correspond to the variance of travel time, the buffer time index may coincide with the CV
- Planning time index: computed as 95th percentile travel time divided by assumed free-flow travel time ; the total time needed to plan for an on-time arrival 95% of the time ; this index indicates the severity of traffic congestion as it represents the worst level of congestion at a given time of day in comparison with the free flow traffic conditions
- Misery index: computed as difference between mean travel time for worst 20% of trips and overall mean travel time, divided by mean travel time ; captures the negative aspect of travel time reliability by examining the average number of minutes the worst trips exceed the average
- Skew of travel time distribution: computed as the difference between 90th and 50th percentile travel time, divided by the difference between 50th and 10th percentile travel time
- Width of travel time distribution: computed as the difference between 90th and 10th percentile travel time, divided by the 50th percentile travel time
- Congestion frequency: percent of time that mean speed drops below a particular speed
- Lateness and earliness indices: can be based on the log-normal distribution
- Probability index: states that travel times should be made within 20% bounds of the median travel time, the percentage of travel times exceeding that value make up the probability index ; computed as the percentage of travel times that are larger than 1.2 of the 50<sup>th</sup> percentile as defined by RWS

There are a significant number of reliability indicators due to the general reluctance towards their acceptance, thus resulting in developing several varieties that address specific downfalls. Out of the enumerated indicators, a limited selection will be made for further use in the analysis.

The different indicators for measuring the reliability have been briefly described and categorised by the method they use. The suitability of each indicator will be discussed by comparing their shortcomings and advantages from available literature.

Statistical range methods include early arrivals, while buffer time and tardy trip only deal with late journeys. Early arrivals also contribute to variable travel times, and are a part of the uncertainty (Chang, 2010). However, Brownstone & Small (2005) conclude that the standard deviation is not accurate enough, and it in turn relies on the measures of the upper tail of the distribution of travel times, represented by the difference between 90th and 50th travel times (buffer time index).

The fact that the standard deviation assumes a normal distribution is considered a limitation (Lomax, Schrank, Turner, & Margiotta, 2003). However there has been suggested to use log of a value in the calculations rather than the value itself to overcome this limitation. This resulted in recommending the percent variation, misery index and buffer index as indicators for reliability.

Multiple studies recommend the buffer time as an indicator for reliability (Brownstone D. &, 2005; Lam & Small, 2001). Some found the buffer time too unstable and erratic to be used as a primary measure to track performance and effects of policy measures, but good as a secondary indicator. These also found the planning time index to be too extreme to be used for policy planning, and suggested using the 80th percentile instead for the planning time index. This resulted in recommending the use of the buffer index, skew statistics and the misery index to identify effects of policy measures (Cambridge Systematics, Inc., 2006).

There is no one absolute indicator available for travel time reliability. The different indicators encompass different elements of the travel time distribution and are derived using different methods. It has been decided that the indicators most used and proven in the state of practice are to be used here. These include the standard deviation, planning time index and the buffer index.

### **Congestion**

The identification of highway sections (corridors) that may experience congestion and can benefit from the implementation of a HOT-lane concept is done in a common manner by applying standards currently used in the Netherlands. These are usually related to a quantification of vehicle loss hours (KiM, 2011). As input for the framework, corridors classified as problem areas are used with their corresponding indicators such as the quantification of vehicle loss hours.

The data used to determine congestion presence can include near present data (historic), from detector loops for example, if the concept is considered to be implemented in the near future, or data as output of the strategic traffic and transportation simulation models used for regional and national planning, e.g. Landelijk Model Systeem Verkeer en Vervoer (LMS). Congestion criteria should be evaluated both for the near-horizon years and for long range planning horizon. Some corridors could be congested currently but not so in longer-terms as a result of committed improvements.

### **Demand**

The indicators or input for providing insight on the potential demand for the HOT-lane can be various. As addressed in section 2.4, these can include detailed travel patterns, distribution of the trips according to trip purpose, or even trip length.

The starting point for the evaluation of certain locations based on existing demand is considered critical to ensure that the implementation has the potential of a success in its opening year. The data in terms of traffic flows expressed in vehicles/hour is used for this initial estimation.

An additional condition that can be posed in the criteria is the trip length distribution. This can be realized by examining specific travel patterns, which include origins and destinations of vehicle

users, providing also insight on the considerations where access can be restricted, as it is preferred. Regional or national travel demand models can be used to analyse overall trip lengths or selected link data for the specific corridors.

An inclusion of potential demand would be represented by analysing existing and likely levels of person's throughput from carpools, vanpools or even transit that can be derived from vehicle occupancy counts (not applicable to the Netherlands) combined with traffic forecasts. This consideration is currently less applicable to the Netherlands in terms of focus on the issue. Nevertheless, forecasting is possible.

### **Physical attributes**

The primary perspective when applying selection criteria to the physical roadway is the opportunity to convert or borrow existing lanes or shoulders lanes. As in most cases (specific problem areas corridors) in the Netherlands, the road space is rather limited resulting in a direct orientation towards the use of the shoulder lanes considering they already serve the purpose of temporary use during traffic peak hours on specific highway sections entitled "rush hour" lanes. Unlike rush-hour lanes, for the HOT-lane facility sometimes a barrier is preferred between it and the general purpose lanes due to safety and enforcement concerns, resulting in the need of a limited extra amount of road space necessary. This is why that a criterion for the physical attributes, total road-way space can be considered.

The other perspective is the connectivity portrayed by the physical configuration of the considered corridors. The frequency of on/off ramps, referred also as access points within this report, on the highway section can influence the performance of the future HOT-lane. A high frequency of access points reflects in a predisposition of short distance trips within the corridor. Short distance trips are not preferred and targeted by the facility due to the possible weaving and throughput friction and the need to maintain operating safety and performance.

When assessing the corridor according to road-way space, besides the data available on the physical width of all lanes that compose the section, other empirical evidence on suitability can be obtained through verification using aerial images and/or field observations and determine if potentially necessary extra road space can be obtained by limited expansion of the existing roadway.

### 3.3.3 Weights for criteria and influencing factors

The rating of the locations/corridors is done in relation to each other, as the selection pool used is already comprised of traffic problems areas that partially comply with the congestion and demand volume. Through further research and more case studies then included in this report it can be possible to determine suitable thresholds as qualifying criteria.

The weighing of the criteria, no matter the expertise of the decision makers, always contains a subjective bias that eventually influences to some extent the result.

According to the (Saaty, 2008) study in order to make a decision in an organised way to generate priorities, first the decision needs to be decomposed into the following steps:

- Define the problem and determine the kind of knowledge sought
- Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives)
- Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it
- The priorities obtained from the comparisons are used to weigh the priorities in the level immediately below, for every element. Then for each element in the level below weighed values are added and its overall or global priority is obtained

The process of weighing is continued and added until the final priorities of the alternatives in the bottom most level are obtained.

In order to be able to make comparisons a scale of numbers is needed in order to indicate how many times more important one element is over another element in terms of the goal in which purpose they are compared. The scale is presented in Table 3.4.

**Table 3.4 The fundamental scale of absolute numbers (Saaty, 2008)**

<b>Intensity of importance</b>	<b>Definition</b>	<b>Explanation</b>
1	Equal importance	The elements contribute equally to the goal
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another

4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An element is favoured very strongly over another; its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of the above	If element <i>i</i> has one of the above non-zero numbers assigned to it when compared with element <i>j</i> , then <i>j</i> has the reciprocal value when compared with <i>i</i>	Reasonable assumption

The congestion component is rated of least importance to other due to the already mentioned fact that the ranking is made among areas with congestion problems, but also because the other criteria have either a direct or indirect effect on the level of congestion. Reliability is regarded as of slightly moderate importance equally over congestion and demand criteria, being a subsequent result of the two. Last, but not least, the physical attributes are of significant importance over the other criteria due to safety concerns and of restricting operations of the facility if it is not adequate. These ratings are presented in Table 3.5.

**Table 3.5 Results of judgements**

	Congestion	Reliability	Demand	Physical abilities
Congestion	1.000	0.333	0.250	0.333
Reliability	3.000	1.000	3.000	0.500
Demand	4.000	0.333	1.000	0.200
Physical attributes	3.000	2.000	5.000	1.000

The resulted weights for the criteria, based on the judgements above, are as follows:

	Congestion	Reliability	Demand	Physical abilities
Weight	0.074	0.289017	0.213231	0.423892

### 3.3.4 Overview

This phase of the methodology is meant to analyse and classify potential locations suitable for a implementation of a HOT-lane concept.

The considered necessary input for this first phase of the methodology is a preliminary list of highway sections that are considered problem areas due to the manifestation to high extent of congestion effects. For these problem areas it is assumed that the spectrum of traffic management solutions considered applicable for their situation already contains the pricing measure in the form of a HOT-lane concept.

The spectrum of potential policy goals and objectives is used to compose the preliminary problem areas considered, as well as in case of necessity reduce it due to any of the concerns or considerations. The additional concerns and consideration are assumed to influence the ability of the corridor to be considered potential candidate.

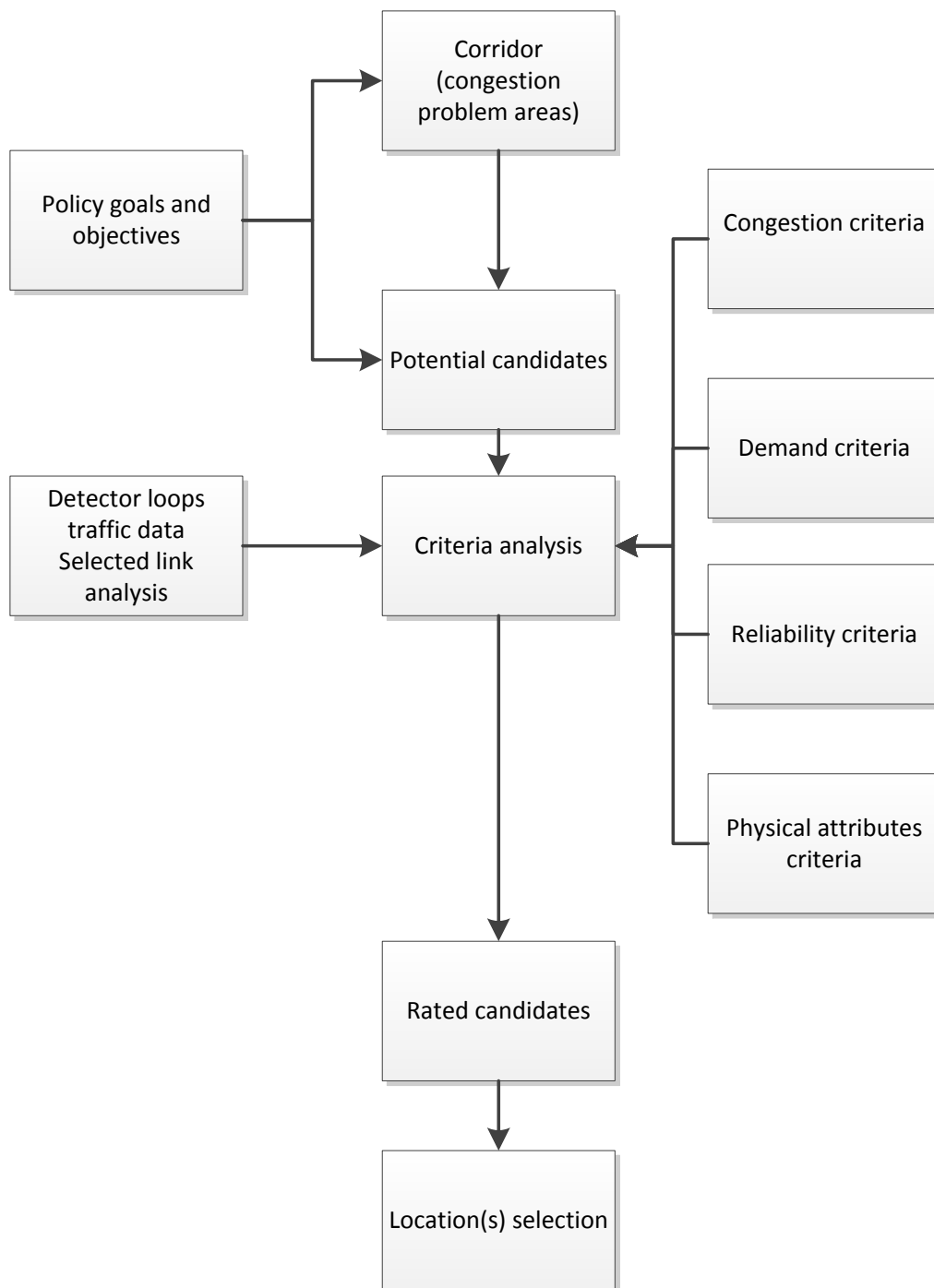
This list of highway sections (corridors) is to be scrutinized on aspects presented in section 3.3.1. The criteria used for their detailed analysis is classified under the following areas of application, which are represented together with the specific criteria:

- Reliability (Buffer Index, Travel time standard deviation, etc.)
- Congestion (Vehicle loss hours)
- Demand (Traffic flows, Trip length distribution, carpool demand)
- Physical attributes (Road-way space per lane, On/off ramps frequency)

To the criteria categorized above there are no specific threshold applied, but they are ranked according to absolute values they present. It is these category rankings that are used as input for the general corridor rating with the use of the weights determined in section 3.3.3.

As a result, the output of the phase is a list of candidate corridors rated according to their overall suitability for the implementation of a HOT-lane. From this ranking, a single or several candidates may be picked for further consideration within the next phase of the methodology.

The procedure described in this overview is represented in Figure 3.6.



**Figure 3.6 Phase 1: Location analysis**

## 3.4 Phase 2: Implementation/design

This phase takes further the consideration of the corridor(s) resulted as best candidates in the first phase of the methodology.

From here, taken into consideration the corridor's specific characteristics and traffic conditions, the determination of best solutions/variations of the implementation setup is realised with the help of scenarios.

The next step of the methodology makes use a traffic simulation model, both for determining the appropriate setup of the implementation and its final assessment. The traffic simulation model module addresses both the possibility of the use of an existing model and the development of a specific and purposely build traffic model.

The final step of the phase consists of a more comprehensive evaluation of a decided upon implementation setup considered most suitable considering the policy goals and objectives and the location characteristics and possibilities.

### 3.4.1 Corridor related design elements

The literature review concluded in section 2.4 indicated that two essential aspects to be considered in the design and operations sections are the pricing strategy and the facility's access points together with lane separation.

The pricing strategy is initially derived from the project's goals and objectives as it can have significant influence on the outcome of the implementation in terms of success. This was evident in the overview from section 2.4, where the differences in performances of the projects was concluded to be affected by the purposes of tolling, price levels, and vehicles eligibility.

The importance of the access points is also linked on the goals of the implementation, as it can have an effect on the potential demand and on the type of traffic the facility attracts. Last, but not least, the lane separation addresses safety, thus dictating the appropriate speed differences to be permitted between the general purpose lane and the HOT-lane and influencing the users' perception on safety.

Design elements including access treatments impact project feasibility. The currently operating pricing projects are very limited access facilities that primarily serve through trips and act as express lanes. This makes designing for enforcement and tolling areas easier. As more and more management strategies are analysed and multiple access points are considered the design implications become much more complex.



Positive separation is used each in of the operating managed lanes projects. This is important because of the different operating characteristics that may occur on adjacent general purpose lanes. As more projects are developed lane separation techniques must be carefully considered in the design phase of project development.

### **Access points and safety**

Safety is one of the most important aspects when considering the implementation of a concept such as HOT-lanes. The related issues to safety include cross-sections, separations and access. It is intended that only the most frequent design issues are addressed, not going into details with designs unique to specific situations.

Even from the beginning, when taking into consideration the proposed concept, according to conducted surveys one of the main concerns of the road users is regarding the possible safety issues that such a facility induces on the corridor. As previously addressed in section 3.3.1, the studies show the potential concerns of drivers due to the weaving action that takes place between the access points of the HOT-lane and the general purpose lane.

These are addressed even further in the analysis of the existing projects, under performance indicators and issues related to the facilities examined, section 2.3.1. The access points where discussed as they directly impact the convenience and safety with which travellers access the facility, coupled together with the necessary enforcement measures. Another issue regarding safety was the separation between the facility and the general purpose lanes together with the number of access points are taken under consideration. The safety factor varies from a solution with demarcation lines and several intermediate access points to one with a concrete barrier and no intermediate access.

Last, but not least, another safety issue was previously considered, under corridor considerations (see section 3.3.1). It concerns the speed differences between the HOT-lane facility and the general purpose lanes. This relates also to impacts of the weaving movements and is dependent on the separation solution adopted.

### **Access points**

The simplest approach to weaving issues is to ensure that the distance between the HOT/HOT access point and the freeway ramp is sufficient to allow for the necessary weaving manoeuvres. Access points should be located so that there is a distance of between 150 and 300 meters or more per lane change required to move from a ramp to the managed lane or vice versa; the higher number being the desired distance and the lower number being the minimum. Access to or from the HOT/HOV lane should be consistent with the above guidance, providing at least the minimum acceptable distance per lane change to set the access point length for each movement. For a

combined access (allowing both ingress and egress), the length of the access point should be at least twice the minimum acceptable lane change distance.

As mentioned previously speed differences is a crucial point. There are several approaches in dealing with this issue.

In cases where speed differences and access volumes are low it may not be necessary to take any special action to address the difference in speeds between the HOV/HOT lanes and the mixed-flow lanes. Motorists wishing to change lanes will need to wait for a suitably long gap to appear before changing lanes. The advantage of this approach is that the cost of more elaborate measures is avoided. A disadvantage is that drivers may slow down when approaching the access/egress points to wait for a suitable gap to appear, thus impeding the flow of the vehicles behind them. Also, motorists may attempt to use narrow gaps thus creating a collision hazard.

In cases where the high access volumes or speed differences are anticipated best practice is to provide a weave lane (auxiliary lane) between the parallel roadways. This approach requires more road way space and thus may be considerably more costly than the previous approach.

In cases where both the access volumes and the speed differences are expected to be high the best practice is to provide separate weave lanes for each movement. This approach is more costly than the previous approach, where access and egress movements shared a weave lane, because more sections of weave lane will be needed.

The ideal access point design will provide separate locations for ingress and egress. Often insufficient right of way or distance between interchanges exists to provide the ideal solution. In such cases, access points can be combined to allow ingress and egress at the same point.

## **Separation**

Several types of treatments can be considered to physically separate a HOT facility from adjacent freeway lanes such as a buffer area with pavement markings, a buffer area with delineators (pylons), and a concrete barrier. Each treatment has issues that must be evaluated. A paint stripe or painted buffer treatment may have safety, enforcement, and toll collection difficulties. Delineator treatments may have maintenance challenges. Concrete barrier treatments may have incident management concerns. Careful analysis must be conducted when considering design trade-offs to provide an operationally effective facility (Stockton, Benz, Rilett, A.Skowronek, Vadali, & Daniels, 2000). Each of the mentioned types of separation come with their own trade-offs as it can be observed in the details provided in Table 3.6.

**Table 3.6 Trade-offs for different types of separation treatments**

Type of separation	Advantages	Disadvantages
<b>Buffer - Markings</b>	<ul style="list-style-type: none"> <li>• Less expensive</li> <li>• Short implementation time</li> <li>• Flexible configuration</li> </ul>	<ul style="list-style-type: none"> <li>• Speed differences reduce safety</li> <li>• Mistaken for shoulder lane</li> <li>• Enforcement difficult</li> </ul>
<b>Delineators - Flexible Posts</b>	<ul style="list-style-type: none"> <li>• Moderates safety and enforcement</li> </ul>	<ul style="list-style-type: none"> <li>• Frequent maintenance due to necessary replacements</li> </ul>
<b>Barrier - Concrete/Metal</b>	<ul style="list-style-type: none"> <li>• Easy enforcement</li> <li>• Increased safety</li> </ul>	<ul style="list-style-type: none"> <li>• High capital costs</li> <li>• Occupies more space on the right of way</li> <li>• Limits the number of access and egress points</li> </ul>

The separation between the HOT and the normal lane can be of influence on traffic safety. Speed differences between the HOT lane and the normal lanes have to be very small if a physical barrier is lacking. Vehicle speeds on the HOT lane are not allowed to be higher than 20 km/h above the vehicle speed on the normal lanes. Under congestion on the normal lanes this would lead to a very low maximum speed on the HOT lane. If a concrete (physical) barrier is applied between the lanes, speed differences can be higher. Speed differences between the lanes have a large influence on travel time profit and therefore on the revenues of the system. Besides this speed difference the HOT lane is easy to control for entering and exiting vehicles if the lanes are physically separated. No vehicle can enter the HOT lane else than at the access zone. A negative consequence of a physical barrier is that emergency vehicles cannot reach the HOT lane in the case of an accident. An accident on the HOT lane certainly leads to traffic problems because vehicles are not able to pass the accident location and block the HOT lane.

As mentioned in the previously, the access arrangements and locations can impact significantly the performance of the facility. Although the main consideration to access is to make sure the HOT-lane address the right demand areas, it's not numbers that guarantee success but locations. Therefore when access is used as a pre-requirement it is mainly sought to match the access location to the trip pattern present in the area of the corridor.

### 3.4.2 Scenarios/Implementation setup

The development of the scenarios that will be evaluated with the use of the traffic simulation model and subsequently will result in the best potential implementation setup is done by deriving from the corridor characteristics and policy objectives the suitable design variations.

The design elements revised previously come with restrictions imposed on the setup of the facility. For example, depending on the available road space of the corridor a certain type of barrier can be chosen that in accordance to safety factors that dictates a maximum difference of speed limits between the general purpose lanes and the HOT-lane. It may be even concluded, by further research, that the barrier in combination with the lane width has an influence even on the capacity of the HOT-lane due to the resulted driving behaviour.

The scenarios evolve as multiple runs of the traffic simulation model are performed that indicates the effects achievable with a certain implementation setup, resulting in a limited trial and error loop. It has to be mentioned again that the methodology is not intended on resulting with a single solution after a one time application.

Based on the results of the evaluation it can be interpreted that the benefits resulted can be increased without affecting the policy goals. This can translate in modifications to scenarios that allow an increase of facility utilization. The increase in demand can be achieved either by simply including additional target groups, e.g. trucks, if they weren't included initially or provide access to zones that can provide extra demand. As mentioned previously in section 3.4.1, it is preferable that the facility has a start-end configuration for a better and more efficient operation, also considering that the possible lengths achievable are at the low end of the spectrum when considering feasibility.

This can result in alternative scenarios that include multiple accesses. The included access points are to be chosen based on the additional demand that they can provide to the facility, but also based on their existing configuration and position along the corridor in such a way that they have limited impact on both the HOT-lanes users and also on the general purpose lanes traffic.

The other design element susceptible to change between scenarios is the pricing scheme, form both its application point of view (flat, variable) as well as the derived toll values from the previous simulation runs.

## Pricing scheme

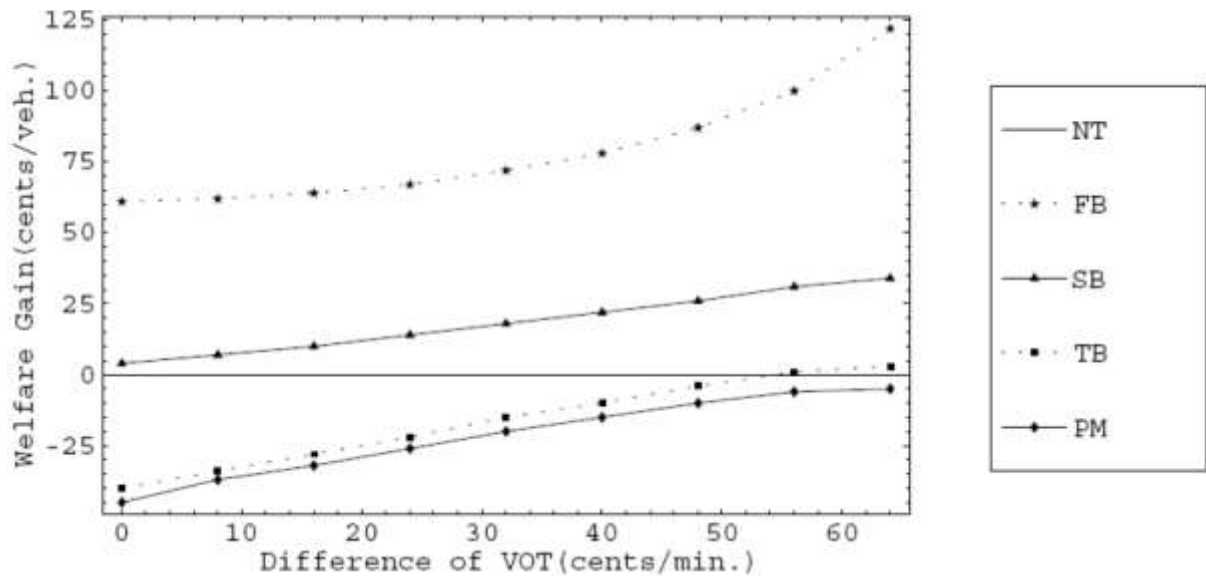
Throughout the different sections dedicated to the methodology, several performance factors were identified and their relations with specific design aspects of the facility were discussed. The first and most important is the pricing strategy which has strong influence on most of the performance factors of a HOT-lane. What is more important to state is that the pricing scheme is dictated by the goals and objectives set for the project. In the previous sections, five main competing (and possibly conflicting) objective functions were identified:

- Maximize vehicle throughput
- Minimize total travel time (time, costs, lost)
- Maximize revenue
- Minimize travel time variance
- Maintain level of service

It is hypothesised that these functions result in different pricing strategy. While the last two can be considered only related to the ability of pricing scheme to maintain "free flow" traffic conditions on the HOT-lane with minimum impact on the adjacent general purpose lane(s), the first three can result into big differences in terms of value of the toll and its schedule.

In order to reach an optimal situation in which all marginal social costs are incorporated in the costs that a road user experiences it is necessary that on all routes in a network a toll that incorporate the marginal costs needs to be imposed. The resulting situation is called the first best (FB) optimum (Williams & al., 2001). Due to the challenges on tolling a whole network according, without leaving any free alternative, according to the previously described principle it is usually the case that a much lower toll only on specific routes is charged. This lower toll optimum is called the second best (SB) optimum, because the optimum is constrained by a number of no-toll routes in the network.

Besides the first and second best optimum, there is also a third best (TB) optimum. This optimum is not only limited by a number of no-toll routes at the network, but also by the number of vehicles present on the toll road, under a specific condition such as to be lower than 80% of its capacity, in order to guarantee a certain level of service. The principle of HOT-lanes can be regarded as a TB optimum. Small et al. (2000) have simulated a FB, SB and TB optimum in their study. Figure 3.7 shows the results of this procedure.



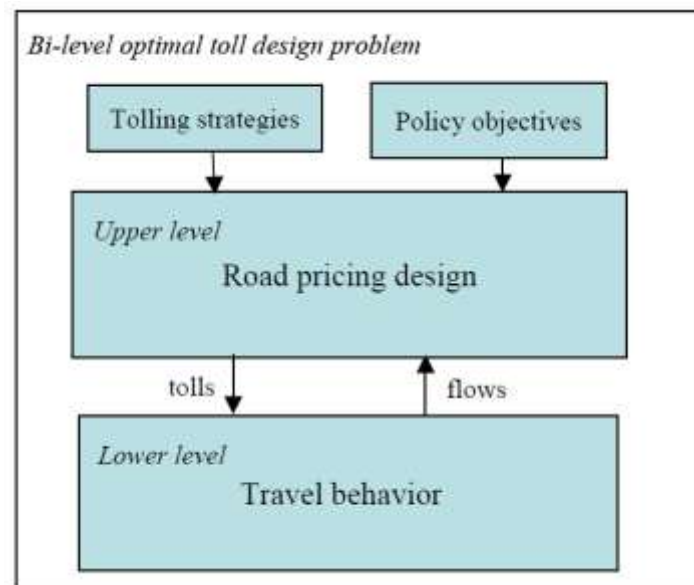
**Figure 3.7 Welfare gain (Small & Yan, 2000)**

The welfare gain increases as the difference of the value of time increases. In other words, price differentiation is more effective when the value of reliability is larger. While the first best pricing appears to be the most effective together with the second best pricing that still performs fairly well resulting in an improvement of social welfare, the third best pricing leads to a worsening of the welfare gain when compared to a no-toll situation. This result seems to indicate that in terms of the total welfare gain as a function of travel time and toll costs, the application of a HOT-lane is less effective than a no-toll situation.

It can be stated that the previously presented results indicate that the condition of a guaranteed low travel time leads to a welfare loss. Based on these findings, the conclusion could be drawn that a general variant of congestion pricing is a better measure than the creation of HOT-lanes.

It has to be mentioned that there are several benefits of implementing a HOT-lane concept that were not taken into consideration in the presented study. The most important advantage of TB-pricing is that travel time uncertainty is reduced for the facility users. As a consequence costs resulting from arriving too early or too late will be much smaller than when a road user uses a free road or a toll road under SB conditions. Another benefit of TB-pricing is that there could be a substantial external valuation for a guaranteed accessibility of certain places.

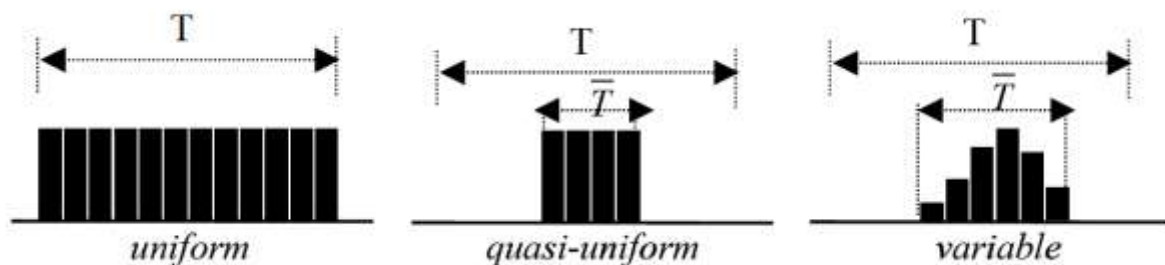
Another study (Joksimovic & Bliemer, 2006) investigated the optimal toll design under different policy objectives. By formulating a mathematical bi-level optimisation problem, which includes a DTA and the policy objective functions, the study was able to determine a second best optimum value of the toll for three different types of tolling schemes. The methodology is presented in Figure 3.8.



**Figure 3.8 Framework of the bi-level optimal toll design problem (Joksimovic & Bliemer, 2006)**

As it can be observed Figure 3.9, the toll patterns considered were:

- uniform tolling scheme (toll levels are constant over the entire study time period  $T$ )
- quasi-uniform tolling scheme (tolls levels are constant over a specified time period and zero otherwise)
- variable tolling scheme (tolls levels are time-varying)



**Figure 3.9 Different tolling schemes with respect to time of day (Joksimovic & Bliemer, 2006)**

Their results show that in the case of maximizing total toll revenues the best tolling scheme is uniform with a specific toll value that in the same time results in a high total travel time. On the other hand, in the case of minimizing total travel time, the variable tolling scheme performs best. However, this toll resulted in low total toll revenue. In other words, maximizing total toll revenues and minimizing total travel time are opposite objectives.

## Interaction of design and operations elements

Numerous factors that need to be met to meet the project's goals and objectives were specified previously throughout the report. The factors were narrowed down to those hypothesized to be most influential in the implementation and further incorporated in the evaluation. These are summarized in Table 3.7.

**Table 3.7 Facility design aspects**

Factor	Description
<b>Cross section</b>	This factor is concerned with the design guidelines proposed HOT lane. These consist of examples of cross sections for barrier and buffer-separated facilities. These cross sections, including lane width and shoulder width should ensure safety.
<b>Lane separation</b>	This factor is concerned with the adequacy of lane separation between HOT and general-purpose lanes to support tolling operations. Three types of lane separation can be considered, each with advantages and drawbacks: rigid barrier, flexible barrier and buffer.
<b>Facility access for HOT demand</b>	The principal consideration for this factor is, "do the access points serve potential HOT lane demand?" By defining the potential users, in priority order, along with their O-D patterns, the location of access points can be determined based on how best to serve their needs.
<b>Pricing strategy</b>	Pricing strategy refers to the overall operating strategy for the HOT lane and how it works in combination with eligibility requirements, facility design, and supporting technology: lane management for priority or target users and setting the toll rate and eligibility requirements.



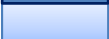

It is important to realise what are the interaction between these design aspects and the performance indicators. For instance, a narrow facility cross section would have a negative impact on several performance factors. The narrow cross section could reduce the vehicle capacity of the lane, thereby reducing HOT lane utilization. It could also increase the crash rate, decrease average travel speeds, and decrease travellers' willingness to pay to use the lane. The interactions accounted for, between facility design aspects and performance factors are ranked as strong, moderate and weak, but still of significance as portrayed in Table 3.8.



**Table 3.8 Interaction of elements that influence the HOT-lane implementation**

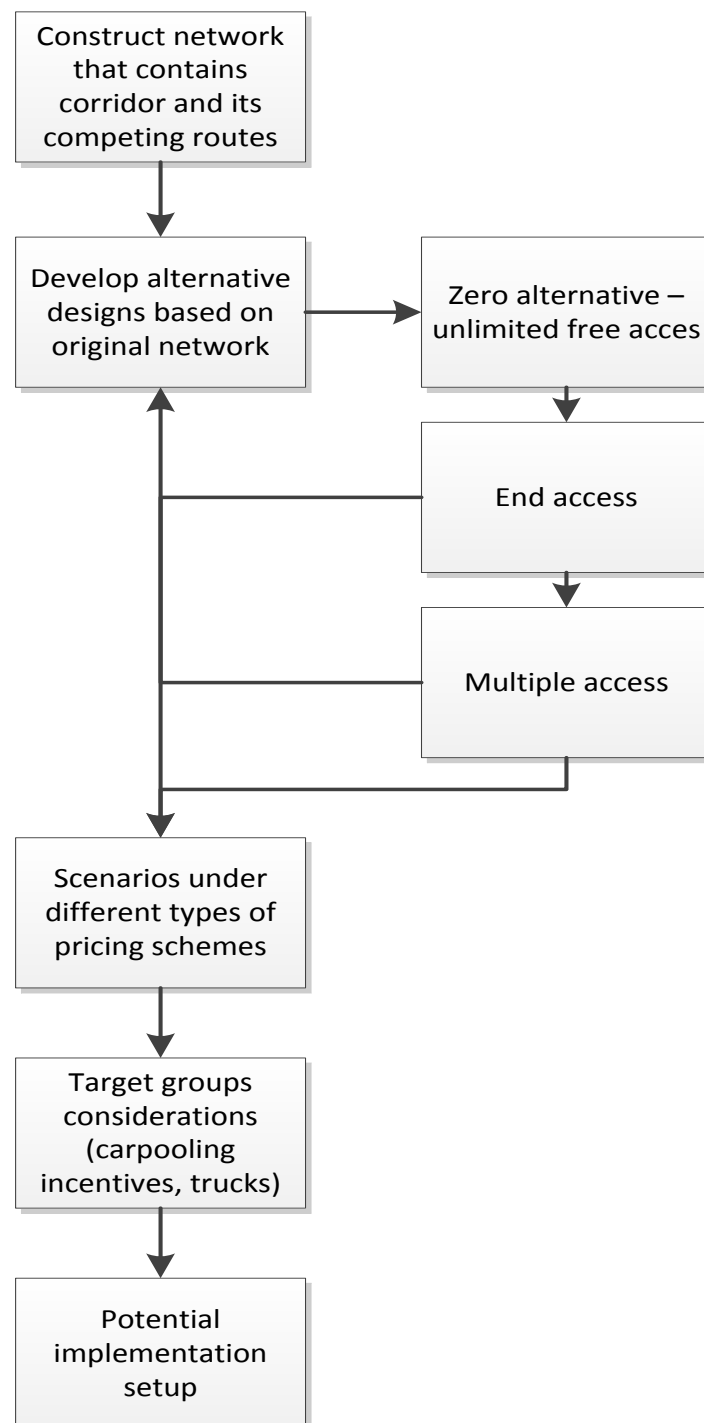
Design aspect	Interaction level				Performance factor
	HOT lane utilization	Travel time	Willingness to pay	Safety	
Cross section	Strong Interaction	Weak, but yet significant, Interaction	Moderate Interaction	Strong Interaction	Anytime any of the performance factors are affected, also the benefits of the HOT-lane are impacted
Lane separation	Secondary Interaction	Moderate Interaction	Secondary Interaction	Strong Interaction	
Facility access for HOT demand	Weak, but yet significant, Interaction	Secondary Interaction	Moderate Interaction	Secondary Interaction	
Pricing strategy	Strong Interaction	Secondary Interaction	Strong Interaction	Secondary Interaction	

Where:

-  • Strong Interaction
-  • Moderate Interaction
-  • Weak, but yet significant, Interaction
-  • Secondary Interaction

This concludes the design aspects that are to be considered in defining the most successful implementation setup, according to the desired and selected project goals and the corresponding objectives. The design aspects will be represented in a modelling procedure that serves both in comprising possible operating scenarios and their evaluation, resulting in an implementation setup that reflects best the policy makers’ goals.

With the use of the modelling and simulation procedure that is developed and presented in the next section of the report, it is sought out to quantify and clarify the extent of the interactions between the aspects that are presented in the above sections. In order to do so, several scenarios and test are considered and presented in Figure 3.10.



**Figure 3.10 Development of implementation setup procedure**

### 3.4.3 Traffic simulation model

As described in the previous section, the traffic simulation model serves a dual role. One involves providing comprehensive results and their effects necessary for making a final evaluation and interpretation of the possible outcome of an implementation. The other role involves providing preliminary results necessary for adjusting the implementation setup with the use of variation of scenarios to be run. These two roles envisioned have of course different levels of details, nevertheless preferably include in the same traffic simulation model.

In this section the guidelines for the selection of an existing traffic simulation model or for the future development of a purposely built model are described. As this research adopted the first option, the aspects addressed are inclined in a specific direction. Based on the findings in the case study section where the adaptation of an existing model is experienced, further recommendations are made in the direction of traffic model developments.

#### Desired model inputs and outputs

For each of the factors considered to be most relevant the probable effects are hypothesized. Relations between different aspects of the implementation are also clearly defined. In the end all these elements are to be assessed on importance and their inclusion into the model.

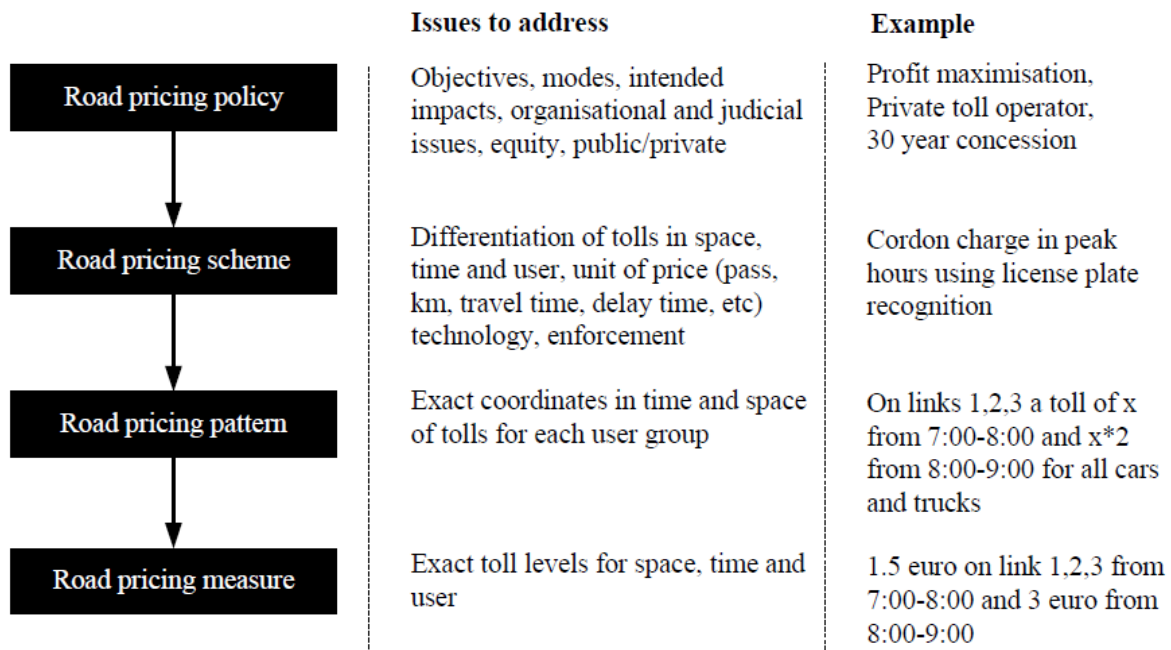
As it was presented in the previous chapter, there are multiple elements that need to represent in order to simulate and evaluate a HOT-lane implementation setup.

The starting point is in making use of the available OD demand and network characteristics at a level of detail at least similar to the existing national and regional models available in the Netherlands, the LMS and NRM respectively. Although the mentioned models consider a classification of demand according to trip purpose, it is preferable that the user-classes to be used are based on an income classification. The reason behind it is to be able to address the equity issue that can arise as an effect of the implementation. The incomes are also hypothesized to have an influence on the willingness to pay as well as mode choice.

The interest of mode choice mentioned previously refers to in this case to the carpool option for travellers that is also required as input. To be able to include the potential carpool users there is the need of stated preference data that address carpooling as mode choice. This should provide the necessary information to represent carpool formation as input.

The different pricing strategies that need to be tested or considered vary across a wide range. The policy process that starts with the chosen objectives can result in various pricing scheme and setups. Translating a policy objective into a specific road pricing measure requires many decisions. Figure 3.11 represents the several levels in policy-making that are part of the whole process. As

consensus between different parties regarding a common objective is reached, the methodology proposed make possible testing of different setups and make use of the portrayed effect in helping with the decision process.



**Figure 3.11 Level of decision making for pricing measure implementation (Amelsfort, 2009)**

The resulted measure(s) are considered input in the traffic simulation procedure.

The output of the modeling procedure should reflect the effect the measure has on the travel behavior of individuals at trip level when faced with a HOT-lane alternative. Considering that the methodology should represent a quick and effective mean of sketch-planning for policy makers, the levels of detail are kept to a required minimum. This results in a reflection of responses on short-term, medium term at most including route and mode choice. This is combined the model's representation at a macroscopic level to show aggregated system changes.

The output should include sufficient indicators that predict the potential demand/use for the facility and the effects it has on the specific corridor. The predication should be able to reflect both on current traffic conditions (2013) and also distant future trends (2030).

The model should be able to provide, in addition to the commonly present speeds, travel times and traffic flows, these preferably separated across user groups, the vehicle loss hours (delay) and the revenue resulted from tolls, which are necessary for the evaluation. In terms of extra details that are to be expected for a better interpretation of the potential implementation, the model outputs should include insights on the travel time's reliability effects.

## Model requirements

This section identifies the necessary technical requirements for the inclusion and reflections of the elements that were presented and addressed throughout the methodology steps so far.

The design of different road pricing measures place different requirements on the model. The road pricing measures considered within this research are time-varying and user-class differentiated road pricing measures. With time-varying road pricing measures, the charge levels change over time. A particular aspect is the dynamic pricing that is not only time-varying, but in the case of maintaining predetermined levels of traffic on the facility, it also considers the current traffic thus depending on the actual conditions on the road. This level of differentiation therefore places the first two requirements on the model: 1) the modelling framework needs to be able to handle time-varying road pricing measures and 2) the travel times for different departure periods need to be calculated accurately.

Another aspect of the concept's implementation is the user-class differentiation. This means that for different groups of travellers, different toll levels may be applied. Different toll levels lead to different behavioural responses. This consists of another requirement on the model: toll levels need to be distinguished per user-class.

Carpooling represents another requirement, which was also mentioned in the previous section. The way carpool can be treated is through mode choice applied to the demand of vehicles, or more extensively in the form of carpool formation when dealing with individual travellers, providing also details on vehicle occupancy as output.

The requirements described so far, in order to be met considering peak changes in toll levels, the time component needs to be considered explicitly. This leads to the general requirement consisting of the use of a dynamic traffic assignment model. This provides the information of the traffic situation on each link in each instant allowing the network characteristics to be time dependent and in consequence allowing time-varying pricing.

Last, but not least, reliability is mentioned on several occasions as an important valuation and benefit when considering the implementation of HOT-lanes. In order to reflect the potential users' valuation of travel time reliability and the influence it has on the overall benefits of the implementation, the model should have the capability to represent and predict travel time variability in accordance with the observed occurrences in actual traffic situations.

A few desired elements are left out, mainly to keep the simplicity of the model at acceptable levels required by a quick methodology, in the form of departure time consideration and elastic demand. The departure time representation would have provided the means of assessing the capability of a HOT-lane to push demand off-peak.

## Model framework

The previously addressed model inputs, outputs and requirements are included in a general modelling framework that is meant to incorporate all the desired aspects regarding a simulation procedure for a HOT-lane scenario. The framework presented in Figure 3.12 serves the role of guideline either for the choosing an existing model to which additions are made or for a ground up purposely built traffic simulation model. The representation is made so that it presents most of the needed elements separate, but depending on the choices made in terms of modelling procedure several aspects can be addressed simultaneously.

The framework is composed of two parts, the first one representing the initiation of the iterative procedures, needed for determining the starting traffic conditions essential for the models that represent specific behavioural choices.

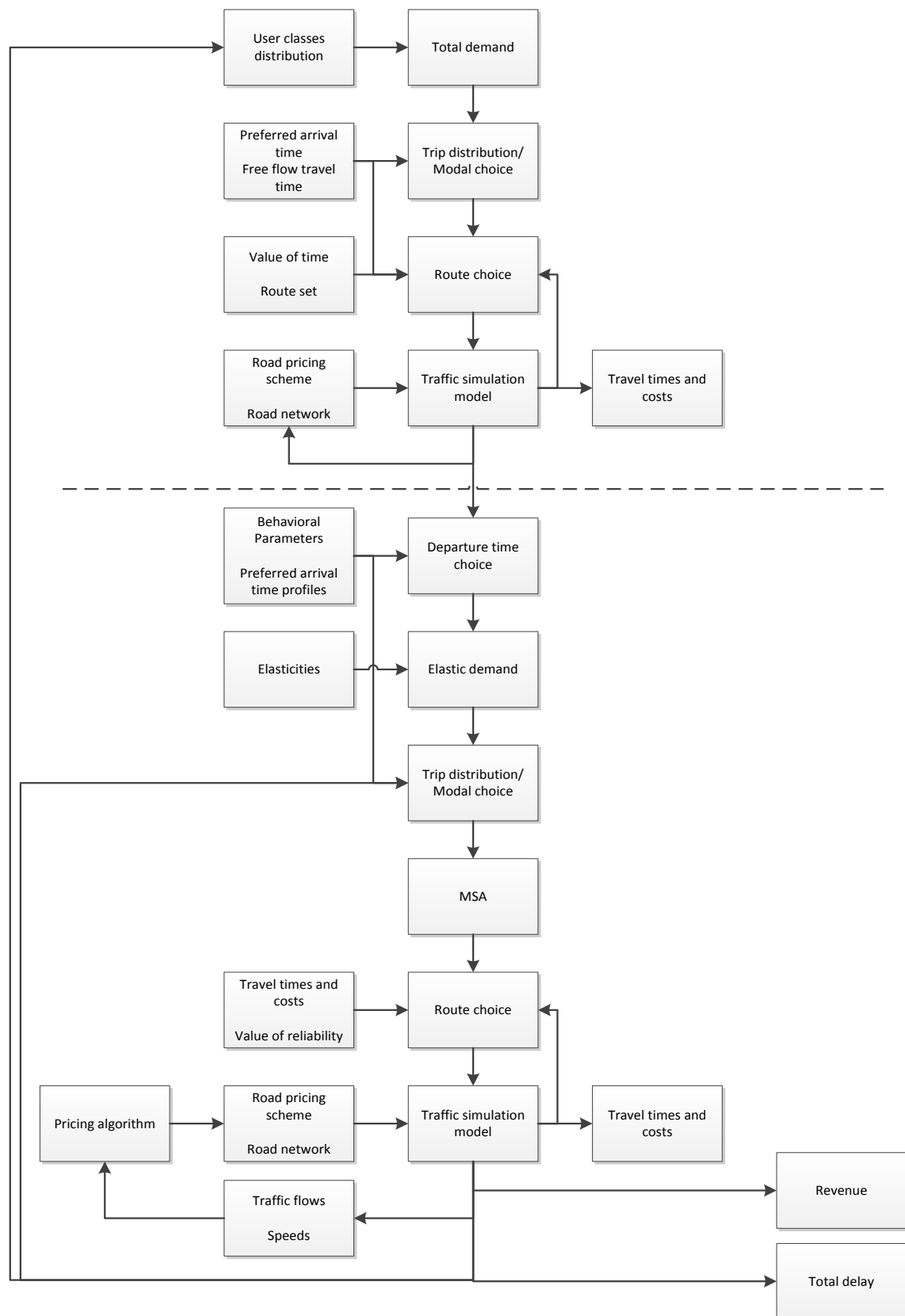
The inclusion of departure time choice is made with the purpose that the model can be able to represent the occurrence of off-peak travel, if necessary. In the same time this can allow the reflection of reliability valuation through the consideration of a schedule delay method.

If the route choice and departure time choice are included as specific choice models, the elastic demand module is included to be able to determine the changes in demand levels, as simple as possible. It can also serve as a direct input for the variation of demand.

The resulting modelling framework should be able to forecast the effects of dynamic pricing on route, departure time and demand levels for different user classes. The setup of the framework is meant to be flexible so that the different components can be changed according to preference of application. A future development could be to consider simultaneous route and departure time choice to incorporate complex discrete choice models.

It is also assumed that the extended dynamic traffic model should also be capable of handling flow or speed dependent road pricing measures.

As a conclusion, the traffic simulation model part of the methodology provides a framework that addresses most of the possible developments and inclusions into the simulation procedure. It is intentionally left general in order to be replaced or adapted accordingly to specific purposes or preferences.



**Figure 3.12 Overview of a modelling framework (adapted from (Amelsfort, 2009))**

### 3.4.4 Evaluation and interpretation

Transportation projects are typically evaluated or prioritized based on multiple evaluation criteria. These can range from engineering-related measures (pavement condition, useful life, structural condition) to safety (accident rate); travel efficiency (reduced delay); environmental (emissions, wetlands impacted); and impacts to the economy. These also apply to HOT-lane projects, whether they are quantitative or qualitative assessments.

Most tolling research studies have focused attention on the following economic concepts:

- Revenue generation provided by tolled facilities and comparing revenues to costs (broadly defined) – This is an important *financial feasibility* issue for both public and private agencies considering tolling
- Benefit/cost analysis from a social accounting and economic efficiency perspective – A very important concept explored within the project evaluation component of the literature review
- Economic impacts of constructing or implementing a tolling facility – These evaluations examine the economic contribution of short-term spending effects on transportation (tolling or non-tolling).

From the perspective of a transportation agency, toll revenue is a benefit. It provides a revenue stream that the agency can use to offset capital or operating costs on tolled or even non-tolled facilities. From the perspective of a traveller who pays the toll, it is a cost. Travel choices are dependent on a variety of travel time, cost, and reliability factors; and adding a toll to an existing roadway or using a toll on a new facility is a cost to the traveller. In social cost/benefit accounting, the toll is simply a transfer from individuals to the public sector, with the common assumption that the public sector can do similarly welfare enhancing activities. For individuals, however, the benefits in travel times, reliability, and accessibility are partially offset by the size of the toll.

Social and economic cost-benefit analysis comes together within the context of demand elasticities where (unlike traffic effects) there seems to be a persistent tendency to underestimate the elasticity. The result can be to underestimate the effect on traffic, and overestimate the revenue. Despite theoretical feasibility the public is unlikely to accept a scheme that is sold purely on the basis of economic cost-benefit analysis. Most people would wish to see the benefits presented in the form of revenue which can be used for something tangible.

There are a set of benefits and costs that should be considered and, if possible, quantified in most tolling or congestion pricing cost benefit evaluations (Cambridge Systematics, 2007).



### **Benefits**

- **Travel time savings** – In many cases, the largest direct benefit of tolling or congestion pricing projects is reflected in terms of reduced travel time. This benefit needs to consider the value of time by different trip purposes and vehicles.
- **Reliability** – As discussed in the literature review, reliability and the reduction in travel time variability are another key benefit of road pricing (Warffemius, 2005).
- **Air and noise emissions** – Similarly, reduced highway trips will typically reduce air and noise emissions, and standard parameters are available to quantify these impacts.
- **Reduction in delay** – Through the accounting for travel time delay (vehicle loss hours) another benefit to the vehicle user can be determined while providing insight on the level of congestion.
- **Revenue** – The revenues is estimated considering the pricing strategy, traffic volume and number of exemptions according to operating strategy

### **Costs**

- **Implementation and/or investment costs** – Whether it be the construction of a new tolled facility or implementing a tolling scheme on existing facilities, there inevitably will be an up-front capital cost to implementation. The costs reflect the changes of markings, eventual barriers, new signings and ITS installations.
- **Operations & maintenance costs** – There are typically annual costs associated with operating any tolling scheme, even one that does not require toll both collectors. This can be in the form of maintenance and purchases of new equipment, compliance and monitoring costs, etc. The fixed costs can include things such as back office operations (monitoring, customer service, handle transactions, etc.). The variable costs address things such as toll transactions through the transponders, toll violations, etc.
- **Deterred drivers** – For those travellers who change mode and decide not to drive due to a toll or congestion pricing policy, there is a cost even if they can substitute transit or other modes to continue making their trip. From an economics perspective, the toll increases the cost of highway travel; and using a demand curve representing the range of travellers and willingness to pay, those that switch to another mode are using a second-best option.

Aggregate social welfare is not something that can easily be measured, thus in practice other HOT lane pricing objectives such as revenue generation or speed are likely to be given greater attention. It is generally assumed in the congestion pricing literature that the toll revenue generated from congestion pricing will be returned to citizens through tax reductions or other

means. As a result, the toll cost experienced by users is exactly offset by the redistribution of toll revenue back to citizens in welfare calculations. In conclusion, the collection and redistribution of revenues cancel each other out and are ignored in welfare calculations.

In the Netherlands, improvements in travel time reliability, in case of automobile traffic, have been added to CBA by means of a 25% surcharge on the travel time gains (Besseling, 2005; Zwaneveld, Romijn, Renes, & Geurs, 2009). It is possible that this 25% surcharge results in an underestimation. Then again it is also possible that existing valuation metrics for travel time already include effects on travel time reliability, making the 25% surcharge an overestimate (Zwaneveld, Romijn, Renes, & Geurs, 2009).

The values for each of the cost and benefits are to be established per specific case and according to available estimates at the time of the calculation. As sources, a correlation can be made with the values encountered in existing and running HOT-lane projects in the U.S., while capital costs can be estimated through the sum of the components included.

### **3.4.5 Overview of the methodology**

Due to the extensive coverage of most of the aspects related to the implementation of a HOT-lane, the levels of details provided by some of the elements included in the methodology vary. Thus an overview of the methodology is provided to summarize the inputs and outputs of each module and how are they correlated amongst each other.

The initiation of the methodology starts with the consideration of the array of goals and objectives presented in Table 3.1 and Table 3.2 from section 3.1.4. These provide the premise for selected a preliminary list of problem areas (corridors) that through considerations such as sufficient length for achieving significant travel time savings that can contribute to their feasibility as potential candidates.

#### **Phase 1**

The first phase of the methodology as described previously includes an analysis of different locations and from a considered list of potential candidates provides the locations that are most likely to ensure a successful implementation of a HOT-lane facility.

#### **Determinants and indicators**

The major determinants for the analysis of the locations are related to the highway section's physical attributes and traffic conditions. It can be said that even the location itself is one of the major determinants, as it dictates which areas of interest it serves (origin and destination as points

of interest) which in turn translates into the presence of a specific travel pattern and even trip length distribution. These determinants are represented through the following selected criteria:

- Reliability
- Demand
- Congestion
- Physical attributes

The previous categories have their corresponding possible indicators. They are referred as possible due to the fact that is not mandatory that all mentioned parameters/indicators are used in the analysis. The varied indicators are as follows:

- Statistical range indicators ; Buffer time indicators ; Tardy trip indicators ; Probabilistic Indicators ; Skew-width indicators
- Traffic flows (vehicles per hour); Trip length distribution ; Carpooling demand (Vehicle occupancy)
- Vehicle loss hours ; Travel times ; Travel speeds
- Road-way space (corresponding width/lane) ; Frequency of on/off ramps; Adjacent space available for limited expansion

For each category of criteria a rating is made based on absolute values. The result of that rating is then combined with the weights determined and established in 3.3.3, resulting in an overall ranking among the locations (corridors) present in potential candidates list.

### **Data and tools**

The data used for the analysis can include as source both historic data from detector loops from the road network or forecasts provided by the national or regional traffic simulation models. The raw data obtained from detector loops can be analyzed directly with software programs such as MathWorks – Matlab or obtained and manipulated through specially developed programs such as Dante or Monigraph. Monigraph (Taale, 2006) is a tool that processes, analyses and visualizes monitoring data from specific data files produced the national monitoring system (MoniCa or MoniBAS). Based on the flows and speeds the travel time for specific highway sections can be calculated with the use of several methods such as instantaneous speeds or trajectory method either based on piece-wise constant speeds or piece-wise linear speeds (Van Lint & Van der Zijpp, 2003). Dante is a Dynamic Geographic Information System (DGIS) designed to work with large and heterogeneous dynamic datasets. It is a software platform that allows users to easily interact with data in both space and time.

## Phase 2

The second phase is more extensive than the previous ones. It contains the development of scenarios for different implementation setups, a traffic simulation module providing a modeling framework as guideline for the inclusion of a model and last but not least the evaluation of the resulting implementation setup.

### Determinants and indicators

In terms of influencing or determining factors, it is first derived from the previous phase the corridor characteristics dictate the choice of design elements such as lane separation (barriers) and access points. Another transferred influence is that of policy goals and objectives that influence the choice of the pricing strategy (scheme).

Based on safety standards available for specific regions, the road space available may dictate the choice of type of lane separation thus imposing a number of trade-off, as presented in Table 3.6, such as limit of speed differences between the facility and the general purpose lanes or limitations on the number/location of access/egress points. This is also presented in the analysis of interaction between determinants in Table 3.8, which show that the cross-section of the road-way and the lane separation can have an influence on HOT-lane utilization, safety and even the travel time and willingness to pay of the potential users.

In the scenarios module presented in section 3.4.2, we can observe as a determinant the pricing scheme selection based on the influence of the considered policy goals and objectives. This results in the selection of a pricing method such as:

- Flat toll rate (static)
- Time-varying toll (static or dynamic)
- Self-adapting toll according to occurring speeds and flows on the corridor (dynamic)

The suitability of the pricing scheme (methods) is determined with the use of simulation traffic model and its results are evaluated according to the following main competing objective functions:

- Maximize vehicle throughput
- Minimize total travel time (time, costs, lost)
- Maximize revenue
- Minimize travel time variance
- Maintain level of service

The indicators used are generally everything considered output from the traffic simulation model and they can include the following: Traffic flows, traffic speeds, Travel times, travel costs, total delay, revenue, etc.

### **Data and tools**

The data used in this phase can be derived from the same sources mentioned for the initial step of the methodology. It comes in the form of travel demand, either directly from the national or regional traffic models and comprised based on a combination of surveys and historic data. The sources depend largely on what is adopted in the place of the guideline modeling framework presented in section 3.4.3 through Figure 3.12 and they should be in line with what was described under model inputs in the same mentioned section.

As for tools, these are represented only by the chosen or developed traffic simulation model.

### **3.4.6 Conclusions**

The methodology portrays a comprehensive coverage of the aspects regarding the implementation of a HOT-lane. Although extensive in form, the levels of details included within its elements vary largely.

The second phase especially provides the flexibility necessary for the inclusion of specific preferences depending on the extent of the study in which it can be applied. The scenarios/implementation setups module makes possible, with the help of the simulation results, to interpret according to specific needs the interaction between the different design elements and consideration that compose the specific scenarios.

In order to provide further insight into the proposed procedures the methodology is applied in the form of a study mainly addressing the Randstad area. In the following report sections, after the analysis of specific locations a case study is set up and an existing model is adopted and adapted for the use of scenarios and final implementation setup evaluation.

## 4 Locations analysis

This section of the report covers the first phase towards assessing the suitability of an implementation by identifying and evaluating possible locations. It is also part of the initial evaluation done with the help of the proposed methodology. Through the use of predetermined criteria the module can assess potential candidate locations. One of the locations ranked in Phase 1 will be the subject of a case study set up with the use of Phase 2 from the methodology.

### 4.1 Data sources

Data sources are presented for each of the indicators corresponding to the criteria used in the assessment of the locations.

#### 4.1.1 Congestion

As mentioned previously in subchapter 3.3.2, the desired conclusion of applying the criteria accounting for presence of congestion is derived from previous studies. The selected study for this purpose comes from TNO, dates from 2011, and studied the different types of congestion in the Netherlands. Although there is data from RWS which classifies the most congested areas, corridors, etc. the TNO study categorizes them into different types and tries to improve the resolution of the data used to classify them.

A particular aspect of the study was the way in which the lost vehicle hours were calculated. This had been done using a fixed reference speed of 100 km/h that was considered for the whole highway network, without taking account of zones with different speeds. This time the lost vehicle hours were determined more specifically by first calculating the normal speed on a particular section of highway in 'quiet' periods, the 'free flow speed'. The study revealed that this makes possible to determine the delay as a result of traffic jams per road section more precisely. This is a calculation method used for the determination of lost vehicle hours in a different way than in the method that Rijkswaterstaat uses in congestion monitoring. There are more differences in the calculation, but the most important differences are the choice of the reference speed, and whether or not inclusion of certain parts of the network, such as on/off ramps.

The top locations where there is occurring congestion were categorised in three tops according to the type of congestion. This resulted in:

- Top Shockwave locations consisting of sections with the most lost vehicle hours accounted to the formation of shockwaves
- Top Incident locations that were mainly comprised of the ring roads around Amsterdam and Rotterdam where most vehicle hours were lost due to occurring incidents

- Top Infrastructural bottleneck locations where congestion occurred due to flows that often exceed the available capacity

The study used detector loops data measured in the period May 2010 – April 2011 that was processed and automatically analysed with the combination of TNO's software tools, RAMON and ATOL. RAMON makes it possible to quickly identify traffic jam locations, while ATOL can automatically categorises them.

The downfall is that the congestion presence criteria is considered the most important and no weight can be assigned to it due to the fact that the selection is done beforehand and independent from the other criteria. This situation can be considered less desirable depending on the main policy goal.

#### **4.1.2 Traffic conditions data**

As a substitution the reliability indicators set in section 3.3.2 will be used for assessing the traffic situation on the candidate corridors. The data necessary for applying the mentioned criteria is obtained using the tool Dante. Dante is a Dynamic Geographic Information System (DGIS) designed to work with large and heterogeneous dynamic datasets. It is a software platform that allows users to easily interact with data in both space and time. More specifically Dante is a software environment in which you can easily work with dynamically changing traffic networks and heterogeneous dynamic sources of traffic and other measurements. Dante is equipped with a set of plugins that allow data to be visualized, searched, edited and transformed. Dante is pre-configured with a dynamic road network of the Dutch Motorways and in total 16000 lane loop detectors. A history of these detectors exists from 2008 onwards.

## **4.2 Candidate Corridors for implementation**

Based on the results of the study mentioned previously the initial list with the candidate corridor is put together. The detailed distinction between different types of congested corridors made easier the exclusion of possible "problem" candidates that were considered unsuitable of the implementation of the proposed concept. Nevertheless, a few exceptions were made as certain corridors appeared in all the three top lists due to their overwhelming traffic. Their inclusion was considered for comparison purposes with the other more eligible candidates that could point at specific differences worth taken into consideration for further studies.

#### **4.2.1 Problem areas**

The three different Top15s which include 28 distinct corridors form the base from which the candidates list is comprised. These candidate corridors will be further subjected to a more detailed analysis using the proposed selection indicators.

As mentioned in previous chapters, one of the criteria used for a right of the start exclusion was the corridor's length. The value considered minimum for assuring enough theoretical travel time savings for the project to be feasible is 10 km. Although some of the studies pointed out shorter distances, due to the uncertainty of the correlation between different projects the larger value of 10 km was considered sufficient to cover the potential travel time gains necessary.

Other corridors, as also proposed in subchapter 3.3.2, were excluded on the basis of the combination between limited length and the presence of major highway connections along them. Besides the major physical limitations that would need to be surpassed, the implementation of the HOT-lane could pose extra safety issues due to the weaving occurring on top of the already existing major interweaving flows.

Last, but not least, the congested corridors, which have as main cause the frequent incident occurrence, were excluded, with some exceptions. The reason of their exclusion has to do with safety concerns. As it was discussed previously, the introduction of the HOT-lanes on existing roadway space brings the need for extra safety considerations, which means that the pre-existing incidents problem on a certain route would only complicate things. Regularly occurring incidents are also one of the main factors influencing travel time variability, hence the reliability indicators of that corridor. Excluding the corridors most affected by incidents can lead to more reliable values of the indicators used further in the analysis.

One other factor that was taken into account in the pre-selection is the program policy that has been underway for the past 4 years: "Spoedaanpak: alle wegen sneller aanleggen" (Ministerie van Infrastructuur en Milieu, 2008). This aimed at the major problem corridors and at the end of May 2011, 30 major solutions were under completion (Rijkswaterstaat, 2011). Nevertheless, several others are still underway spreading over a period of time until 2014. In the reports of Dienst Verkeer en Scheepvaart (DVS) it can also be observed that many of the corridors present in the tops used in this project are affected by the construction works that are underway (Rijkswaterstaat Dienst Verkeer en Scheepvaart, 2012). Using the information from the quarterly traffic report form DVS, the corridors that still had construction works underway throughout 2011 were excluded from the candidate list. Although it was observed that the corridors in question have been part of the top problem areas also prior to the undergoing construction works (De VerkeersInformatie Dienst, 2008), the reliability indicators would still be influenced. The resulted list, after these initial considerations, is presented in **Table 4.1**. Marked with red are the corridors excluded due to road works influence and with orange the ones that are kept for analysis purpose although they are part of the incidents influenced congestion top.

The table provides many details that were included in the previously mentioned study that produced these results. For instance, under the first three columns of values the S/In/Infra marks the differentiation on the cause of the vehicle loss hours (VLH), even in length representing the extent of congestion in under different circumstances.



**Table 4.1 Pre-selected candidate corridors considered for HOT-Lane implementation**

Name	Delimitations	Length	(Km)	VLH	(x1000)	VLH/Km	(x1000)	Rush-hour lane
		S/In/Infr		S/In/Infr		S/In/Infr		
<b>A28R</b>	Utrecht-Centre -> Amersfoort	19		265		14		
<b>A12R</b>	Waddinxveen -> The Meern	19/16/13		175/48/412		9/3/32		17 km Woerden - Gouda
<b>A15L</b>	Gorinchem -> Papendrecht	15		112		8		~5 km Papendrecht - Wijngaarden
<b>A1R</b>	Watergraafsm. (A10) -> Muiderberg (A6)	10/9/11		110/48/465		11/6/42		~6+2 km Watergraafsm. - Muiderberg
<b>A27L</b>	Eemnes -> Bilthoven	12		94		8		~6+5+2 km Heteren-Vaalburg -Ewijk
<b>A2L</b>	Kerensheide (A76) -> Roosteren	11		80		7		~17 km Vonderen-Urmond
<b>A13R</b>	Ypenburg (A4) -> Kleinpolderplein (A20)	14/12/14		193/52/383		14/4/28		~5 km Berkel en Rodenrijs - Delft Zuid
<b>A1L</b>	Bussum -> Diemen (A9)	8/11/11		112/47/375		14/4/34		~6+2 km Watergraafsm. - Muiderberg
<b>A27R</b>	Everdingen (A2) -> Veemarkt	22		87		4		
<b>A50L</b>	Waterberg (A12) -> Ewijk (A73)	24		164		7		
<b>A12L</b>	Veenendaal -> Driebergen	16/12		89/379		6/30		~ 8 km Veenendaal - Ede
<b>A16L</b>	Ridderkerk South (A15) -> Pr. Alexander	10/11		79/26		8/2		
<b>A4R</b>	Roelofarendsveen -> Zoeterw.-Village	11/11		49/619		4/56		

#### 4.2.2 Data analysis

From the list presented in 4.2.1, **Table 4.1**, only 8 corridors were considered suitable for a detailed analysis. The delimitations for the corridors remain the same, as they are representative for the specific sections, but for comparison considerations the lengths of the analysed sections were shortened so that all the lengths are as close as possible. This was done so that the corridors have almost the same free flow speed so that the reliability indicators values are comparable. The resulting corridors are listed in Table 4.2.

**Table 4.2 Selected corridors for analysis (screening)**

<b>Name</b>	<b>Delimitations</b>	<b>Length (Km)</b>
<b>A13R</b>	Ypenburg (A4) -> Kleinpolderplein (A20)	12.3
<b>A15L</b>	Gorinchem -> Papendrecht	12.9
<b>A1L</b>	Bussum -> Diemen (A9)	12.9
<b>A1R</b>	Watergraafsm. (A10) -> Muidenberg (A6)	12.4
<b>A27L</b>	Eemnes -> Bilthoven	13.2
<b>A27R</b>	Everdingen (A2) -> Veemarkt	11.2
<b>A28R</b>	Utrecht-Centre -> Amersfoort	11.9
<b>A2L</b>	Kerensheide (A76) -> Roosteren	11.8

As mentioned previously, the dataset used for this analysis is in the form of detector loops data (MoniBas & Monica) together with the computed travel times, on a 6 minutes aggregation interval, and was obtained through the use of Dante. The data is for the year 2011 with the exclusion of weekends and public holidays, as demand patterns are usually different on those days compared to regular weekdays (Peer, Koopmans, & Verhoef, 2010). The summer months (June, July & August) were also excluded as effects on the travel time distributions were believed to be more smoothed out when including these months (in 't Veld, 2009).

In the next section each corridor will be described, together with the individual interpretation on the results of their analysis. The details discussed address the main criteria for selection. In the matter of demand, only the traffic flows will be mentioned as for the characteristics of trips and potential users are addressed in the modelling section of this report.

### A13R Ypenburg (A4) -> Kleinpolderplein (A20)

On this stretch a combination of measures has been used to improve the flow. In the evening peak there is a shockwave from the traffic on the A20 (accounting for 30% of the congestion). Interestingly, the weaving movements at the beginning of this trajectory at the connector on the A4 is not a problem, but the combination of the limited amount of merging traffic at the flyover ramp Delft North and the viaduct cause a lot of traffic jams.

On the analysed length of 12.3 kilometres, there are four on/off ramps locations, excluding the end interconnections with the A4, respectively A20, out of which two are for interconnections with national roads (N470 & N209) and two are accesses to the city of Delft. As for the matter of additional lanes it was observed that on some sections of the corridor there is little space available (infrastructural bottleneck effects).

This corridor is one of the candidates that appear in all the top lists of congested highway sections used in this study, being affected by all the types of congestion problems, including incidents.

The traffic flow over the period of a day is portrayed in Figure 4.1, together with the corresponding standard deviation. The presented distribution is averaged across all days considered for the year 2011, and across all detectors along the studied corridor. It can be observed that flow reaches a maximum of ~6000 vehicles/hour in the morning peak, stabilising for the mid-day between 4000-5000 while maintaining similar values throughout the evening peak. The lower flows in the evening peak can be attributed to the shockwave coming from the A20. The resulting daily average for the A13R corridor is 3316 vehicles/hour.

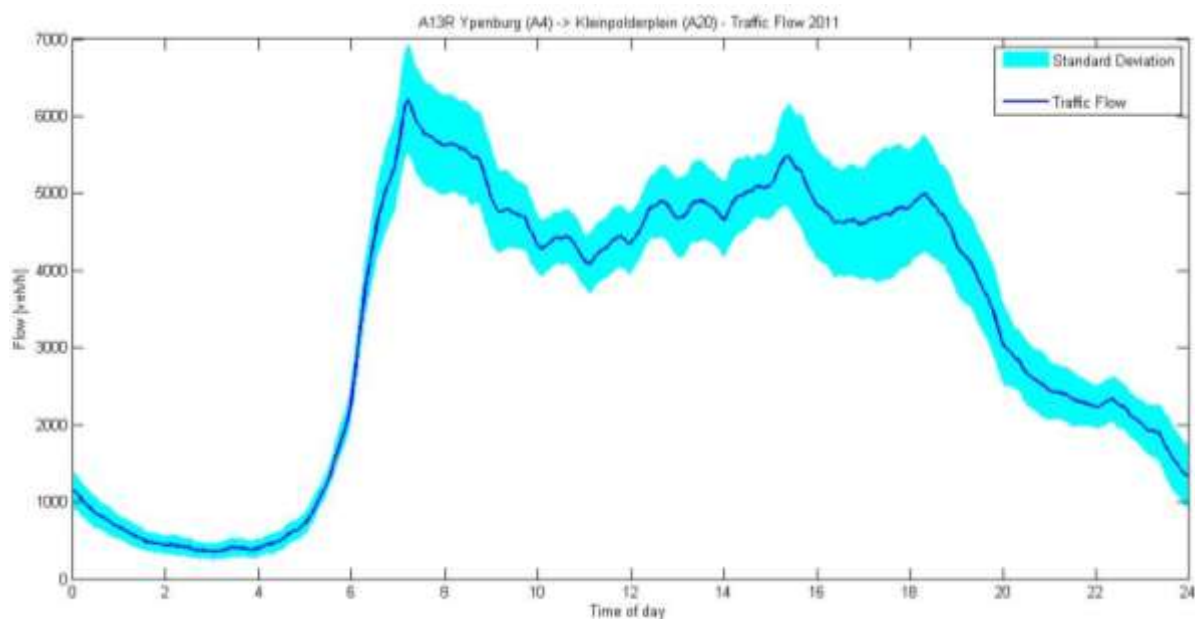
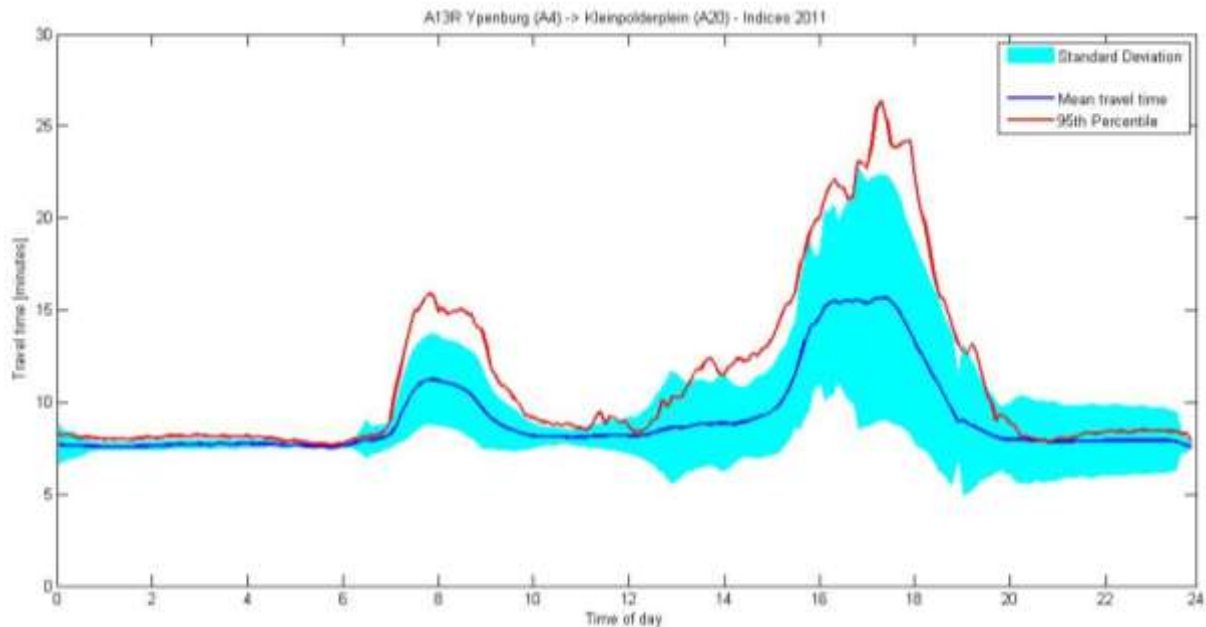


Figure 4.1 A13R Traffic flows 2011

The travel times computed and present on this corridor are portrayed in Figure 4.2. It can be observed that the average travel times during the evening peak are 50% higher than in the morning and almost double when looking at the 5% worst travel times recorded (95<sup>th</sup> Percentile).



**Figure 4.2 A13R Indices 2011**

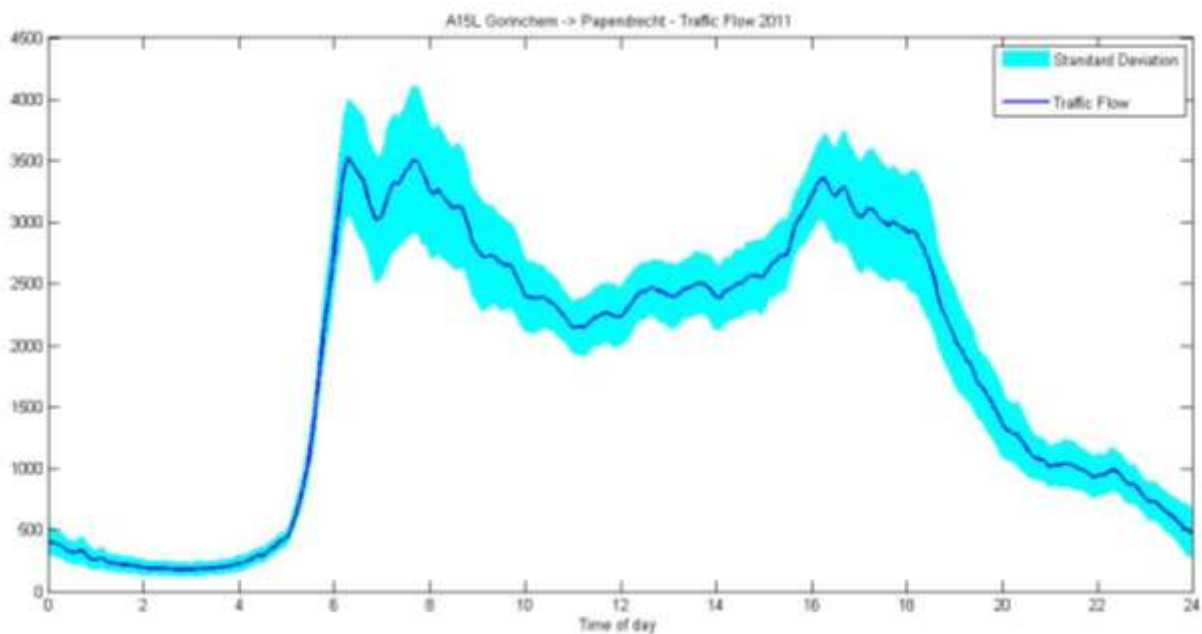
When looking at the distribution of the main reliability indices considered, the planning and the buffer index, it can be observed that the planning index has an exaggerated representation of the distribution while the buffer index has a more spread detailed representation. Although the monthly mean travel times show a stable trend throughout the year, it is not the same case with the worst travel times and the buffer indices. The monthly 95<sup>th</sup> percentiles show that during the evening peak the travel times can be as much as three times higher than in the morning. It is almost the same case with the buffer index. The buffer index is considered most representative for selection purpose and its values will be used further on. Also due to the varied and large differences across the year between peaks the buffer index will be considered in average values of a day, separate for morning and evening peak as well as for the whole day.

#### **A15L Gorinchem -> Papendrecht**

The corridor with the length of 12.9 kilometres is part of the top corridors suffering from shockwave effects accounting to most of the occurring congestion. This can be attributed to the Noordtunnel and the traffic situation around Ridderkerk. Along its route there only three access points for on/off traffic, two accounting for the villages with access and one for the connection with national road N482.

The road space is generally scarce, most of the corridor being in the 2x2 lane configuration and a shoulder.

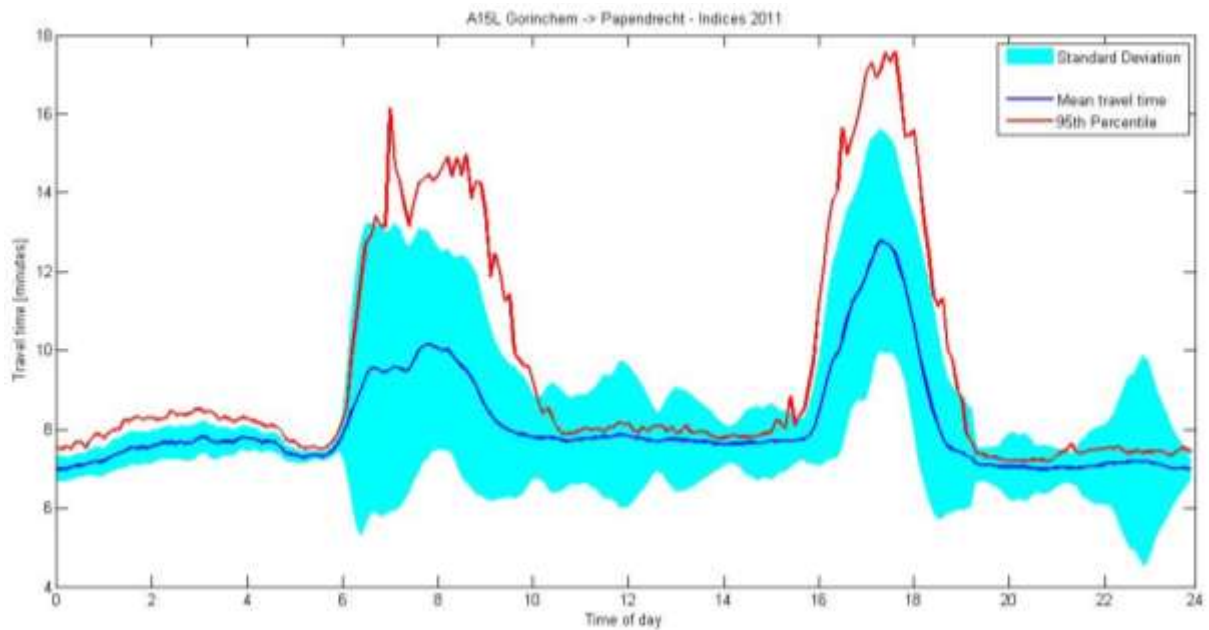
The distribution of flows over a day, on average for 2011 as seen in Figure 4.3, shows slightly higher morning peak flows that dissipate rather slowly at not so low values, mainly due to the shockwave effects present on this corridor. The resulted average daily flow has a value of 1830 vehicles/hour.



**Figure 4.3 A15L Traffic flow 2011**

The distribution of the average travel times encountered, together with the worst represented by the 95<sup>th</sup> Percentile, are portrayed in Figure 4.4. Although the morning peak spreads over a longer period it looks like the evening peak suffers more severely from congestion. The worst registered travel times have almost the same value between peaks, but more vehicles suffer from congestion as the mean travel time is a higher in the evening.

From the reliability indices point of view, the planning and buffer index, the traffic situation looks rather different depending on the indicator. While the planning index shows the same situation as described previously, the buffer index shows an almost equal representation of the two peaks. It can be assumed that the sharp increasing flows and travel times from the morning peak have the same effect on reliability as the same high travel times endured by more vehicles. Across the whole year, the mean travel times are consistent for the evening peak, but with a slight variation for the morning peak. Both monthly representations, over the whole year, of the buffer indices and the 95<sup>th</sup> percentiles show a rather hectic variation during and in between the peaks which is mostly characteristic to shockwaves.

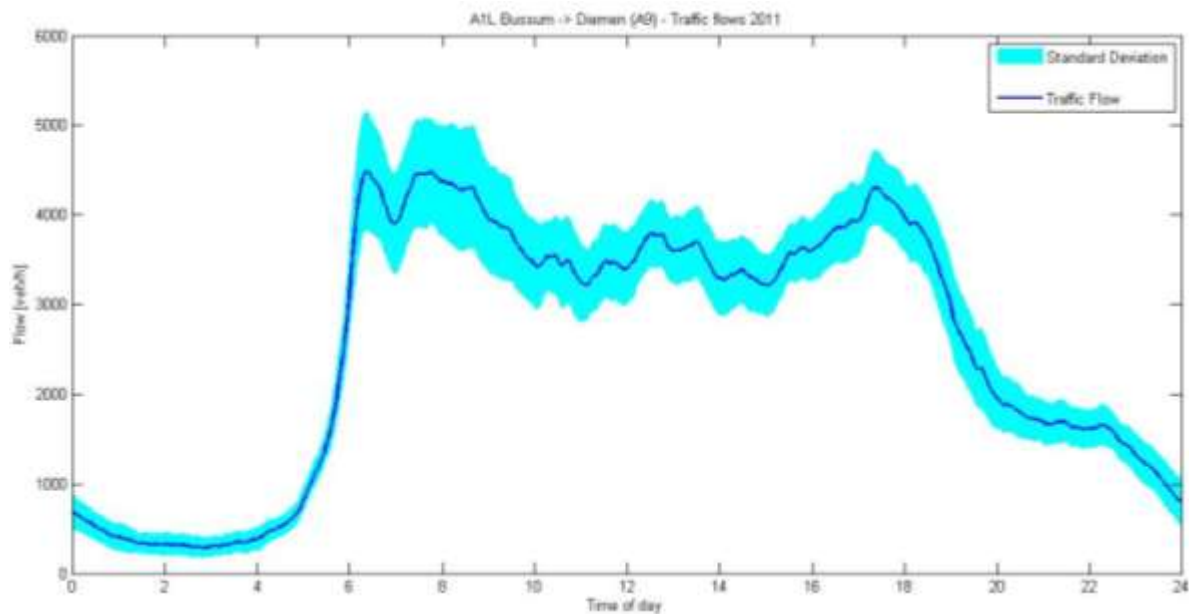


**Figure 4.4 A15L Indices 2011**

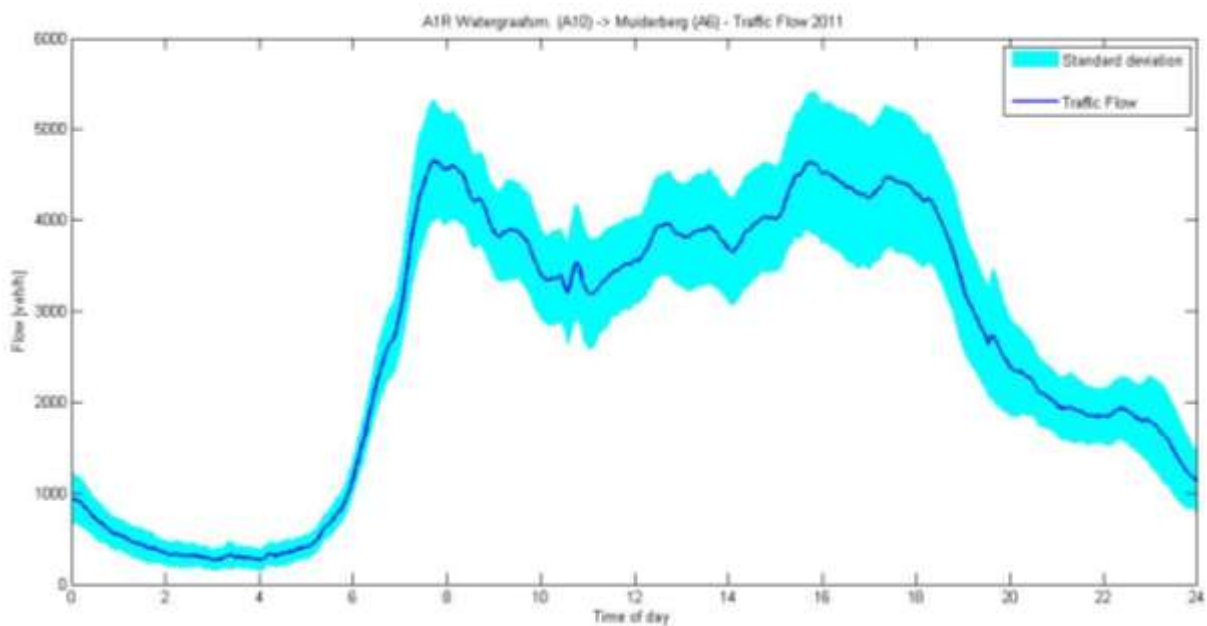
**A1L Bussum -> Diemen (A9) & A1R Watergraafsm. (A10) -> Muiderberg (A6)**

The two considered corridors represent both ways of the same section, which is one of main routes connecting Amsterdam and the “newly” developed urban area of Almere through the connection with the A6 and its “Hollandsebrug”. While the A1L is bringing commuters mainly to Amsterdam, the A1R is only heavily used in the evening, when the commuters return home. On this stretch there is a different peak pattern over the day to be seen. In the evening there is a problem with the flow commuters from Amsterdam to Almere, while in the morning no traffic jams occur. For this flow there are few alternatives. There remains a bottleneck upstream on the A9 at

the "Hollandsebrug".



**Figure 4.5 A1L Traffic flows 2011**

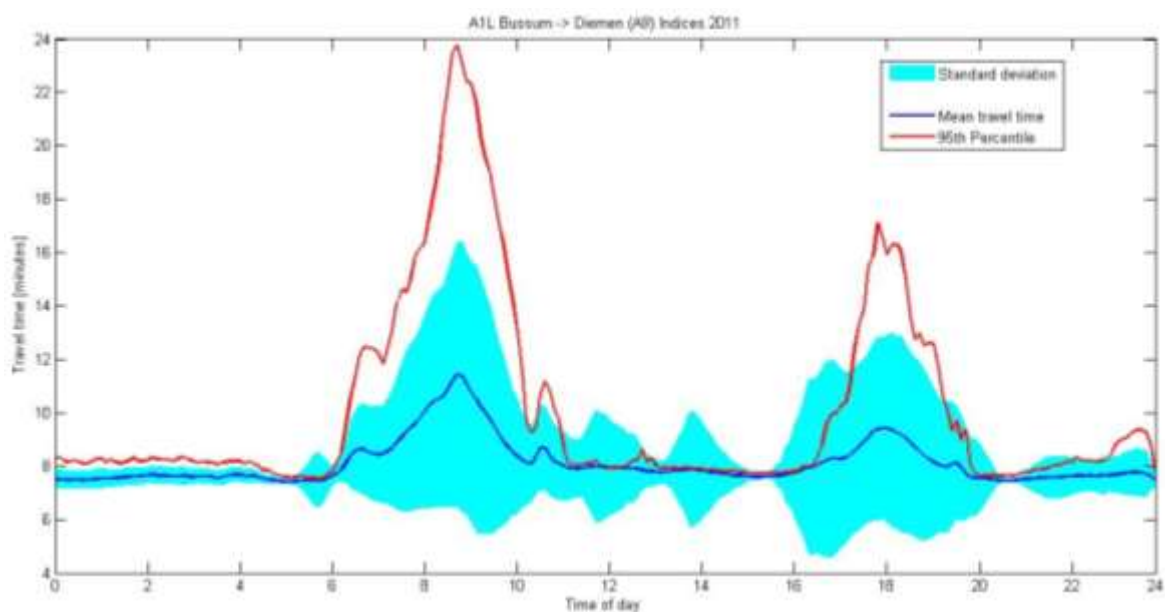


**Figure 4.6 A1R Traffic flows**

In Figure 4.5 and Figure 4.6 the flows for the two considered corridors are shown for the year 2011. For the A1L high traffic flows throughout the main part of the day with a longer morning peak, while on the A1R the morning peak has lower flows over a shorter time and in the evening peak the mirrored situation from the morning on the A1L. The average flows for a whole day on a yearly base are 2540 vehicles/hour and 2613 vehicles/hour, respectively for A1L and A1R.

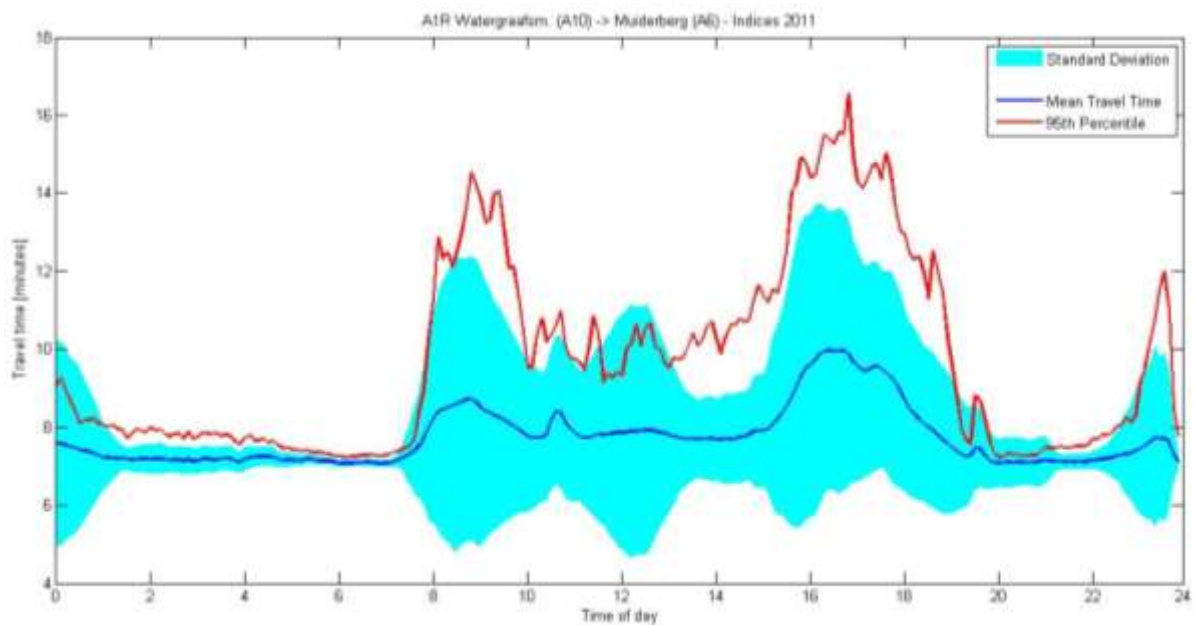
The roadway was recently enlarged to two lanes per way and there is a scarcity of available space for future enlargements. There are three main access points along the routes, two accounting for local connection to residential areas while the third represents the major connection with the A6 which is the main route for commuter using the corridor.

As for the travel times, the previous observations are endorsed by the distribution of travel time indices over they presented in Figure 4.7 and Figure 4.8. On the A1L the more congested morning peak can be seen, with a sharp increase in travel times for both mean and 95<sup>th</sup> percentile. As for the A1R a slight increase in travel times can be observed during the morning peak, suggesting a more free-flowing traffic, while during the evening peak an increase although not as high as the morning situation on the A1L.



**Figure 4.7 A1L Indices 2011**



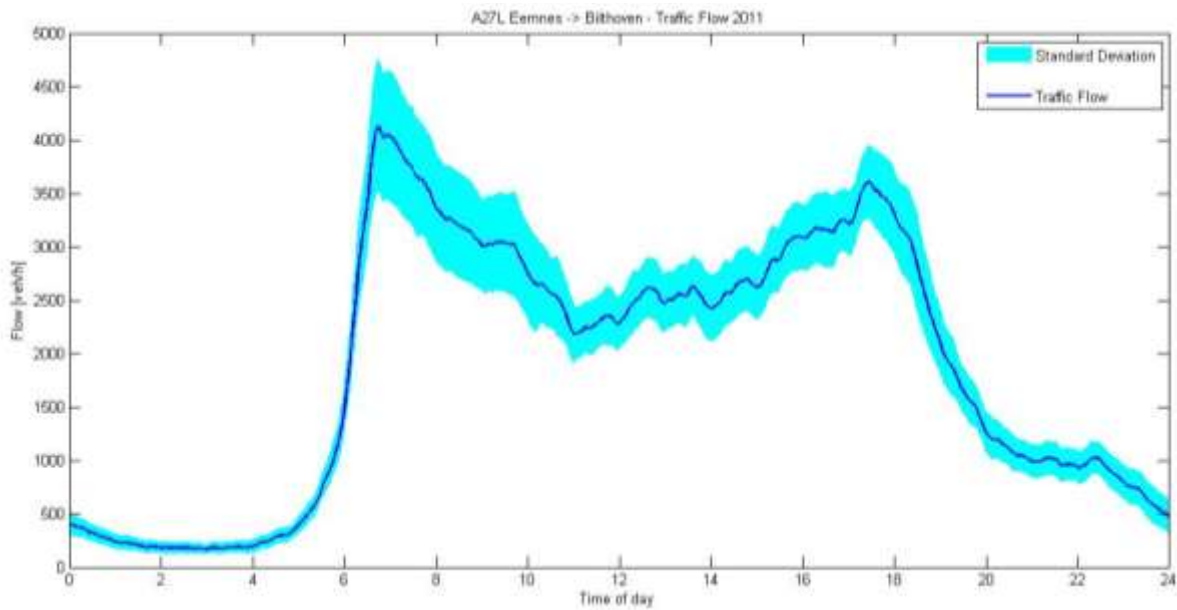


**Figure 4.8 A1R Indices 2011**

The reliability indices from the A1L appear to be almost the same in the form of the distribution shown. In the case of the A1R, the buffer index is showing a more even distribution over the day, while the planning index is showing more evident increase during the two traffic peaks of the day. The monthly mean travel times over the year appear to be consistent in trends, although with slight variations in maximums, although they vary more for the case of the A1R accounting for the low traffic during the morning peak that spread towards the evening one. The same pattern holds for both the representation of the 95<sup>th</sup> percentiles and monthly buffer indices.

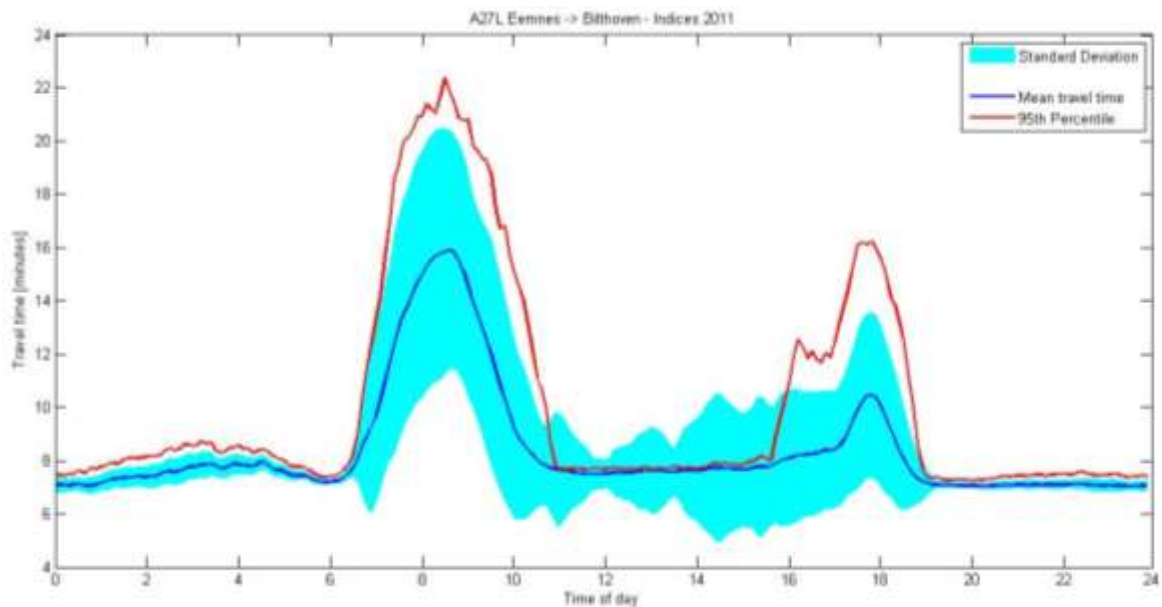
#### **A27L Eemnes -> Bilthoven**

This corridor with the length of 13.2 kilometres links the interconnection between the A27 and the A1 near Hilversum with the “central hub” city of Utrecht. This section of highway has two main access points, one connecting with the N201, the ring of Hilversum, and the other one connecting with the N234 at Bilthoven. The trends show a more accentuated morning peak with possible commuters going to Utrecht and a gradually building evening peak with slightly lower flows, as it can be observed in both Figure 4.9 and Figure 4.10. The monthly mean travel times appear to be consistent throughout the year, as well as the 95<sup>th</sup> percentiles which show a slightly different increasing rate towards the evening peak.



**Figure 4.9 A27L Traffic flow 2011**

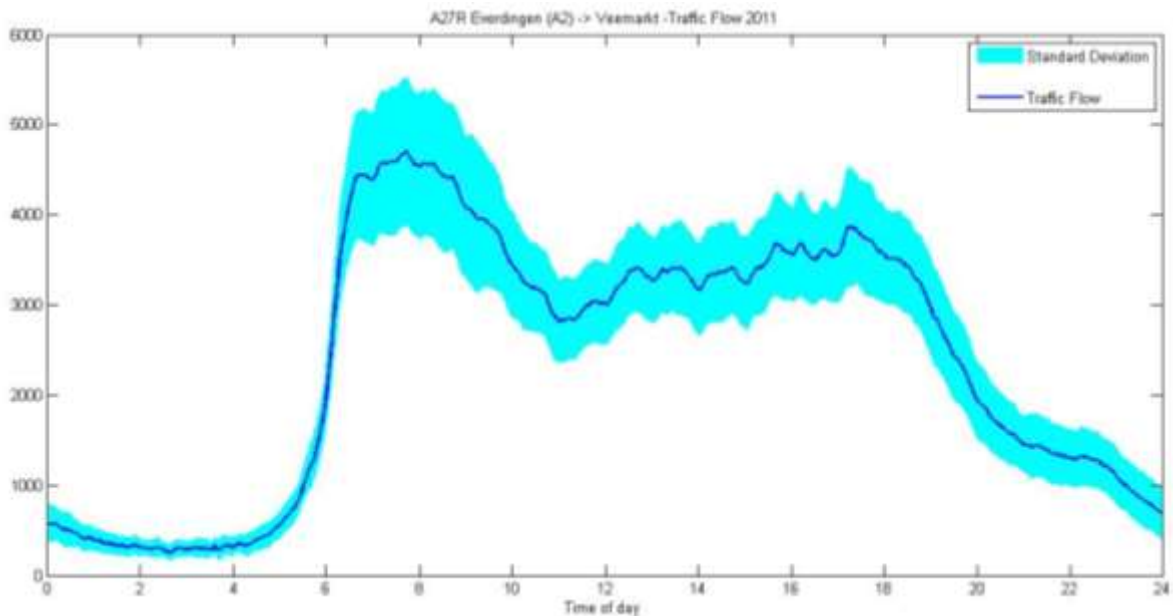
In term of reliability indices, the buffer index shows highly similar values for both daily traffic peaks with the morning one spread over a longer period than the evening, while the planning index is in line with the trends that appear in the case of the mean travel times. The monthly distributions of the buffer index over the year are consistent with the mean yearly one, as in the case of the mean travel times.



**Figure 4.10 A27L Indices 2011**

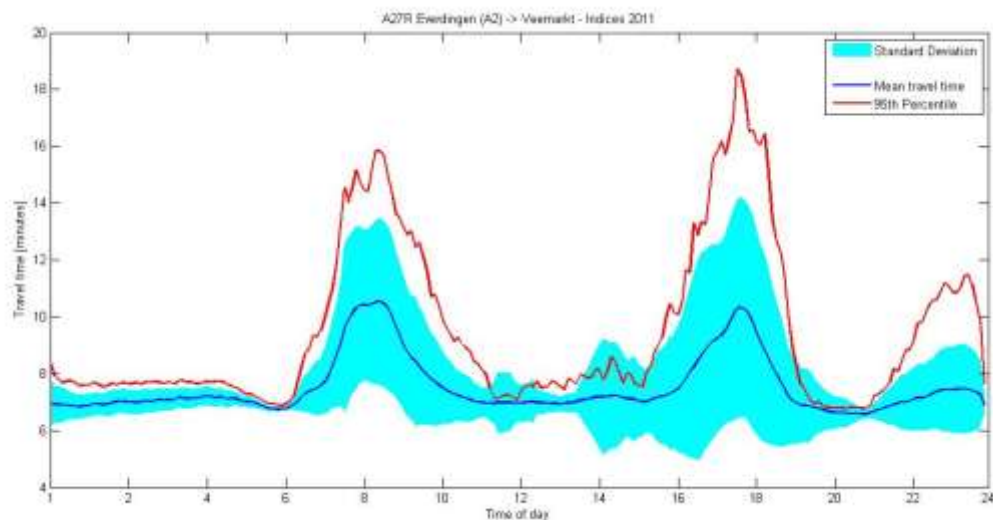
### A27R Everdingen (A2) -> Veemarkt

This corridor with the length of 11.2 kilometres is another section of highway linking Utrecht to the small cities surrounding it, such as Nieuwegein, Vianen and Houten, all of them representing the main major access points of this route. As the daily flow shows, there is a busy morning peak with Utrecht attracting its commuters, with a flat turnout for the rest of the day including the evening peak, as seen in Figure 4.11.



**Figure 4.11 A27R Traffic flow 2011**

Travel times show the same trend as described previously, although a more defined evening peak with almost the same values as the morning peak, but slightly higher, as seen in Figure 4.12. The monthly mean travel times and 95<sup>th</sup> percentiles paint a slightly different picture, with mean travel times showing much more equal values registered for both peak periods and the 95<sup>th</sup> percentiles showing worse times in the case with the evening peak spread over a longer period.



**Figure 4.12 A27R Indices 2011**

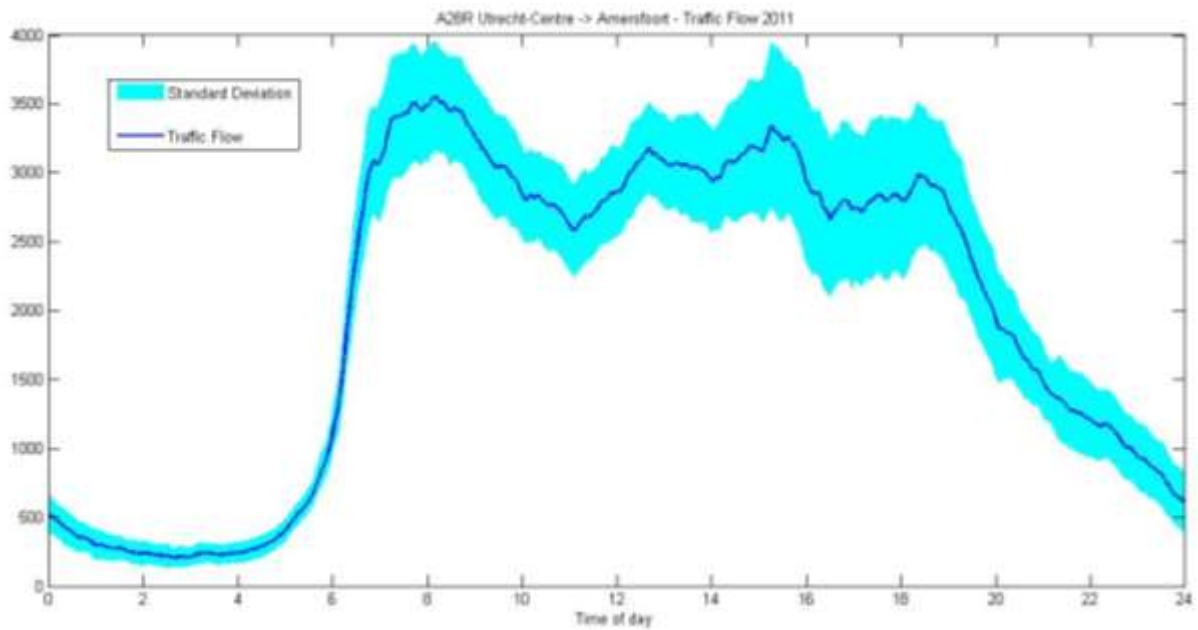
The road-way space is scarce for expanding the highway due to large overpassing sections over major canals.

In the case of the reliability indicators, they both show the same pattern with a worse off evening peak accounting for the shockwave effects, with the buffer index portraying a more spread over time situation for both peaks.

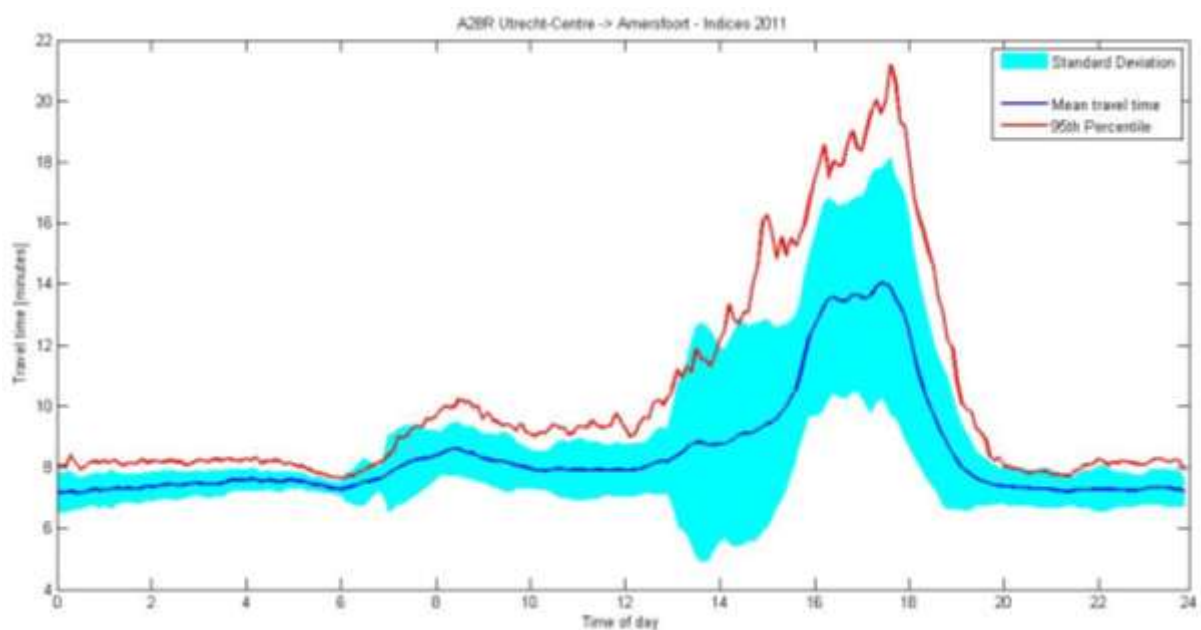
#### **A28R Utrecht-Centre -> Amersfoort**

The A28R corridor connects the cities of Utrecht and Amersfoort and has a length of 11.9 kilometres. It is the top shockwave location with two bottlenecks: one in Utrecht and one the town of Amersfoort. Shock waves occur before and during the ramp bottleneck N221 at Amersfoort and store all the way back to Utrecht. Upstream of the bottleneck there are two shock waves taking place that create spill back in the bottleneck. The Uithof ramps and the A27 traffic accounts for both capacity and shockwave congestion. As it gets busier the shockwaves grow until together they form congestion on the whole section.

The traffic flows show a sharp increase in the morning peak with gradual slight decrease throughout the day including the evening peak, as it can be seen in Figure 4.13.



**Figure 4.13 A28R Traffic flow 2011**



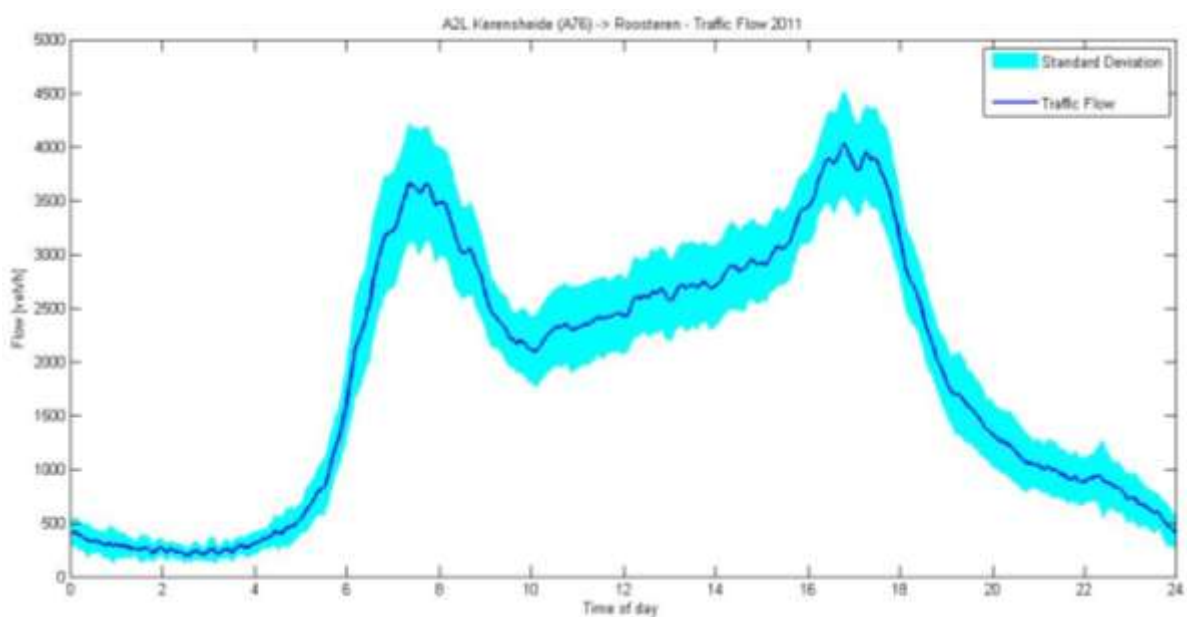
**Figure 4.14 A28R Indices 2011**

In terms of travel time, the morning peak shows almost no trace of congestion while we can see the travel times building up in value as the shockwaves mount towards the evening peak when congestion occurs, as observed in Figure 4.14. The monthly mean travel times and the 95<sup>th</sup> percentiles show consistent trends in distributions throughout the year and are in the same line as the traffic situation described so far.

As for the reliability indices, the planning time index portrays the situation as described so far showing the build-up towards the evening peak, while the buffer index makes a clear distinction showing the worse occurring situation right before the evening peak as well.

### A2L Kerensheide (A76) -> Roosteren

The A2L corridor is an 11.8 kilometres section of the main highway that brings in traffic from the south of Netherlands, and it is located right before the split of flows towards Roermond and Eindhoven. The corridor is suffering from the commonly source of congestion as most of the candidates, and that is shockwaves. The flows show a normal morning period with traffic starting to build up towards the evening along with the occurring shockwaves, as portrayed in Figure 4.15.



**Figure 4.15 A2L Traffic flow 2011**

Travel times distributions indicate slightly higher values for the morning peak, but a more time wise spread evening peak with the standard deviation showing shockwaves before and after it, as it can be observed in Figure 4.16. The monthly mean travel times are fairly consistent throughout the year, while the 95<sup>th</sup> percentiles portray the more hectic situation induced by the shockwaves throughout both the day and the year.

In terms of reliability indicators, both the planning and the buffer index show the same pattern that fits the situation described so far. The monthly distributions of the buffer index portray the same hectic variation over the day and the year as the 95<sup>th</sup> percentiles did.

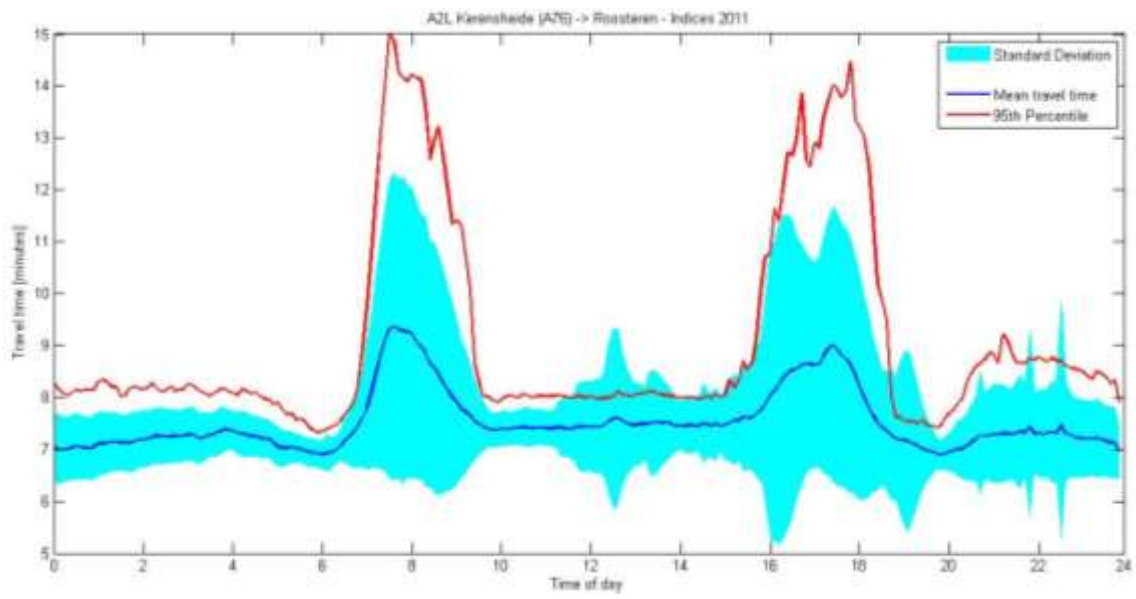


Figure 4.16 A2L Indices 2011

### 4.2.3 Selection and classification

The results out of the data analysis are to be used according to the general guidelines set in subchapter 3.3.2, where the selection criteria were discussed. The three main categories mentioned previously included: the presence of congestion, demand and the physical attributes.

In terms of presences of congestion, the values expressing the loss vehicle hours throughout a year are taken into account. With some of the candidates having multiple values according to the source of congestion it was decided to only take into consideration the biggest value attributed to that corridor. Instead of instating a threshold requirement, as it would be appropriate for a pre-selection of possible candidates, due to the nature of the source for the candidate corridors it is assumed that all of them qualify as having extensive problems due to congestion. As a result it is more appropriate to rank them in relation to each other. For the ranking in terms of congestion the value vehicle loss hours per kilometre is used.

The top scorers received their rating numbers according to hundreds of thousands of vehicle lost hours, while for the low scorers the distribution over length was also factored in as they were close values displayed for each. If we take a look at the comparison of travel times between all candidates, for the mean and 95<sup>th</sup> percentile travel times, the top rated one appear with the highest values in either morning, evening or both peaks. The exception is the top rated corridor, A1R which doesn't register among the highest values of travel times.

Coupled with the congestion are the values provided by the analysis undertaken using reliability indicators. As the analysis in the previous section showed, throughout all the candidate corridors, the buffer index provided a detailed and accurate interpretation of the traffic situation. A high degree of variation was present throughout the time of day among the candidate corridors of the congestion's characteristics. Thus it has been decided that the average values of the buffer index proposed to be used is to be calculated for each of the two traffic peaks. The morning peak is taken into account as occurring between 7 – 9 am and the evening peak between 16 – 18 pm. For each corridor an average of the two ratings for the two peaks will serve a selection criterion.

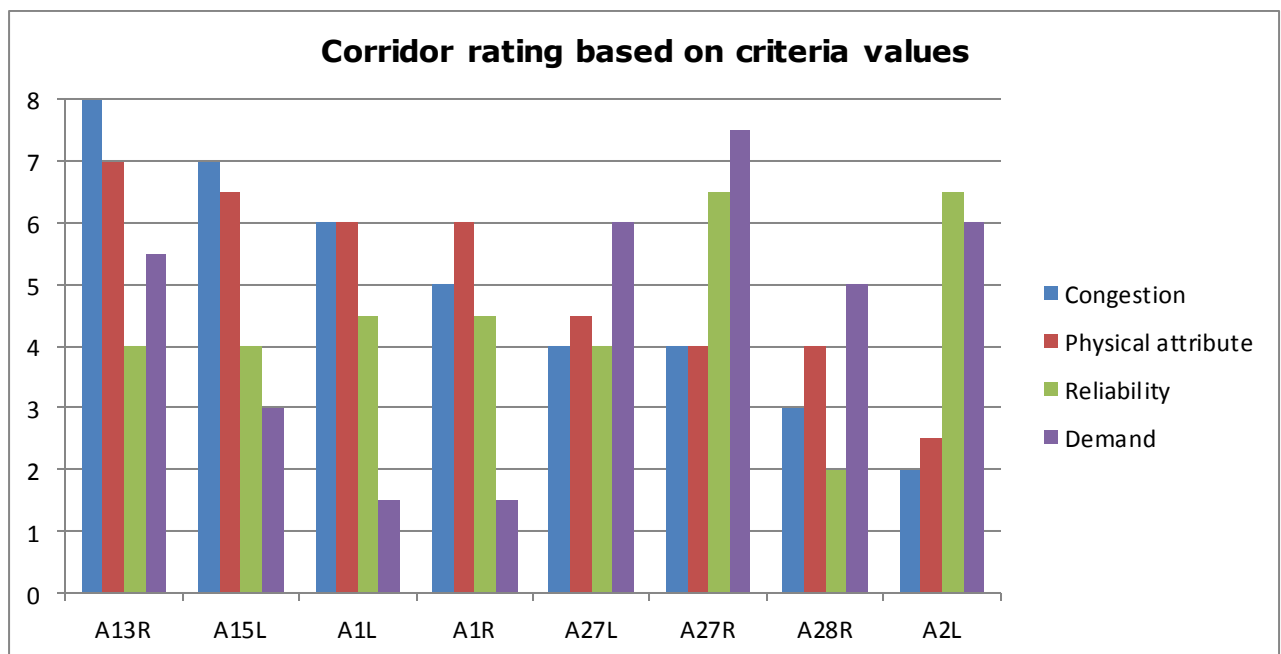
Splitting up the buffer indices averages on time of day has a positive influence on the overall rating of candidates. The daily averages seem to flatten too much the trends that are shown by the traffic peaks. Classifying them according to an average rating across all periods gives more freedom to interpret better the travel time reliability over the corridors. The comparison of buffer indices between candidates is consistent with what the overall ratings show.

In the case of demand, at this stage only the vehicle demand is used for categorising the candidates. The corridors will be rated according to the relative difference between their resulted flows and what would be considered a qualifying minimum of traffic.



In terms of physical attributes the greatest attention is paid to the density of access/egress points. Already a limited availability of road-space poses some difficulties to the realisation of the HOT-lane and a high number of on/off ramps will only add a lot more design issues. It was mentioned that the ability of the HOT-lane to provide significant travel time savings depends on the fact that it is an alternative for people who make longer trips to avoid congestion. In conclusion, the higher the number of access points the more traffic is affected both on the HOT-lane and the adjacent free lanes. Another aspect considered is space. Not just road space, but also the surrounding space as it can be considered that adequate safety measures have to be taken into account thus some limited modifications to the roadway have to be made.

The summarized ratings based on the criteria and its corresponding values are presented in Figure 4.17. It is interesting to see the close correlation between the ratings for congestion and physical attribute, despite the rather loose classification of the latter.



**Figure 4.17 Corridor ratings**

These rating are subsequently combined with the weights that were previously derived in section 3.3.1, and to be found mentioned again below.

	Congestion	Reliability	Demand	Physical abilities
Weight	0.074	0.289017	0.213231	0.423892

The final ranking is presented in Table 4.3.

**Table 4.3 Final ranking of the candidate corridors**

	<b>A13R</b>	<b>A15L</b>	<b>A1L</b>	<b>A1R</b>	<b>A27L</b>	<b>A27R</b>	<b>A28R</b>	<b>A2L</b>
Average rating over all criteria	4.68	3.15	4.89	4.75	5.70	5.32	3.71	5.71
Ranking	<b>#6</b>	<b>#8</b>	<b>#4</b>	<b>#5</b>	<b>#2</b>	<b>#3</b>	<b>#7</b>	<b>#1</b>

### 4.3 Conclusions

The initial step of this phase addressed the reasoning behind the set goals and objectives and their influence on the considerations to be taken further. One of the problematic areas in which the goals and objectives are to be linked to is the choosing of the considered weights for the screening criteria. Although a method that mitigates biases and focuses the knowledge to finding the appropriate weights was used there can still be doubts over the resulting values.

In terms of the criteria used for the screening, a significant aspect was left out. The flow values used for the evaluation can be considered rather crude representations of demand, not to mention that their influence is already largely portrayed by the congestion. An alternative for these values would be trip patterns derived from the validated models already used for national and regional planning. Although this seems to be against the main considerations of a quick application of the methodology, there are cases where the substitute can prove to be very valuable.

If the data is available for all of the potential candidates considered, even the same traffic simulation model used in the second phase can be applied to provide further insight on the potential demand.

## 5 Case study setup

The purpose of this section of the report is to further clarify and exemplify the application of the second phase of the methodology that addresses the implementation/design of a HOT-lane on a specific location picked from the results of Phase 1 presented in section 4.2.3. This includes the use and adaptation of an existing traffic simulation model and the analysis of several scenarios.

### 5.1 Adopted model and corresponding modelling framework

Based on the previous subchapters, comprising of the specification of input and output desired, as well as the derived requirements needed for modelling a HOT-lane implementation and assessing its effects, an existing traffic simulation model is selected.

Considering that the various existing traffic management measures influence many aspects of a travellers' behaviour and that traffic simulation models usually incorporate only (small) parts of this behaviour (well), there is not one single simulation tool which is valid for all types of measures. It can be observed that not all the specified requirements are present in the table above, as they are not commonly represented in commercial traffic simulation software. They are usually treated in custom built specialised models developed for the sole purpose of their representation.

MARPLE is chosen mainly due to the nature of methodology which is to provide sketch-planning means to policy makers. Marple is also interoperable with the data used and resulted in the two Dutch national traffic simulation models, and it is included in the Regional Traffic Management Explorer, which is the second tool regional authorities' use. It is regarded as a sketch planning and modelling tool that facilitates sustainable traffic management by quantifying benefits of traffic management strategies. It allows the user to compare different scenarios to identify the most effective strategies based on the policy objectives built into the tool on accessibility, and safety. It provides the impacts of operational strategies and system improvements based on such factors as travel time and delay, speed, and traffic volumes on origin-destination pairs, routes, and road sections.

It is also considered to be sufficiently adaptable such that the missing components for representation of aspects such as carpooling and travel time reliability will be dealt with as an external additions and procedures that will provide the information as input for Marple. The missing user-class specific toll application is implemented by the developer of the model as it needs to be included in the model's route choice procedure.

### 5.1.1 Travel time variability

There is extensive literature on how travel behaviour is affected by the variability of travel time. Most of the studies seek to model transport decisions such as route choice, mode choice, or departure time choice in the presence of travel time variability.

Two competing approaches are commonly used: The mean-variance approach and the scheduling approach. Both methods formulate the utility of the traveller in terms of travel time variability and other attributes of the trip, but they differ in their assumptions of how variability is perceived and interpreted by the traveller. The scheduling approach assumes that variability affects utility through scheduling considerations: How often one arrives late, and how much one arrives late (or early) on average. The mean-variance approach describes the inconvenience travellers experience from variability due to the uncertainty itself, no matter if one arrives early or late.

The mean-variance approach assumes that the traveller's utility depends on travel cost  $C$ , the expected travel time  $E(T)$ , and the standard deviation  $\sigma_T$  of travel time:

$$U = \delta C + \alpha E(T) + \rho \sigma_T \quad \mathbf{5-1}$$

$\delta$ ,  $\alpha$ , and  $\rho$  are the marginal utilities of cost, travel time, and variability, respectively, and are expected to be negative. The model is very popular because of its simplicity, but it has the serious drawback of lacking a solid economic foundation. Rather than being based on a theoretical description of individual travel demand, it is based on the measures of travel time variability directly available from network models describing the supply-side of the transport system, such as the mean and standard deviation of travel times. A similar approach involves the median travel time instead of the mean and the difference between the 90<sup>th</sup> and 50<sup>th</sup> quartiles instead of  $\sigma_T$ . This approach is used by Brownstone and Small (2005), Lam and Small (2001), and Small et al. (2005).

The scheduling approach was originally proposed by Noland and Small (1995), based on work by Small (1982) on departure time choice without uncertainty.

The traveller's utility depends on travel cost  $C$ , travel time  $T$ , on whether he arrives before or after his preferred arrival time (PAT), and by how much he arrives early/late compared to PAT. These attributes depend on the choice of departure time  $t_h$ , and possibly on the choice of route and transport mode. The model presented below considers departure time choice only, but can be generalised to include other types of choice as well. The utility function is:

$$U(t_h) = \delta C + \alpha T + \beta SDE + \gamma SDL + \theta DL \quad \mathbf{5-2}$$

where  $SDE$  and  $SDL$  are schedule delay early and late, respectively; the amount of time by which the traveller arrives early/late compared to PAT.  $D_L$  is a dummy for arriving late.  $\delta$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  are

the marginal utilities of travel cost, travel time, minutes early and minutes late, while  $\theta$  is a fixed penalty for arriving late, no matter the size of the delay. All parameters are expected to be negative.

### **Considered adaptation**

As it can be observed, there are several methods available for the valuation of reliability and the inclusion of the variability into the model assignment. Because of the extensive modifications that have to be implemented into Marple in the restricted time-frame available to the project it is decided that for travel time variability, the estimated and fitted distribution from the detector loops traffic data is used.

In the ideal traffic model there is extensive information about the expected travel time and its variation. In this case the only available information is the current travel time variability at the investigated corridors expressed as an either lognormal or Burr distribution with their corresponding parameters. In the newly studied situations where the network's characteristics are modified, this travel time variability will change.

For this reason some assumptions are made to be able to estimate the travel time variability under different circumstances. The first assumption is that the travel time variability in the new situations can be described as a distribution for which the same parameters as previously determined from detector loops data can be used. The resulting distribution can subsequently be split up in two parts. The first part is the average travel time and the remaining part is the variation of the travel time in relation to the average travel time.

The average travel time for the changed situation is assumed to be the result of the traffic assignment that is executed for the traffic model, as will be described in the next chapter. The variation that will be present on the general purpose lanes, in the new conditions, is assumed to be the original travel time variation multiplied with a variation factor that depends on the scenario, while for the HOT-lane the variability is assumed to be zero assuming that they provide "free flow" conditions.

The parameters resulted from the distribution are determined for each time interval (15 minutes) and are used to describe the travel time distribution.

The Burr distribution was proven to be a useful statistical model to represent travel time reliability through studies of the day-to-day variability in travel times. This distribution has a flexible shape and the ability to describe the very long upper tails (and hence significant skewness) seen in observed distributions of travel time variations.

The Burr distribution is algebraically tractable, which means that percentile values can be computed directly. In this way various travel time reliability metrics can be computed from the fitted Burr parameters.

The probability density function (pdf)  $f(x, c, k)$  of the (2-parameter) Burr distribution is

$$f(x, c, k) = ckx^{c-1}(1+x^c)^{-(k+1)} \quad \mathbf{5-3}$$

where  $x > 0$ ,  $c > 0$  and  $k > 0$ . The cdf  $F(x, c, k)$  is given by

$$F(x, c, k) = 1 - (1+x^c)^{-k} \quad \mathbf{5-4}$$

In the first instance the  $r$ th moment of the distribution  $E(x^r)$  will only exist if  $ck > r$ , in which case

$$E(x^r) = \mu'_r = \frac{k\Gamma(k-\frac{r}{c})\Gamma(\frac{r}{c}+1)}{\Gamma(k+1)} \quad \mathbf{5-5}$$

where  $\Gamma(y)$  is the mathematical Gamma function. The mean of the Burr distribution is thus

$$E(x) = \bar{x} = \frac{k\Gamma(k-\frac{1}{c})\Gamma(\frac{1}{c}+1)}{\Gamma(k+1)} \quad \mathbf{5-6}$$

A further advantage of the Burr distribution is its algebraic tractability, which means (for instance) that percentile values can be computed directly.

Percentiles for the Burr distribution may be computed using the following approach. Given the cdf defined previously, we can solve for a given value of  $F(x, c, k)$  for percentile  $P$

$$P = 1 - (1+x^c)^{-k} \quad \mathbf{5-7}$$

from which

$$x_p = \sqrt[c]{(1-P)^{-1/k} - 1} \quad \mathbf{5-8}$$

The median is then

$$x_{50} = \sqrt[c]{2^{1/k} - 1} \quad \mathbf{5-9}$$

and the 95th percentile is

$$x_{95} = \sqrt[c]{20^{1/k} - 1} \quad \mathbf{5-10}$$

In terms of the scaled travel time variable  $x = \alpha t$  where  $\alpha > 0$  is a constant, we can write a Buffer Index, as it follows:

$$BI_x = \frac{x_{95}}{\bar{x}} - 1 \quad \mathbf{5-11}$$

which written in Burr parameters becomes

$$\frac{\sqrt[c]{20^{1/k} - 1}}{k\Gamma(k - \frac{1}{c})\Gamma(\frac{1}{c} + 1)} - 1 \quad \mathbf{5-12}$$

$$\Gamma(k + 1)$$

which is a relatively simple function of  $c$  and  $k$ .

Previous research shows that also the lognormal distribution gives the best results for approaching the occurring distribution. A lognormal distribution has a relative small density to the left of the top (the travel time with the highest probability density) and a relative large and widespread density at the right of the top.

The lognormal distribution is described by the formula:

$$f(x, \mu, \sigma) = \frac{1}{x \cdot \sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(\ln(x) - \mu)^2}{2\sigma^2}} \quad \mathbf{5-13}$$

Opposite to a normal distribution function, the parameters  $\mu$  and  $\sigma$  are not the same as the mean and standard deviation. Instead the mean and variation of a lognormal function can be calculated with the formulas:

$$M = e^{\mu + \sigma^2/2} \quad \mathbf{5-14}$$

$$S = (e^{\sigma^2} - 1) \cdot e^{2\mu + \sigma} \quad \mathbf{5-15}$$

Rewriting the formulas above results in:

$$\mu = \ln(M) - \frac{1}{2} \ln\left(1 + \frac{S}{M^2}\right) \quad \mathbf{5-16}$$

$$\sigma^2 = \ln\left(\frac{S}{M^2} + 1\right) \quad \mathbf{5-17}$$

### 5.1.2 Value of reliability (VOR)

There are two major sources of preference data, revealed and stated preference, from which through discrete choice modelling the VOR is derived. Empirical studies of traveller's choice behaviour rely on data from observing what people actually do, named revealed preference (RP) data, but also data from people's choice under hypothetical situations can be used, and is referred to as stated preference (SP) data.

Although assessing the value of travel time reliability is not as common as assessing the value of time, several SP and RP studies were conducted to provide insight into the valuation of travellers' willingness to pay to reduce variability of travel times. Table 5.1 summarizes some of valuations resulted from different studies. It can be observed that even though that the variation is quite large in relation to value of time (VOT), recent studies find that travellers value improvement in reliability is very close to reducing travel time, making the value of reliability comparable to the value of travel time.

**Table 5.1 VOR – Different studies' valuation**

Study	Value of Reliability	Method and data
(Black & Towriss, 1993)	0.55-0.70 times VOT	Data from SP survey of travellers in London; Measured as standard deviation of travel time
(Small, Noland, Chu, & Lewis, 1999)	2.37 times VOT	SP survey of travellers in SR-91 corridor in Orange and Riverside counties in Southern California, conducted in 1995 ; Reliability is measured by standard deviation of travel time
(Tilahun & Levinson, 2007)	Equivalent to VOT	Data from a SP route choice survey of University of Minnesota employees, Minneapolis/St. Paul, MN ; Difference between actual late arrival and usual (mode) travel time
(Tseng, Ubbels, & Verhoef, 2005)	0.5 times VOT	Data from surveying Dutch commuters, 2004; Difference between early /late arrival time and preferred arrival time. Early and late arrivals are modelled separately
(Jong, Kouwenhoven, Kroes, Rietveld, & Warffemius, 2009)	0.8 times VOT	Expert meetings

Theory suggests that a risk-averse traveller would be willing to pay a monetary sum to decrease travel time uncertainty or willing to accept longer but more reliable travel times. The differences in valuations are plausible as market conditions may differ by country.



For this research the valuation of reliability will be equivalent to a ratio of 0.8 of the VOT, being defined in a study with regards to the Netherlands. The same study provides also a more extensive analysis on the VOR in the case of freight movers. The value of 1.24 is somewhat larger than what was obtained for cars (0.8), but this is in line with prior studies' expectations. The valuation of travel time itself hardly contains any logistics element. The trade-off ratios between time and costs roughly correspond with the costs for labour and transport vehicles.

### 5.1.3 Toll setting procedures

As presented in section 3.4.2, under the consideration of pricing, a study that concluded the suitability of different pricing setups for various objective functions. Although the procedure described takes advantage of direct implementation in a Dynamic Traffic Assignment (DTA), this is not achievable in this project's case.

The methodology developed by Joksimovic (2006) includes a DTA in combination with a Road Pricing Model based on a grid-search procedure. The algorithm starts with an initial feasible price vector satisfying the lower and upper bounds of the prices. For each iteration the algorithm finds a user equilibrium solution and sets new prices that can potentially decrease the objective function. The procedure comprises of the following steps:

Outer loop: PRICING

Step1: Initialization

- Maximum number of pricing iterations (N)
- Initial values for tolls, and links to be tolled
- Time period(s) in which tolls will be applied

Step 2: set next toll combination

Step 3: inner loop: DTA

Step 4: Computing the objective function

Step 5: Stop criteria

In order to apply the same principles a more time consuming method is applied. As in the case described the tolled links, the tolled time intervals, and the link tolling patterns are assumed to be known. The aim is to find the set of optimal maximum toll levels that provide the best result for any given objective. As a result, in the case of a uniform toll, the method consists of trial and error for which Marple simulation runs are used for the DTA.

In the case of the time varying tolling, an algorithm is used that takes into account the actual traffic conditions on the model network in every time period. As shown in the section 2.3.5, these

applications generally measure real time traffic flow speeds and adjust the toll rates to obtain a specific Level of Service (LOS) which refers to a minimum speed. Based on these principals, Zhang, et al. (2008) provided a feedback based step-wise tolling model for HOT lane operations. The model presented is easy to implement when the necessary infrastructure is present. It uses traffic flow speeds as the threshold parameter for the toll rate changes.

It considers the fact that the logit model that determines the choice between the a tolled and free alternative is basically a function of independent variables such as travel times and toll rates and the dependent variable P, which is the probability of choosing the alternative considered .

In order to determine the optimum increment, in terms of probability to use the HOT-lane which in respect provides the resulting flow , a feedback control mechanisms is developed that considers the differences in speed between the GP and HOT-lane applicable for three different manipulation zones. The manipulation zones represent speed intervals categorized according to their robustness. For example the first zone is  $S_{HOT} > 80$  km/h, which indicates sufficient HOT lane capacities are available, and the toll needs to be decreased if there is a need to carry more traffic; the second zone is  $80 \geq S_{HOT} > 70$  km/h, which shows the traffic density on the HOT lane is close to its critical level, and the toll should be maintained at the same level; the third zone is  $S_{HOT} \leq 70$  km/h, indicating the overflowing traffic has degraded the HOT lane performance and the toll must be increased to reduce the HOT lane volume.

$$P_{HOT}(t+1) = P_{HOT}(t) + \Delta P_{HOT} = P_{HOT}(t) + \begin{cases} b_1 + k_1(S_{HOT}(t) - S_{GP}(t)) & S_{HOT}(t) > 80 & \mathbf{5-18} \\ sign \cdot [b_2 + k_2(S_{HOT}(t) - S_{GP}(t))] & 80 \geq S_{HOT}(t) > 70 & \mathbf{5-19} \\ k_3(S_{HOT}(t) - 70) & S_{HOT}(t) \leq 70 & \mathbf{5-20} \end{cases}$$

where,  $P_{HOT}(t+1)$  and  $P_{HOT}(t)$  are the flow ratios for HOT lane usage at time interval  $t$  and  $t+1$ , respectively;  $\Delta P_{HOT}(t)$  is the feedback increment;  $b_1$ ,  $b_2$ ,  $k_1$ ,  $k_2$ , and  $k_3$  are the parameters indicating control intensities of feedback quantities;  $S_{HOT}(t)$  and  $S_{GP}(t)$  are the average traffic speeds on HOT and GP lanes at time interval  $t$ , respectively;  $sign$  is a variable describing the changing pattern of  $P_{HOT}$ , and is defined as:

$$sign = \begin{cases} 1 & P_{HOT}(t-1) > P_{HOT}(t) & \mathbf{5-21} \\ 0 & P_{HOT}(t-1) = P_{HOT}(t) & \mathbf{5-22} \\ -1 & P_{HOT}(t-1) < P_{HOT}(t) & \mathbf{5-23} \end{cases}$$

Thus the toll rate can be calculated as follows:

$$TR_{HOT} = \frac{1}{\frac{1}{\alpha TT_{GP}} - \ln\left(\frac{1-P_{HOT}}{P_{HOT}}\right)} - \alpha \cdot TT_{HOT} \quad \mathbf{5-24}$$

Where  $\alpha$  is the VOT,  $TR_{HOT}$  is the toll rate for the HOT-lanes,  $TT_{GP}$  and  $TT_{HOT}$  are the travel times for the general purpose lane and the HOT -lane.

#### 5.1.4 Mode choice for carpooling

The choice of travel mode of travellers depends on the availability of transport means, especially cars, and on the travel resistance for each mode from origin to destination. Each travel mode has its specific advantages and disadvantages besides travel time and travel costs. The traditional approach to traffic modelling is the four stage model, comprised of the following: trip generation, trip distribution, modal split and route choice.

In this case the mode choice is modelled in sequence, making use of the trip generation and distribution results from Marple. Thus, the input to the mode choice model in this case is the total travel demand between each Origin-Destination (OD) pair.

A commonly used approach is to distribute the total travel demand for a given OD-pair over the available modes using the logit model:

$$\beta_{ijv} = \frac{\exp[bV_{ij}^v]}{\sum_w(\exp[bV_{ij}^w])} = \frac{\exp\sum_k \alpha_k^v X_{ijk}^v}{\sum_w(\exp\sum_k \alpha_k^w X_{ijk}^w)} = \text{proportion using mode } v \text{ on OD - pair } ij \quad \mathbf{5-25}$$

$$T_{ijv} = T_{ij} \beta_{ijv} \quad \mathbf{5-26}$$

With:

$b$  = variance (or scale) parameter in logit model

$V_{ij}^v$  = observable part of utility of traveling between OD-pair  $i-j$  with mode  $v$

$X_{ijk}^v$  = the  $k$ th explanatory variable for mode  $v$  on OD-pair  $i-j$  (travel time travel costs, mode specific constant)

$\alpha_k^v$  = weight parameter for the  $k$ th explanatory variable for mode  $v$  on OD-pair  $i-j$  (the value of time).

The previously presented variables denote the observable attributes of a trip using mode  $v$ . However many factors that influence mode choice cannot be observed, or can only be observed at a cost which is very high. Examples are non-physical factors like comfort, status, image, and safety of the travel mode. The impact of these factors is usually summarized in a mode specific constant.

The data about carpooling and its formation is scarce in the Netherlands. Nevertheless the source used in this project, which is the Dutch national survey on mobility, provides some general indications on participants in carpooling, if the passengers are from within or outside the household, as well as the trip purpose of the driver or the passenger.

The aim of the Survey on Trips in the Netherlands (Onderzoek Verplaatsingen in Nederland - OViN) is to map how and when the Dutch population participates in the traffic (Centraal Bureau voor Statistiek, 2011). This information is important in the development of traffic and transport policy. In this study, people are asked for a day to track where they go. The participants then also specify with what means of transport (walking, cycling, car or train) they were traveling, what was the destination of the trip, the time of departure and arrival, and how far it was (the distance).

As presented in section 2.3.2, there are several hypotheses and conclusions coming from considerable research on the subject. It can be safely assumed that the main factors that are considered in the choice of carpooling or not are the travel time (with the inclusion of the necessary carpool formation time) and trip costs. The associated costs should be accounted for in relation to income, household income more specifically as it can carry the correlation with vehicle ownership and household size.

The findings are that carpooling is predominantly present in home-work trips and with people coming from the same household. The carpool formation time is  $\sim 10\%$  of the total trip time (4.3 minutes for an average trip length of 45.3 minutes (Appiah, 2004) ; 4.8 minutes in the case of 47 minutes average trip time (Billheimer, 1990)). In the case of the Netherlands, considering only home-work trips, the last reported statistics showed that for an average trip of 39 minutes the formation time was 6 minutes, which is only slightly higher when compared to the US case (Molnár & Konen, Carpoolen in het woon-werkverkeer, 2003). The same study also showed that carpoolers have a longer average travel time due to the fact that they leave further away from their workplace, having on average a 10 kilometers longer trip. It also has to be mentioned that majority of the carpooling vehicles only carry 2 persons.

Differentiating between passengers (casual, co-worker or household member) one of the previously mentioned US studies (Appiah, 2004) shows that the only difference in formation time is for household members, where usually the pick-up phases of the trip is non-existent thus approximately halving the additional time.

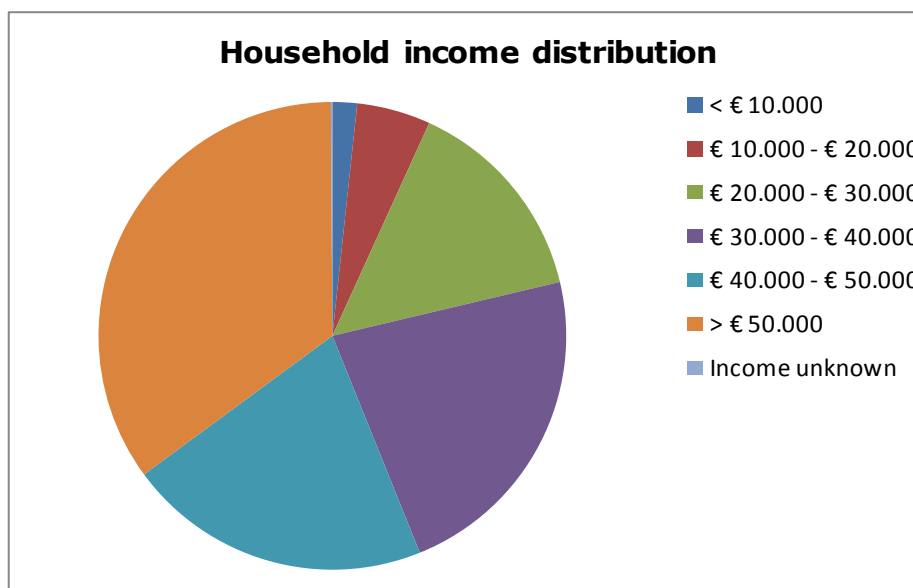
Because the OviN provides only information as a trip journal, there are choices reflected in the data. Thus with the use of previously discussed general characteristics the following assumption is made: the carpooling trip takes 15% longer than in the case of solo drivers and the costs are 40% smaller (split costs between participants, which are usually no more than two). A differentiation is made for when a household member is the passenger, in which case only 7% of additional trip travel time is considered. The costs are to be derived from the trip length data that can be found in the survey. Based on the percentage of diesel or gas powered car ownership that was found (<http://statline.cbs.nl/statweb/>, 2013) and combined with the overall average consumption (Bundesministerium für Verkehr, Bau und Stadtentwicklung), a cost per kilometer is derived. Thus, with the trip distance and a per-kilometre vehicle operation cost applied, the driving costs are obtained. The previously made assumptions help to add the parameters of the travel alternatives the trip makers had when the choice was made, parameters missing from the observations from the survey, thus adding more context. This is necessary because the data described in the previously forms the data set to support model estimation. In the trip format, each record has to provide all the relevant information about an individual trip, including the trip related variables, mode related variables for all available modes and a variable indicating which alternative was chosen.

The data set described previously will provide the input for developing a mode choice model by using discrete choice modelling. Discrete choice models can be used to analyse and predict a trip maker's choice of one alternative from a set of alternatives, by modelling individual choice responses as a function of the characteristics of the alternatives available to and socio-demographic attributes of each individual. This is done with the help of Biogeme (Bierlaire, 2003), which is an open source freeware designed for the estimation of discrete choice models. As output, the software will estimate and provide the weights corresponding to the explanatory variables part of the logit model, described previously, as well as the mode specific constant.

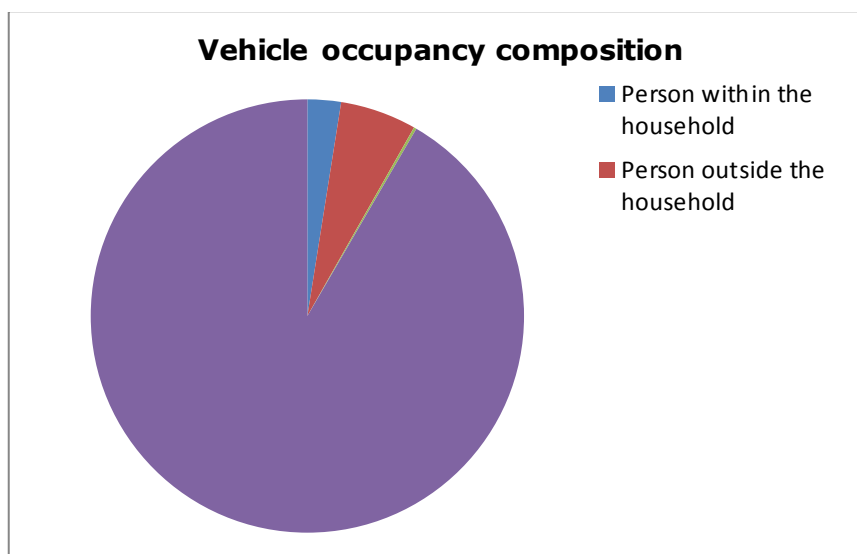
The analysis of the data is done with consideration only data to home-work trips for reasons of consistency with the studies from which the assumptions are derived. Because the available demand in Marple is in terms of vehicles, the dataset corresponds only to car mode trips in which the respondent is the driver. The details of the data set used are presented in Figure 5.1 and Figure 5.2 with their corresponding values to be found in the adjacent tables (Table 5.2 and Table 5.3).

**Table 5.2 Car driver - Household income distribution**

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	< € 10.000	219	1.7	1.7	1.7
	€ 10.000 - € 20.000	637	5.1	5.1	6.8
	€ 20.000 - € 30.000	1829	14.5	14.5	21.3
	€ 30.000 - € 40.000	2849	22.6	22.6	43.9
	€ 40.000 - € 50.000	2649	21.0	21.0	64.9
	> € 50.000	4419	35.0	35.0	99.9
	Income unknown	10	0.1	0.1	100.0
Total	12612	100.0	100.0		

**Figure 5.1 Car driver – Household income distribution****Table 5.3 Car driver - Vehicle occupancy composition**

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Person within the household	315	2.5	2.5	2.5
	Person outside the household	714	5.7	5.7	8.2
	Both	24	0.2	0.2	8.3
	Alone (solo driver)	11559	91.7	91.7	100.0
	Total	12612	100.0	100.0	



**Figure 5.2 Vehicle occupancy distribution**

The estimations are done using different data sets corresponding to the user classes previously selected in section 5.2.3. The weights and their corresponding parameters are presented in the tables below, for each user class. Accompanying are the statistical values that attest their relevance (Biogeme also reports statistics and "robust" statistics about the estimated parameters such as standard errors,  $t$ -tests and  $p$  values). Also in Table 5.4, the utility functions and the parameters are presented as they were considered for the estimation.

**Table 5.4 Mode choice utility functions**

Alternative	Utility function
SOV (solo)	$ASC\_SOV + B\_TIME * SOV\_TT + B\_COST * SOV\_C$
HOV (carpool)	$ASC\_HOV + B\_TIME * HOV\_TT + B\_COST * HOV\_C$

Where:

ASC\_SOV – driving alone mode specific constant

ASC\_HOV – carpooling mode specific constant

B\_TIME – weight for the travel time variable

B\_COST – weight for the cost variable

SOV\_TT –travel time for driving alone

HOV\_TT –travel time for carpooling (includes formation time)

SOV\_C – drive alone travel costs

HOV\_C – carpooling travel costs

**Table 5.5 Estimated parameters' values for user class 1 (<30.000€)**

Name	Value	Std. err	t-test	p-value	Robust Std. err	Robust t-test	p-value
<b>ASC_HOV</b>	<b>-2.54</b>	0.115	-22.06	0.00	0.296	-8.57	0.00
<b>B_COST</b>	<b>-0.534</b>	0.0798	-6.69	0.00	0.281	-1.90	0.02
<b>B_TIME</b>	<b>-0.135</b>	0.0401	-3.37	0.00	0.158	-0.85	0.05

**Table 5.6 Estimated parameters' values for user class 2 (30.000-50.000€)**

Name	Value	Std. err	t-test	p-value	Robust Std. err	Robust t-test	p-value
<b>ASC_HOV</b>	<b>-2.26</b>	0.0840	-26.94	0.00	0.140	-16.16	0.00
<b>B_COST</b>	<b>-0.658</b>	0.0652	-10.09	0.00	0.125	-5.25	0.00
<b>B_TIME</b>	<b>-0.247</b>	0.0341	-7.24	0.00	0.0729	-3.39	0.00

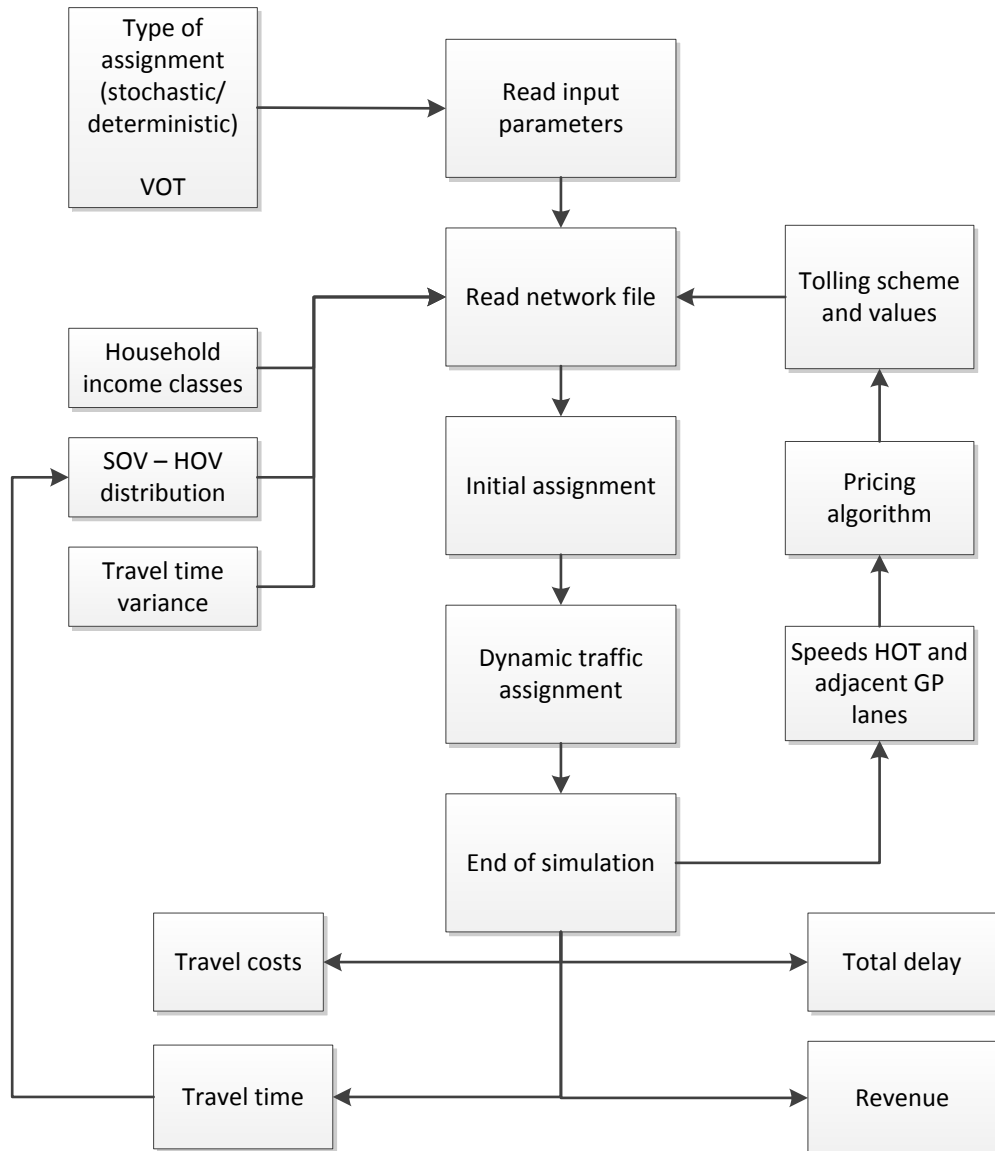
**Table 5.7 Estimated parameters' values for user class 3 (>50.000€)**

Name	Value	Std. err	t-test	p-value	Robust Std. err	Robust t-test	p-value
<b>ASC_HOV</b>	<b>-2.34</b>	0.0905	-25.89	0.00	0.182	-12.87	0.00
<b>B_COST</b>	<b>-0.416</b>	0.0576	-7.22	0.00	0.153	-2.72	0.01
<b>B_TIME</b>	<b>-0.150</b>	0.0295	-5.08	0.00	0.0867	-1.73	0.04

### 5.1.5 Resulting framework

As a result of previously mentioned addition and adaptation around the existing traffic simulation model Marple, a specific modeling framework is comprised as represented in Figure 5.3.





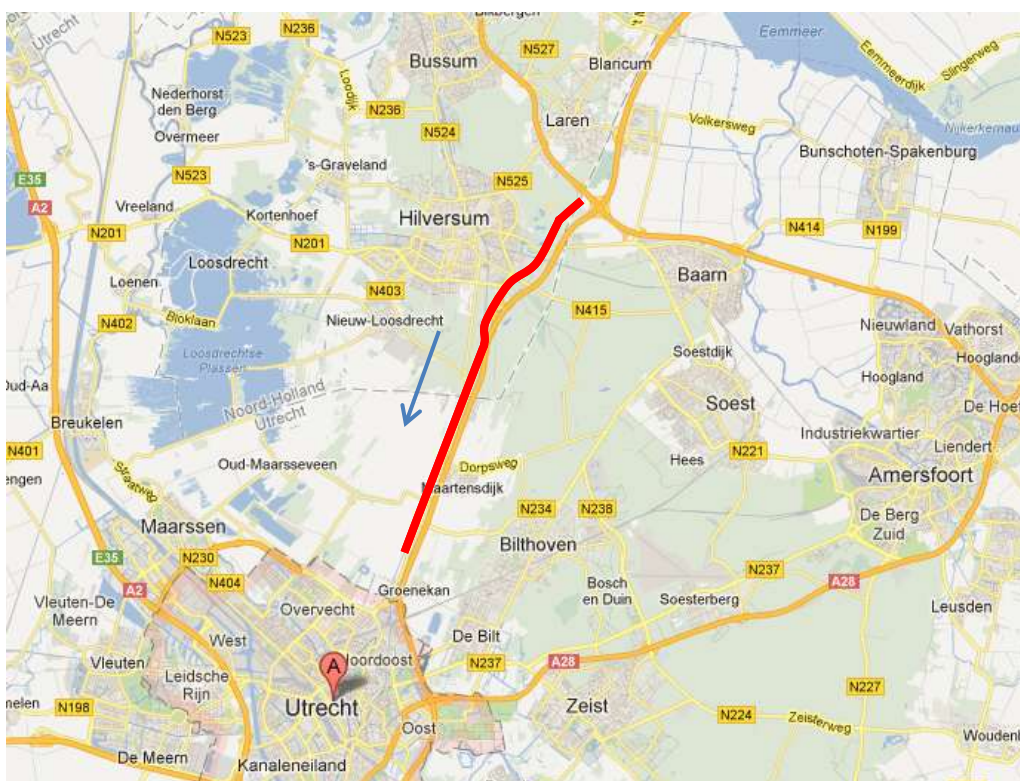
**Figure 5.3 Adapted modeling framework**

## 5.2 Scenarios and development of the implementation setup

In this section the modelling framework presented previously is applied to one of the locations ranked in Phase 1. Further details are presented regarding the use of available data and the consequences it has on the simulations.

### 5.2.1 Creation of the location's model

The highway section (corridor) chosen for the application of the methodology is the A27 stretch between intersection Eemnes, between the A27 and the A1, and Bilthoven, up to the ring road of Utrecht (see Figure 5.4).

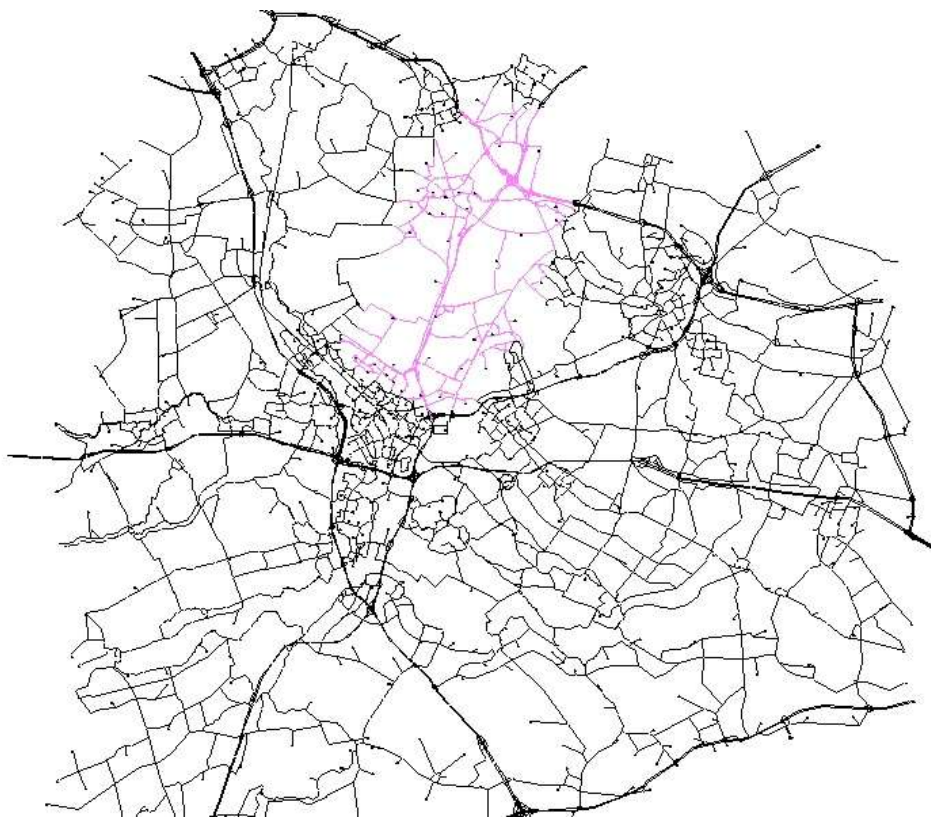


**Figure 5.4 A27L corridor (Eemse - Bilthoven)**

The main reason for choosing this location was the available data for the Utrecht region, data which is used as the base for the input of the model. The corresponding demand for the Utrecht network covers the morning peak period containing trips made between 6 and 10 am. The data was comprised and derive from the NRM and used for regional planning, being calibrated to reflect the state of traffic for the year 2012. Due to the limitation of the region it represents, the demand does not contain long distance traffic that can originate from outside the region thus possibly limiting the demand for a potential HOT-lane.

Nevertheless the network is extensive enough to include several similarly sized corridors that can be alternative routes for the studied corridor. Although it is recommended to include at least such a corridor in the derived sub-network comprising of the study location, there is a substantial impact on Marple's running time even for a reduced area.

Because the additions to the model are not directly integrated into the simulation procedure, they require a substantial amount of model runs to be performed. Therefore, at the time of this analysis, the sub-network used for the analysis is comprised only of the studied corridor, with the afferent connections to other highways and to some extent the national roads network around it (see Figure 5.5). It has to be said that at this point, the potential HOT-lane implementation only considers the same direction of the corridor as the one also analysed in section 4.



**Figure 5.5 Selected subnetwork containing A27L corridor**

### **5.2.2 The realisation of the sub-network**

In the same lines as the national traffic models, Marple also provides the option to perform a "Selected link analysis". The procedure, based on the link(s) specified by the user, provides the OD-pairs that use those link(s) and the extent of their contribution in terms of traffic flows. This provides a good overview on where the demand originates and what are the areas that need to be included. In the case of the studied network there aren't any extra considerations made evident by

the selected link analysis. The data from the analysis can serve to other purposes, other than providing an overview, further in the investigation.

It is worth mentioning that the data was examined to check any indication on other corridors that can take the role of an additional free alternative, besides the adjacent general purpose lanes, once the HOT-lane is implemented. The results show that less than 0.5% of the demand from OD-pairs that use the A27L corridor, use the alternative A28 highway section between Utrecht and Amersfoort. The low percentage only gives indication on the current situation meaning that the alternative route still has the potential of attracting traffic depending on the effects of the HOT-lane on the general purpose lanes. Due to reasons mentioned earlier, regarding simulation running time, it was decided that a sub-network comprised only of the studied corridor is to be created.

A cordon is created that represents the boundary of the future sub-network and the links that it intersects will be replaced with new zones that are comprised of the demand entering and leaving the sub-network. The routes that contain these links are accounted for in terms of traffic entering and exiting. For a better correlation when it comes to calibration and verification, the elements that the sub-network consists are copied directly from the Utrecht network to maintain the same composition and numbering.

### **HOT-lane**

The length of the HOT-lane facility is set to avoid the two major interconnections, with the A1 and the Utrecht ring, resulting in a length of 13.3 kilometres. There are two types of HOT-lane variants added to the sub-network:

- Start – end access (the access to the HOT-lane can only be gained at the start and at the end of the corridor)
- Intermediate access (variations that include one or both of the access points with the on/off ramps present along the corridor)

One intermediate access point connects the A27 corridor with Hilversum's ring road and the other with the N234 national road leading to Bilthoven.

Unlike the start-end variant, which is comprised of only one link, the intermediate variants have five links with lengths matching the summation of the general purpose links adjacent to each of them.

The start-end variant is always preferable due to less interference caused by interweaving effects at the access and egress points. In case the HOT-lane has significant spare capacity, intermediate access points are to be added in order to further alleviate the traffic on the general purpose lanes.

## Travel time classes

In order to keep the effects of the already limited trip lengths, the travel times corresponding to the trips that have the origin and/or the destination outside the sub-network are included in travel time classes.

With the use of the data from the selected link analysis, the travel times of the trips that pass the studied corridor are analysed. The data contains the total travel times from zone  $i$  to zone  $j$ . However the travel time classes are based on the time to reach the corridor and the time from the corridor to the destination. In order to estimate these travel times a zone (centroid) that is located near to the end of the corridor is used. The travel times from all the trips that have as destination the selected zone are collected.

For each trip, the travel time from the end of the corridor is equal to the difference between the travel time between zone  $i$  and  $j$  and the travel time from zone  $i$  to the selected zone. Further deducting the travel need to pass the corridor, which can also be obtained from Marple, also the travel time to reach the corridor is found. By applying the same procedure to all the OD-pairs that use the corridor, the travel times before and after the corridor with the corresponding trips are accounted for. The resulted values are shown in Table 5.8, where they are categorized on travel time classes.

**Table 5.8 Traffic flows for morning peak classified by time before and after the corridor**

		Time from the corridor			Origins total trips	Percentage of total trips
Travel time class		0-10	10-20	>20		
Time to reach the corridor	0-10	7286.832	6311.242	8130.298	21728.37	20
	10-20	32254.05	19145.62	33696.08	85095.75	79
	>20	255.9538	218.3014	139.9287	614.1839	1
Destinations total trips		39796.84	25675.16	41966.31	107438.3	
Percentage of total trips		37	24	39		

In order to reflect these travel time within the corridor's model the corresponding connector links are given characteristics that in result in travel times equal to the medians of each class. All the new connector links are set to have similar maximum speeds as the links they connect to in order to prevent congestion effects as the demand enters the network.

Due to the higher travel times experienced to enter the network, the effect of latent demand may be experienced. Knowing that the medians of the travel time classes only exceed the duration of two periods, the whole demand is shifted two periods.

### 5.2.3 Income classes

For the purpose of this study, several user classes are constructed. The main reason is to reflect the distribution of future users for the HOT-lane based on income, in order to identify and address possible equity issues, as presented in section 2.3.3. The income has its most impact in value of time and by extension on the VOR due to the use of the correlation between the two previously decided in section 5.1.2.

The study of Tseng et al. (2005) describes the results of a Stated Choice study. This study is made by questioning 1115 Dutch commuters. A couple of choice panels are stated and the respondents are asked to give their preferred travel alternative under the stated conditions (toll, travel time, travel time uncertainty and arrival time). Based on this study the valuation of travel time and schedule delay is deduced for different respondent characteristics. From the studies' results the distinction is made by household income with the following categories and their corresponding values of time:

- <28.500€ - VOT 4.88€
- 28.500-45.000€ - VOT 6.08€
- 45.000-68.000€ - VOT 12.31€
- >68.000€ - VOT 10.10€

As the valuation of users on travel time savings and the reliability of travel time vary substantially between user classes, this will have important consequences on the result of the HOT-lane simulation. This leads to an even more crucial aspect in the form of how the distribution of the user classes is performed within the traffic model.

The desired source for the travel demand to be used for the simulation is from the national traffic models used in the Netherlands (LMS/NRM). The obtained OD-matrices represent the number of trips made between different zones during specific time periods in a day. The output data of the national traffic models should also contain information on the number of households within the income classes within each region.

The trip frequency distribution is determined based on the statistical data provided by OViN. Table 5.9 presents the trip frequency and the average travelled distance per person per day for different individual income classes. Because instead of the individual income the household income is selected as the user class, these trip frequencies cannot be used directly.

**Table 5.9 Average trip frequency and distance travelled per person per day as a car driver**

Individual income	Trip frequency	Distance travelled	Average trip length
<20.000€	0.67	8.34	12.45
20.000-30.000€	0.96	11.73	12.22
30.000-40.000€	1.48	22.84	15.43
40.000-50.000€	1.69	30.48	18.04
>50.000€	1.99	44.83	22.53

To estimate the trip frequency for the different household incomes the individual incomes have to be related to household incomes. Again the statistics provided by CBS, contain the distribution of household incomes for different characteristics including the number of persons in a household with an income. This distribution is presented in Table 5.10.

**Table 5.10 Households X 1000 distributed according to number of persons with income**

Household income	Number of persons with income in the household			
	1	2	3	4
<28.000	504	36	4	1
28.000-45.000	818	154	4	0
45.000-75.000	844	544	32	4
>75.000	371	1389	368	221

For each number of persons in a household with income and each household income, a distribution over individual incomes is estimated. For example, a household of two persons with a total income between 28.000€ and 45.000€ is defined to correspond to 0.7 persons with an individual income smaller than €20.000, 1.0 person with an income between € 20.000 and € 30.000 and 0.3 persons with an income between €30.000 and € 40.000. Knowing that there are 154.000 of this kind of households and the average trip frequencies for these three individual income classes are 0.67, 0.96 and 1.48 respectively (see Table 5.9), the estimated number of trips for this class is:

$$154.000 \text{ households} \cdot (0,7 \cdot 0,67 \text{ trips} + 1,0 \cdot 0,96 \text{ trips} + 0,3 \cdot 1,48 \text{ trips}) = 300.000 \text{ trips}$$

In Table 5.11 there are presented the calculated number of trips for all household incomes classes and number of persons with income. The trips are summed up for each household income class and subsequently divided by the total number of households in this class. This results in the average trips per household.

**Table 5.11 Total number of trips per household**

Household income	Number of persons with income in the household (Trips x 1000)				Total trips (x1000)	Number of households (x1000)	Trips per household
	1	2	3	4			
<28.000	440	54	6	1	501	546	0.92
28.000-45.000	1040	300	7	0	1347	975	1.38
45.000-75.000	1406	1247	73	10	2736	1424	1.92
>75.000	739	5078	1346	810	7972	2350	3.39

The average trip frequency can be multiplied with the number of households in each zone  $i$  for each income class  $k$  to estimate the total number of trips  $O_{ik}$  that are result from each zone for each income class. Because these trips are for whole day, the estimated trips cannot be considered as the absolute trip production for each zone  $i$  and income class  $k$ , but they are only used as a scaling factor that can be applied to the total trip production, using the formula:

$$O_{ik} = \frac{Households(i,k) \cdot average\ trip\ frequency(k)}{\sum_k (Households(i,k) \cdot average\ trip\ frequency(k))} \cdot O_i$$

The distribution of income classes is derived using the procedure described previously in the section 5.2.3 with the consideration that, where possible, the statistical figures specific for the Utrecht province were used. The resulted distribution is presented in Table 5.12.

**Table 5.12 Trip distribution between income classes for the sub-network**

Percentage of total demand	User classes based on income			
	<28.500€	28.500-45.000€	45.000-68.000€	>68.000€
	23%	34%	26%	17%

The mode choice model applied to the initial model run results in a distribution of **6.2%** carpooling (HOV) vehicles and **93.8%** driving alone (SOV).

### Travel time variability

With the use of the same data collected for the location analysis from section 4, the travel time distribution is analysed and is statistically fit with one of functions described in section 5.1.1. The data set corresponds to the 6 to 10 am time period and is comprised of travel times collected over 37 Tuesdays during the year 2012, resulting in a collection of 296 travel times corresponding to each 15 minute period.



The distribution fit shows that, although in the case of some of the time periods, the Burr function performs better statistically there are circumstances when no estimation is possible. Thus it is opted for the lognormal fit and the resulting values and parameters are presented per time period in Table 5.13.

**Table 5.13 Lognormal parameters for all considered time periods**

<b>Time period</b>	<b>Mean</b>	<b>Variance</b>	<b>Standard dev.</b>	<b><math>\mu</math></b>	<b><math>\sigma</math></b>
06:00-06:15	7.3	0.01	0.1	1.98	0.01
06:15-06:30	7.56	0.05	0.22	2.02	0.03
06:30-06:45	8.74	2.71	1.64	2.15	0.18
06:45-07:00	10.78	10.81	3.28	2.33	0.29
07:00-07:15	12.92	14.29	3.78	2.51	0.28
07:15-07:30	15.58	19.39	4.40	2.70	0.27
07:30-07:45	17.02	19.13	4.37	2.80	0.25
07:45-08:00	17.91	19.21	4.38	2.85	0.24
08:00-08:15	18.01	17.96	4.23	2.86	0.23
08:15-08:30	17.83	19.62	4.43	2.85	0.24
08:30-08:45	17.53	23.10	4.8	2.82	0.27
08:45-09:00	16.37	21.43	4.63	2.75	0.27
09:00-09:15	15.14	21.95	4.68	2.67	0.30
09:15-09:30	13.98	26.49	5.14	2.57	0.35
09:30-09:45	12.03	22.36	4.73	2.41	0.38
09:45-10:00	10.23	15.10	3.88	2.25	0.36

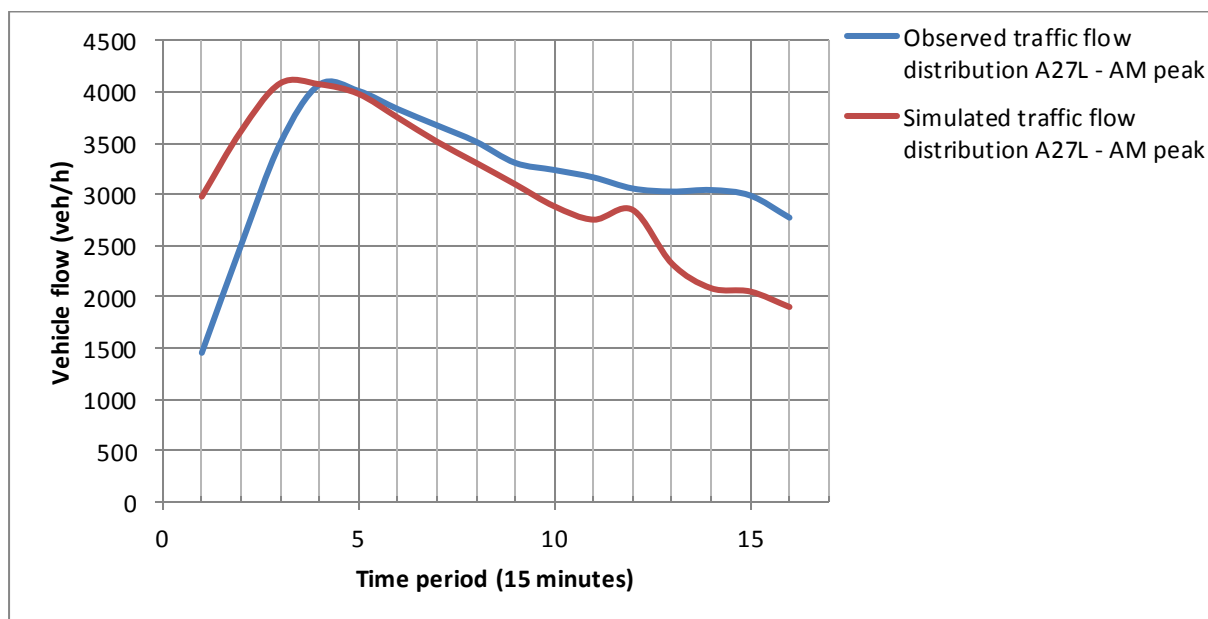
Assuming that the travel time assignment estimates the mean travel time, the travel time variability is determined with the use of the parameters determined previously. As a consequence, in order to consider the assumption realistic, the model's ability to produce travel times that fit the average distribution found from empirical traffic observations. This will be evaluated further in the next section, where the model's calibration and verification is addressed.

Due to the fact that there is no prediction of the travel time variability based on the changed traffic conditions of the multiple implementation variations that need to be investigated, it is consider that the variation for the new alternatives is expressed proportionally to the observed one with a certain factor. The factors are based on the expected influence that the new traffic conditions have on travel time reliability.

### 5.2.4 Calibration and verification of the model

The results of the modelled corridor are to be compared against direct observation from the detector loops data, same data that was used previously in section 4. Ensuring that the model is construct value, calibration actions are taken.

Due to the less extensive nature of the sub-network modelled, the calibration is done only with respect to traffic data along the A27L corridor. The Utrecht network is also used for comparison purposes in order to further validate the construction validity and evaluate the effects of limiting the model only to the corridor area. As the Utrecht network is used for regional traffic planning purposes, its validity and prediction capability is already partially assumed.



**Figure 5.6 Traffic flows comparison between simulation and historic data**

Figure 5.6 shows the flows distribution comparison over the morning peak for the whole corridor, in the case of the base sub-network. The representation is only for an overview of differences due to the differences on how the two distributions were computed for the whole length of the corridor.

For calibration purposes, three links are used corresponding to the beginning, middle and end of corridor. By comparing the link flows with the data collected from the detector loops averaged for all working days and only for the months March-April and October-November, considered to be periods that are considered most representative. The differences, before and after calibration are summarized in Table 5.14.

**Table 5.14 Deviations results before and after calibration**

		06:00-07:00	07:00-08:00	08:00-09:00	09:00-10:00
Corridor section					
Start	Before	+10%	+8%	+4%	-14%
	After	-0.2%	+3%	0%	+5%
Middle	Before	+30%	+3%	+24%	-9%
	After	+1%	0%	+5%	-2%
End	Before	+14%	+6%	-20%	-24%
	After	0%	+1%	+4%	+3%

It appears that due to the adjustment made to prevent latent demand as cause of the travel time classes, resulted in an overestimation of the early hours. The underestimation of the later periods appears to be an effect prior to the addition of travel time classes as an increase of demand should also have been experienced during this time.

### 5.2.5 Potential development of scenarios

The starting point of the development of what are defined as scenarios is the implementation of a start-end variant of the HOT-lane. As mentioned in the previous subchapter, this is preferable due to the limiting factor on the interweaving disturbances created at the access and egress point of the facility. Another consideration that makes this approach favourable is that the HOT-lane in essence is providing a congestion free alternative and to be able to maximize this benefit it needs to cover the whole length of the reoccurring congestion.

For each variant that is to be comprised its performance will be evaluated in correspondence to different objectives. As concluded in chapter 3, the effects of the goals and objectives are considered to influence a HOT-lane implementation in terms of access/egress points' setup, pricing scheme and target groups for potential demand.

The effects of the implementation are also compared to a "free" alternative representing an addition of capacity corresponding to an extra lane, which can be regarded as a rush-hour lane.

The pricing schemes are considered and their effects evaluated based on three pricing objectives:

- Minimize total travel costs
- Maximize revenue
- Maintain minimum speed of 80 km/h

The total travel cost represents the aggregated total travel time costs calculated only for the trips that pass the whole corridor. The reductions of these costs are not to be correlated directly with welfare gains as the road users that use the corridor benefit only marginally from the toll income. In addition to the toll income also the costs afferent to the variability applied to the general purpose lanes is added.

#### **Start-end variant**

The HOT-lane is added to the network as an extra route composed of five links for allowing later on to use the same links for the composition of the variants that include access at the intermediate on/off ramps present on the corridor.

The capacity of the HOT-lane is set to 2000 veh/h in order to reflect the possible safety concerns and influence of the limited road space available.

Due to the model's use of a C-logit route choice algorithm, the assignment penalizes overlap in routes. Because the size of the sub-network is also limited, the HOT-lane overlaps almost entirely with the routes of OD-pairs that use the whole length of the corridor. Because of this, the route random generation applied by Marple rules out the alternative provided by the HOT-lane making

necessary the manual introduction of routes comprising of the HOT-lane links for each of the routes from which the corridor is part of.

### **Intermediate access**

In case of poor demand or spare capacity depending from which perspective the outcome of the investigation of a start-end HOT-lane is regarded, the inclusion of intermediate access corresponding to on/off ramps along the highway corridor can be assessed. Although this is not generally the case of the corridor under analysis, an attempt to isolate the effects of such an implementation is made.

In the case of the A27 corridor there are two locations where on/off ramps are located thus there are three variants comprised with the following setups:

- Access only to the first on/off ramps location granted
- Access only to the second on/off ramps location granted
- Access both on/off ramps location granted

The high traffic interferences occurring at the on/off ramps as a result of providing access to the HOT-lane resulted in an extensive congestion on the HOT-lane.

## **5.3 Overview**

As it can be observed in the contents of section 5.2.5, there is no presentation of results or effects resulting from the simulation of different scenarios.

The reason behind this situation is that at the moment of the writing of this report, the results resulted out of Marple were not considered realistic as they could not be validated in any case. The causes of this lays with the modifications within the internal simulation procedure of the traffic model that needed to be imposed in order that all the additions and aspects included in the modeling framework could work. Unfortunately the time required for the sorting out of the risen issues could not be fitted into the limited time-frame available for this research.

Although the modeling procedure was developed in detail and although numerous, the additions imposed on the existing traffic simulation model Marple were numerous, their level of detail was kept to a minimum. The overlook was with regards to the internal modifications of the modeling procedure that were needed to ensure an acceptable compatibility between the existing traffic model and the additions that included extra inputs provided by externally developed procedure. The compatibility obtained would have allowed a reliable traffic simulation procedure to provide the necessary results.

In conclusion, all of the results obtained to this point were omitted due to the uncertainty they can pose on the evaluation of the implementation. Nevertheless, important lessons can be drawn with regards to the modeling framework included in the methodology. The results only pry us of a specific example of a potentially successful implementation setup derived with the use of the proposed methodology.

The various scenarios are meant to provide insight on the outcome of the evaluation when applying different pricing schemes, also to show the effects of allowing access on multiple points on the performance of the facility and the evolution of the traffic conditions for the whole corridor. Another aspect that is to be varied within the scenarios is the different setups of user groups that are given access to the HOT-lanes.

Several insights can still be obtained, as for example of the mode choice procedure that was developed to work outside the traffic model.

With the help of the mode choice developed for carpooling based on the use of limited data and extensive assumptions a basic indication of current carpooling practices can be provided. Due to the assumptions made, the choice ratios vary slightly and at levels that can be considered slightly lower than current practice in the Netherlands. Nevertheless this is arguable as the latest, rather distant time-wise, study (Molnár & Konen, 2003) showed a steady trend of decreasing vehicle occupancy in the Netherlands.

The values represented in the model have an average of 7% carpoolers. The previously mentioned study concluded in 2002 that the number of carpooling vehicles in 2002 decreased with 30% compared to the year 1995 resulting in percentage of 8% out of the total home-work traffic.

From this perspective it was tried to see the effects of assuming an increase in incentive for carpooling is experienced. This was achieved simply by doubling the mode specific constant corresponding to the HOV mode. This results in a rather significant increase of carpooling vehicles that reach the value of 19% out of all trips.

As it is to be expected this results in a higher participation of HOVs in the HOT-lane that it is hypothesized to lead to a decrease in revenue. Nevertheless the pricing of carpooling vehicles can be considered to limit the impact, although in practice it is resorted to the measure of increasing the vehicle occupancy requirements.

A different situation is when the demand for the ODs that use the highway is increased with 8% to reflect the participation of heavy vehicles and they are granted access to the HOT-lane. The similar loss of revenue can be avoided, and rather increased, by charging the freight related traffic a higher toll which is more easily accepted due to their significantly higher VOT. A possible

disadvantage can be that due to their speed limitation, these participants influence negatively the performance of the facility and its safety.

The differences in resulting effects and the results of the evaluation due to the application of several type of pricing scheme can be expected to be in the lines shown from previous research (Joksimovic & Bliemer, 2006). The mentioned study has shown the trade-offs between achieving maximum revenues and minimizing travel time costs. As a conclusion, depending on the mentioned objective functions in section 3.4.2 that can be assume by the facility's operator, there are different optimal tolling schemes with different toll levels.

## 5.4 Conclusions

The adapted modeling procedure proved to pose several issues due to not seamlessly intertwining of an existing traffic simulation model, externally developed procedures and adapted input and network from other existing models, rather than from the ground up. In conclusion the results necessary for the final evaluation of the case study example couldn't be used.

The expected interactions and influences of the different design aspects such as access points, pricing scheme and also variants for the operating strategy in terms of user groups that can use the facility were discussed and their hypothesized effects can be expected to come close to validated results.

The mentioned effects include possible insights to be obtained by assuming increased incentive for carpooling in terms of reduced potential revenue that is compensated in the evaluation by the more substantial benefits of increased throughput of people due to overall increased vehicle occupancy. The same goes for allowing freight vehicles the use of the facility although this case can result in negative effects that outweigh the increase of revenue.

The effects of applying various pricing schemes is also hypothesized and derived from previous research. The effects reflect the fact that for different objective functions (maximizing revenue, minimize total travel time, etc.) considered by the facility's operator, there are different optimal tolling schemes with different toll levels.

The aspects that could not be addressed, due to the lack of validated results, are concerning the influence of different access points' setups (start-end access, multiple accesses) and of the accountability of reliability on the facility's performance.

## 6 Evaluation of the methodology

This chapter is meant for the resulting reflections on the practical application of the methodology on specific cases. The reflections are regarding the efficiency, the practicality and the ease of using and applying the methodology. Each phase and its steps are assessed both individually and in relation to each other.

### 6.1 Considerations on Phase 1:

Phase 1 was applied on a preliminary list of problem areas, and with the help of the methodology's specified criteria and of historic data obtained from the national network of detector loops, the potential candidates were rated across aspects such as: congestion, reliability, demand and physical attributes.

#### 6.1.1 Relevance of indicators

The indicator used for representation of congestion is already widely use in traffic states evaluation in the Netherlands and its representativeness is considered acceptable. In the case of reliability, it is advisable that the chosen indicator applied to historic data can also be determined from the traffic simulation results, if reliability effects are considered to be reflected within the modeling procedure.

When it comes to the evaluation of suitable potential demand for the HOT-lane it is advisable, if it doesn't affect negatively the efforts and time required for the application of the methodology's steps, to include more indicators such as the trip length distribution. This can result in a better evaluation of candidates without going to great extents such as forecasting HOT-lane demand using regional or national traffic simulation models. This can be achieved to less extensive procedure such as selected link analysis performed on small sections of highway within the problem areas.

In terms of physical attributes of the corridors it is possible that through further research on the effects of design restrictions on driving behavior, more specific interval of measurements can be used for the evaluation of highway section suitability for such a concept.

#### 6.1.2 Weights for criteria

The final rating of the potential candidates was achieved through the use of determined weights. The method applied for the computation of the weights is the Analytic Hierarchy Process (Saaty, 2008) that through pairwise comparisons and judgments of experts can determine priority of



scales. Although the method focuses on obtaining better consistency it still is subject to bias. Thus the prioritization of the criteria can be argued upon.

### **6.1.3 Location selection**

In this report, only the case of rating of the potential candidate corridors through comparison relative to each other was presented in detail. Another approach when considering applying Phase 1 would be consisting of the use of threshold values for the criteria that evaluate any possible highway section and determine if it is suitable to be considered as a potential location for implementation.

## **6.2 Considerations Phase 2**

Phase 2 consists of developing a potentially successful implementation setup of a HOT-lane through the use of scenarios, a traffic simulation model and a final evaluation. The development of the scenarios is initiated based on the characteristic of the location considered and the policy goals and objectives. The latter give indications the choice of design elements such as pricing scheme and operating strategy in terms of user groups that are given access to use the HOT-lane facility.

The preliminary evaluation of the effects of the scenarios is performed with the use of simulation results obtained from the traffic model. Once a certain scenarios performs in terms of what can be considered best results, the simulation model's results are further used for a more comprehensive evaluation by comparison of achieved benefits against assumed costs.

### **6.2.1 Scenarios development**

The scenarios development relies substantially of the understanding that the methodology offers to the user with regards to the connections between certain aspects of the concept and the interaction between its various design elements.

With the forming of a sort of feedback loop between the traffic simulations and the adjustments of scenarios, a best case for implementation can be intuitively reached. On the other hand this kind of flexibility offered can lead to negative results by including sometimes complexity levels that can be considered unnecessary in certain situations.

### **6.2.2 Modeling framework**

The general and comprehensive modeling framework portrayed in Figure 3.12 and proposed as guideline for either model development or choice of an existing traffic simulation procedure can be considered to be addressing potential user of the methodology with more expertise in traffic modeling than most policy makers.

The key lies on the adjustment of the framework to provide a more intuitive choice of aspects that can be left out thus resulting in less troublesome finding of an existing model that is suitable for use without extensive additions or modifications. Nevertheless, the aspects that are left out should not influence the necessary connections between the traffic simulation procedure with the scenarios development and evaluation modules

### 6.2.3 Final evaluation

The evaluation is set up in manner of a less extensive cost benefit analysis. Only general options are offered as choices in order to make it as adaptable as the traffic simulation model can also be, both devised in order to be able to cater specific needs.

## 7 Conclusions and recommendations

This part of the report has the purpose of summarizing the most important lessons drawn from the presented research as consequences of the process that addressed the main proposed goal. The overview will include subsequent findings that throughout the report helped to reach the answer of the main research question. Not to be excluded are conclusions resulted in the evaluation of the methodology with regards to its efficiency and applicability.

Last but not least recommendations are given for the pursuit of further actions in practice as well as of future research developments.

### 7.1 Findings

The main research question that was formulated at the beginning of the project is as follows:

*[What are the methodological steps needed for defining and evaluating a potential implementation of a HOT-lane in the Netherlands and what are they comprised of?]*

Through the careful investigation of the current practice with regards to the HOT-lane concept in the U.S., it has been observed that the multitude of projects have a high variation in their characteristics. The variations are observed to address common aspects and are influencing the outcome of the operations. The main aspects are as follows: location which addresses the considerations of equity and acceptability by including factors such as travel patterns, potential travel time savings, etc.; design elements such as access points that address the demand factors, safety issues, etc.; pricing scheme.

Previous research has shown that most of the proposed and developed methods addressed a limited number of aspects, by including specific considerations of an implementation, without

consideration to flexibility and variation. From this starting point, the decision was made that the methodology is composed of two phases. Phase 1 includes the contextual considerations regarding the implementation by assessing suitable locations which can provide favourable characteristics and traffic conditions for the potential success of a HOT-lane implementation, while taking into consideration a spectrum of potential goals and objectives. With the use of Phase 2, the design elements and other operational considerations are treated. The same goals and objectives are carried on together with a specific location's characteristics and help to impose limits of the achievable variation of scenarios.

With the help of traffic simulation model, the results necessary for deciding the proper adjustments of the scenarios' setup are provided. The same model provides results for a more comprehensive and final evaluation of what is to be considered the best implementation setup after several iterations in the development of scenarios. The final evaluation translates the model's results into potential benefits that are put against assumed costs.

By applying the methodology to specific cases it was discovered that special attention has to be accorded to the choosing or development of a traffic simulation model. Its compatibility with the inputs and outputs necessary for seamless connections with the other modules present in Phase 2. In contrast to the adapted modelling framework, Phase 1 proved that it can benefit from the inclusion of additional indicators that could provide extra detail to the assessment without imposing too much extra time necessary for its application.

In the end the methodology proved useful by providing great flexibility that ensures adding extra details or including/replacing whole modules without too many complications. An implementation setup can be thus intuitively reached and evaluated.

## 7.2 Conclusions

The main conclusions included in this section are derived from the evaluation of the methodology which was addressed in section 6.

Phase 1 is straight forward, while comprehensive enough to properly rank the locations considered as potential candidates. The indicators used under the different categorized criteria can be supplemented or replaced easily. For instance, in terms of reliability, any other indicator considered to be most suitable and in line with the rest of the steps of the methodology can be used. When evaluating the potential demand for each of the corridors several other sources and indicators can be used for a more detailed evaluation.

The procedure adapted to setting the weights can be easily adapted if it is considered biased or not in line with more recent findings regarding the relevance of specific aspects of the implementation represented by certain criteria. The output of Phase 1 can be further addressed by including

threshold values for the indicators in order to ensure at a greater extent that any unsuitable location was included.

Phase 2 is able to derive specific limitation or indications provided from the goals and objectives set for the implementation as well as from the characteristics of the considered location. The procedure of developing and adapting scenarios with the use of the results provide by the modelling module is proven to be intuitive by clearly showing the influences of certain design choice of the performance of the facility. In certain cases, due to the uncertainties posed by high level of complexity it can be overwhelming to be able to reach a best implementation setup.

The proposed modelling framework as guideline, although it portrays all possible options it can be create confusion on what should or should not be included in the traffic simulation procedure. Due to this very fact, a sufficient compatibility could not be established between the adaptations and inputs provided and an existing model, leading to results that could not be validated or considered in the evaluation of scenarios.

### **7.3 Recommendations**

This section is set to include recommendations for further research and practical development regarding HOT-lanes

Regarding further research it has become evident that in terms of modeling developments suitable for such a comprehensive methodology that includes a multitude of aspects there is still a significant way to go until such performance can be reached. The combination of such diverse and numerous behavioral aspects that need to be included proves to be quite a challenge. Although it can be considered going to extreme lengths to include most of them, due to their high number the possibilities of associations between them represents a challenge. It is thus advised that further research should be conducted in determining the integration of behavioral aspects that is most relevant to HOT-lane implementation.

Other specific research should be continued in the direction of forecasting travel time variability thus providing reliability effect similar to real situations.

In order to provide further support for the methodology, in the Netherlands there is the need to focus more on research that can provide insight into carpooling incentives and its formation. Also for the improvement of the methodology, multimodality should be considered and included for the specific cases where the corridor competes directly with public transport for the same major production and attraction point for travel demand.

In terms of practical recommendation it can be advised that the methodology is incorporated into the regional or national planning frameworks, making possible for the HOT-lane concept to be considered as an alternative.

Special attention should be given also to the combination of HOT-lane operations with dedicated freight trucks lanes in order to compensate for the limited occurrence of carpooling. In the meantime, also for improvement of benefits that can be gained from the implementation and for dealing with acceptability issue, other policies should be developed for the revitalization of the carpooling phenomenon in the Netherlands.

Last, but not least, it is recommended that in order to accelerate the gain of knowledge with regards to the potential of the concept in the Netherlands, a pilot study should be developed that could also provide insight applicable to other traffic management measures as well.

The location analysis performs as expected and it can easily be improved through the use of more detailed information before screening.

It has to be said that further considerations have to be taken in terms of equity issues and acceptability which were not treated in the methodology and can pose great hurdles, especially in the Netherlands.

Also regarding the first phase, a more extensive integration of the methodology should be achieved with the planning practices from the Netherlands. This also includes the comparison of the HOT-lane against other measures that fit the goals and objectives considered.

While the modelling procedure presented is capable of predicting outcomes under a broad range of policies with limited information, it has some shortcomings that should be highlighted and which represent areas for future improvements. The accountability of reliability is quite crude and limits the possibility of making accurate predictions.

## 8 Bibliography

- AECOM Consult. (2006). *Final Report: Issues and Options for Increasing the Use of Tolling and Pricing to Finance - Task Order 05-002*.
- Amelsfort, D. v. (2009). *Behavioural Responses and Network Effects of Time-varying Road Pricing*. TU Delft.
- Appiah, J. (2004). *An examination of factors affecting high occupancy/toll lane demand*. Texas A&M University.
- Baker, R. (2008). *Moving beyond Lexus Lanes: Equity considerations for managed lanes*. Transportation Research Board.
- Bates, J., Polak, J., Jones, P., & Cook, A. (2001). The valuation of reliability for personal travel. *Transportation Research Part E*, vol. 37, 191-229.
- Besseling, P. G. (2005). *Economische analyse van verschillende vormen van prijsbeleid voor het wegverkeer*. Centraal Planbureau.
- Bianco, M. (2000). Effective transportation demand management combining parking pricing, transit incentives, and transportation management in a Commercial District of Portland, Oregon. *Transportation Research Record 1711*, 48-54.
- Bierlaire, M. (2003). BIOGEME: A free package for the estimation of discrete choice models. *Proceedings of the 3rd Swiss Transportation Research Conference*. Ascona.
- Billheimer, J. W. (1990). *San Francisco Bay Area HOV Lane User Study: Final Report*. Los Altos: Metropolitan Transportation Commission.
- Black, I. G., & Towriss, J. G. (1993). *Demand Effects of Travel Time Reliability*. Cranfield Institute of Technology.
- Brownstone, D. &. (2005). Valuing time and reliability: assessing the evidence from road pricing demonstrations. *Transportation Research Part A: Policy and Practice*, 279-293.
- Brownstone, Ghosh, D., A.Golob, Kazimi, T. F., & C. Amelsfort, D. (2003). Drivers' willingness-to-pay to reduce travel time: evidence from the San Diego I-15 congestion pricing project. *Transportation Research Part A*, 373-387.

- Bundesministerium für Verkehr, Bau und Stadtentwicklung. (n.d.). [http://www.bmvbs.de/DE/Home/home\\_node.html](http://www.bmvbs.de/DE/Home/home_node.html). Retrieved February 2011
- Burris, M. W., & Appiah, J. (2004). Examination of Houston's QuickRide participants by frequency of QuickRide usage. *Journal of the Transportation Research Board: Issue 1864*, 22-30.
- Cambridge Systematics. (2007). *The Future of Tolling in Oregon: Understanding How Varied Objectives Relate to Potential Applications*. Oregon Department of Transportation.
- Cambridge Systematics Inc. (2006). *I-394 MnPASS technical evaluation: final report*. Oakland: Minnesota Department of Transportation.
- Cambridge Systematics, Inc. (2006). *Guide to effective freeway performance measurement (Final Report and Guidebook)*. National Cooperative Highway Research Program (NCHRP).
- Centraal Bureau voor Statistiek. (2011). *Onderzoek verplaatsingen in Nederland 2010*. Den Haag: CBS.
- Centraal Bureau voor Statistiek. (2013). <http://statline.cbs.nl/statweb/>. Retrieved February 1, 2013, from [www.cbs.nl](http://www.cbs.nl).
- Chang, J. S. (2010). Assessing travel time reliability in transport appraisal. *Journal of Transport Geography*, 419-425.
- Chu, L., Kalandiyur, N., & Benouar, H. (2007). Priority-based High-occupancy-vehicle Lane Operation. *Transportation Research Board 86th Annual Meeting*. Washington D.C.
- Collier, T., & Goodin, G. D. (2002). *Managed Lanes: A New Concept for Freeway Travel*. Texas Transportation Institute.
- Concas, S., & Winters, P. (2007). The impact of carpooling on trip chaining behavior and emission reductions. *Proceedings of the Transportation Research Board 86th Annual Meeting*. Washington, D.C.
- D., B., & Small, K. (2005). Valuing time and reliability: assessing the evidence from road pricing demonstrations. *Transportation Research Part A*, vol.39, 279-293.
- Davis, R. W. (2009). Factors affecting Willingness to Pay for High-Occupancy-Toll Lanes. *Transportation Research Board 88th Annual Meeting*, (p. 22).
- De Dios Ortúzar, J., & Willumsen, L. (2001). *Modelling Transport*. Chicester: Wiley & Sons Ltd.

- de Jong, G., Kouwenhoven, M., Kroes, E., Rietveld, P., & Warffemius, P. (2009). Preliminary Monetary Values for the Reliability of Travel Times in Freight Transport. *European Journal of Transport and Infrastructure Research*, 83-99.
- De VerkeersInformatie Dienst. (2008). <http://www.vid.nl/top50.html>. Retrieved September 30, 2012, from <http://www.vid.nl>: <http://www.vid.nl/top50.2007.html>
- Duecker, K., Bair, B., & Levin, I. (1977). Ride sharing: psychological factors. *Transportation Engineering Journal of ASCE* 103, 685-692.
- Federal Department of Transportation. (2011). *95 Express Annual Report*. Miami.
- Federal Highway Administration (FHWA). (2003). *A guide for HOT lane development*. FHWA.
- Federal Highway Administration (FHWA). (2004). *Managed Lanes - A Cross-Cutting Study*. FHWA.
- Federal Highway Administration (FHWA). (2008a). *Economics: pricing, demand and economic efficiency: a primer*. Washington: FHWA.
- Federal Highway Administration. (2008). *Managed Lanes - A Primer*. Washington: FHWA.
- Finkleman, J. (2010). *The HOT Solution: An Examination of the Desirability for High-Occupancy/Toll (HOT) Lanes in the Greater Toronto Area*. Waterloo: University of Waterloo.
- Fisher, G., & Goodin, G. (2005). *DECISION FRAMEWORK FOR SELECTION OF MANAGED LANES STRATEGIES*. Austin: Texas Transportation Institute.
- Florida Department of Transportation. (2009). *Final Report- 95 express midyear report project status for urban partnership agreement*. Miami: FDOT.
- Golob, T., Golob, J., & Supernak, J. (2001). *I-15 congestion pricing project monitoring and evaluation services, task 8, phase II year three attitudinal panel study*. San Diego.
- Halvarson, R., Nookala, M., & Buckeye, K. (2006). *High Occupancy Toll Lane Innovations: I-394 MnPass*. Transportation Research Board.
- Hamilton, B. A. (2006). *Investigation of Implementation Issues for Congestion Charging*. Wellington : Land Transport New Zealand.
- Hau, T. (1992). *Economic Fundamentals of Road Pricing: A Diagrammatic Analysis*. Washington: The World Bank.



- in 't Veld, R. (2009). Monitoring of the main effects of rush hour lanes in the Netherlands. *Proceedings of the European Transport Conference*. Leeuwenhorst Conference Centre: Centre of Transport and Navigation of the Netherlands.
- Joksimovic, D., & Bliemer, M. (2006). *Different policy objectives of the road authority in the optimal toll design problem*. Delft.
- Jong, G. d., Kouwenhoven, M., Kroes, E., Rietveld, P., & Warffemius, P. (2009). Preliminary Monetary Values for the Reliability of Travel Times in Freight Transport. *European Journal of Transport and Infrastructure Research*, 83-99.
- K., S. (1982). The Scheduling of Consumer Activities: Work Trips. *The American Economic Review*, vol. 72, 467-479.
- KiM. (2011). *Mobiliteitsbalans 2011*. Kennisinstituut voor Mobiliteitsbeleid. Ministerie van Infrastructuur en Milieu.
- Kim, E. (2002). *HOT lanes: a comparative evaluation of costs, benefits, and performance*. University of California.
- Kooten, J. v., & Adams, K. (2011). Gebiedsgericht Benutten Plus. In *Handboek Verkeersmanagement*. CROW.
- Lam, T. C., & Small, K. A. (2001). The value of time and reliability: measurement from a value pricing experiment. *Transportation Research Part E: Logistics and Transportation Review*, 231-251.
- Lam, T., & Small, K. (2001). The value of time and reliability: measurement from a value pricing experiment. *Transportation Research Part E*, vol. 37, 231-251.
- Li, J. (2001). Explaining high-occupancy-toll lane use. *Transportation Research Part D*, 61-74.
- Lindsey, C., & Verhoef, E. (2000). *Traffic Congestion and Congestion Pricing*. Amsterdam: Tinbergen Institute.
- Lint, H. v. (2011). *Innovations in Dynamic Traffic Management*. TU Delft.
- Litman, T. (1999). *Using road pricing revenue: Economic efficiency and equity considerations*. Victoria Transport Policy Institute.
- Lomax, T., Schrank, D., Turner, S., & Margiotta, R. (2003). *Selecting Travel Reliability Measures*. Texas Transportation Institute.

- Loudon, W. (2009). Sketch Planning Assessment of Managed-Lane Options for I-5 Freeway Corridor Master Plan. *Transportation Research Board 88th Annual Meeting*. Washington D.C.
- Lyman, K., & Bertini, R. L. (2007). *Using Travel Time Reliability Measures to Improve Regional Transportation Planning and Operations*.
- Mahendra, A., Grant, M., Higgins, T., & Bhatt, K. (2010). *Road Pricing: Public Perceptions and Program Development*. National Co-operative Highway Research Program (NCHRP).
- Mastako, K. A., Rillet, L. R., & Sullivan, E. C. (1998). Commuter behavior on California state route 91 after introducing variable-toll express lanes. *Transportation Research Board*, 47-54.
- Mastako, K., Rilett, L. R., & Sullivan, E. C. (1998). Commuter Behavior on California State Route 91- After Introducing Variable-Toll Express Lanes. *Transportation Research Record 1649*, 47-54.
- McGuckin, N., Srinivasan, N., & Murakami, E. (2005). *Do Race and Ethnicity Make a Difference in Travel and Commuting Behavior?*
- Middelham, F. (2006). *State of practice in Dynamic Traffic Management in the Netherlands*. Rotterdam: Transport Research Centre (AVV), Ministry of Transport Public Works and Watermanagement.
- Ministerie van Infrastructuur en Milieu. (2008, September 19). <http://www.rijksoverheid.nl/documenten-en-publicaties/persberichten>. Retrieved September 30, 2012, from <http://www.rijksoverheid.nl: http://www.rijksoverheid.nl/documenten-en-publicaties/persberichten/2008/09/19/spoedaanpak-alle-wegen-sneller-aanleggen.html>
- Ministrie van Verkeer en Waterstaat. (1999). *Betaalstroken: Een alternatieve uitbreidingsvariant nader onderzocht*. Rotterdam: Rijkswaterstaat, Adviesdienst Verkeer en Vervoer.
- Mirshahi, M., Obenberger, J., Fuhs, C. A., Howard, C. E., Mayhew, R. M., Moore, M. A., et al. (2007). *Active Traffic Management: The Next Step in Congestion Management*. FHWA.
- MnDOT. (2008). *I-394 HOV report including 2008- 1st quarter January – March*. Regional Transport Management Centre.
- Molnár, H., & Konen, R. (2003). *Carpoolen in het woon-werkverkeer*. CBS.

- Molnár, H., & Konen, R. (2003, October 27). Een kwart minder carpoolers. *Web Magazine*. Netherlands.
- Morency, C. (2007). The ambivalence of ridesharing. *Transportation* 34, 239-253.
- Munnich, L., & Barnes, G. (2004). *Minnesota Value Pricing Project Final Report*. Humphrey Institute of Public Affairs.
- Munnich, L., & Buckeye, K. R. (2007). I-394 MnPASS high-occupancy toll lanes planning and operational issues and outcomes (lessons learned in year 1). *Journal of the Transportation Research Board No. 1996*, 49-56.
- Nesamani, K. C. (2010). Policy Implications of Incorporating Hybrid Vehicles into High-Occupancy Vehicle Lanes. *Journal of Transportation Systems Engineering and Information Technology*, 30-41.
- Noland, R., & Small, K. (1995). Travel-Time Uncertainty, Departure Time Choice, and the Cost of Morning Commutes. *Transportation Research Record*.
- OECD. (2010a). *Improving reliability on surface transport networks*. Organization for Economic Co-operation and Development.
- Parkany, E. (1999). Can high-occupancy/toll lanes encourage carpooling? Case study of carpooling behavior on the 91 Express Lanes. *Journal of the Transportation Research Board*, 46-54.
- Parsons Brinckerhoff. (2003). *A guide for HOT lane development*. Washington: FHWA.
- Parsons Brinckerhoff, Texas Transportation Institute. (2003). *A Guide for HOT Lane Development*. Federal Highway Administration.
- PB Study Team. (2002). *HOV Performance Program Evaluation Report*. Los Angeles: Los Angeles County Metropolitan Transportation.
- Peer, S., Koopmans, C., & Verhoef, E. T. (2010). Predicting travel time variability for cost-benefit analysis. *Tinbergen Institute Discussion Papers No. 10-071/3*. Tinbergen Institute.
- Perez, B. G., & Sciara, G.-C. (2003). *A Guide for HOT-lane development*. Federal Highway Administration.
- Plotnick, R., Romich, J., & Thacker, J. (2009). *The impacts of tolling on low-income persons in the Puget Sound region*. Seattle: Washington State Department of Transportation.

- Rijkswaterstaat. (2011, June). [http://www.rws.nl/wegen/plannen\\_en\\_projecten](http://www.rws.nl/wegen/plannen_en_projecten). Retrieved September 30, 2012, from [http://www.rws.nl: http://www.rws.nl/wegen/plannen\\_en\\_projecten/spoedaanpak\\_30\\_knelpunten/](http://www.rws.nl: http://www.rws.nl/wegen/plannen_en_projecten/spoedaanpak_30_knelpunten/)
- Rijkswaterstaat Dienst Verkeer en Scheepvaart. (2012). *Publieksrapportage Rijkswegennet*. RWS.
- Rijkswaterstaat. (2005). *Gebiedsgericht benutten - Werkboek*.
- Rountree, & al., e. (2008). Georgia's approach to congestion with four T's: Tolling, transit, telework, and technology. *Transportation Research Board 87th Annual Meeting*, (p. 17).
- Rufolo, A. M., & Bertini, R. L. (2003). Designing Alternatives to State Motor Fuel Taxes. *Transportation Quarterly*, Vol. 57, No. 1.
- Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences*, 83-98.
- Samuel, P. (2003). *Tolls and Surface Transportation Reauthorization*. The Heritage Foundation.
- Scholten, S., Jankovic, S., & Uden, J. v. (2000). *De weg van de minste weerstand - Literatuur Onderzoek gedragdeterminanten Betaalstroken*. De Adviesdienst Verkeer en Vervoer.
- Schreffler, E. (1998). *I-15 Congestion Pricing Project monitoring and evaluation services*. San Diego: San Diego University, Department of Civil and Environmental Engineering.
- Shao, H., & Lam, W. (2006). A demand driven travel time reliability based traffic assignment problem. *Proceedings 85th TRB*.
- Small, K. C. (2005). Uncovering the distribution of motorists' preferences for travel time and reliability. *Econometrica*, vol. 73, 1367-1382.
- Small, K., & Yan, J. (2000). *The value of "value pricing" of roads: Second-best pricing and product differentiation*. Resources for the Future.
- Small, K., Noland, R. B., Chu, X., & Lewis, D. (1999). *Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation*. Washington: Transportation Research Board.
- South Florida Commuter Services. (2009). *June 2009 - 95 Express Survey Results*. Tampa: University of South Carolina - Centre for Urban Transportation Research.

- Stockton, W., Benz, R., Rilett, L., A.Skowronek, D., Vadali, S., & Daniels, G. (2000). *INVESTIGATING THE GENERAL FEASIBILITY OF HIGH OCCUPANCY/TOLL LANES IN TEXAS*. Austin: Texas Transportation Institute.
- Stockton, W., Edmonson, N., Hughes, P., Hickman, M., Puckett, D., & Q. Brown, A. (2000). *An Evaluation of the Katy Freeway HOV Lane Pricing Project*. Texas Transportation Institute.
- Sullivan, E. (1998). *Evaluating the Impacts of the SR 91 Variable-Toll Express Lane Facility*. Cal Poly State University.
- Sullivan, E. (2000). *Continuation study to evaluate the impacts of the SR-91 value-priced express lanes: Final report*. Luis Obispo: California State Department of Transportation.
- Sullivan, E., & Harake, J. E. (1998). California route 91 toll lanes impacts and other observations. *Journal of the Transportation Research Board* 1649, 55–62.
- Supernak, J. (2005). *HOT Lanes on Interstate 15 in San Diego: Technology, Impacts and Equity Issues*. Cancun: PIARC.
- Supernak, J., Golob, J., Golob, T., Kaschade, C., Kazimi, C., Schreffler, E., et al. (2002). San Diego's Interstate 15 congestion pricing project: traffic-related issues. *Journal of the Transportation Research Board* No. 1812, 43-51.
- Taale, H. (2006). Analysing loop data for quick evaluation of traffic management measures. *European Transport Conference*. Strasbourg.
- Tilahun, N. Y., & Levinson, D. M. (2007). Value of Time Comparisons in the Presence of Unexpected Delay. *Third International Conference on Transport Network Reliability*. Delft.
- Tseng, Y. Y., Ubbels, B., & Verhoef, E. (2005). *Value of Time, Schedule Delay and Reliability. Estimation Results of a Stated Choice Experiment among Dutch Commuters Facing Congestion*. Amsterdam: Free University.
- Tu, H., Van Lint, J., & Van Zuylen, H. (2008). Travel time reliability model on freeways. *Proceedings 87th TRB*.
- Turnbull, K. (2005). 12th international HOV systems conference: improving mobility and accessibility with managed lanes, pricing. FHWA.
- U.S. Government Accountability Office. (2012). *Traffic Congestion - Road Pricing Can Help Reduce Congestion, but Equity Concerns May Grow*. GAO.

- van Lint, J. W., van Zuylen, H. J., & Tu, H. (2008). Travel time unreliability on freeways: Why measures based on variance tell only half the story. *Transportation Research Part A: Policy and Practice*, 258-277.
- Van Lint, J., & Van der Zijpp, N. (2003). An improved travel time estimation algorithm using dual loop detectors. *TRB 2003 Annual Meeting*. Washington D.C.: TRB.
- Verhoef, E., & Ubbels, B. (2006). *CASE STUDY: POLITICAL HISTORY AND ACCEPTABILITY OF ROAD PRICING IN THE NETHERLANDS*. Amsterdam.
- Verhoef, E., & Ubbels., B. (2004). *Case Study: Political History and Acceptability of Road Pricing in the Netherlands*. Free University Amsterdam.
- W., E., Wilner, H., Bolin, M., Stockton, W., Burris, M., Goodin, G., et al. (2006). *Evaluating Criteria for Adapting HOV Lanes to HOT Lanes: Development and Application of HOT START Software Tool*. Texas Transportation Institute.
- Warffemius, P. (2005). *Using the standard deviation of the travel time distribution as an indicator for valuing the reliability of travel time*. AVV Research Program.
- Washington State Department of Transportation. (2009). *January 2009 Focus Groups Final Report*. WSDOT.
- Washington State Department of Transportation. (2010). *SR 167 HOT Lanes Pilot Project - Second Annual Performance Summary*.
- Weggemans, T., Veling, I., Tertoolen, G., & Uden, J. v. (1999). *Gedragaspecten experiment betaalstroken*. Rotterdam: Rijkswaterstaat, Adviesdienst Verkeer en Vervoer.
- Wilbur Smith Associates. (1995). *Potential for Variable Pricing of Toll Facilities*. Federal Highway Administration, U. S. Department of Transportation.
- Wilbur Smith Associates. (2002). *Volume 1 traffic, revenue and traffic operations: I-15 managed lanes value pricing project planning study*. San Diego Association of Governments.
- Williams, H., & al., e. (2001). Highway investment benefits under alternative pricing regimes. *Journal of Transport Economics and Policy*, 257-284.
- Zwaneveld, P., Romijn, G., Renes, G., & Geurs, K. (2009). *Maatschappelijke kosten en baten van verstedelijkingsvarianten en openbaarvervoerprojecten voor Almere*. Centraal Planbureau.