Effects of road pricing on the traffic flows in the region of Eindhoven

A model study about the effects of three forms of road pricing on the traffic flows in the region of Eindhoven

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Final version

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By

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Preface

By finishing this thesis, a period of approximately 8 months of research has ended. This research forms the conclusion of my Master in Civil Engineering and Management with the Transport Engineering and Management as specialization.

This research is carried out at Royal HaskoningDHV in Eindhoven, Amersfoort and Nijmegen. I would like to thank all colleagues of the department of Transport and Planning for having a fun and informative period. Many colleagues were helpful and interested in my research, what helped by getting the research to a higher level. In particular, I owe many thanks to Mathijs Huisman who really helped with structuring the research and by thinking of new ideas to improve my research. Besides, he was always concerned with my well-being in general and helped me to find my way in the company. Furthermore, I would like to thank William van Genugten for helping me out with the traffic model, but also with other questions I had. I also would like to thank Peter Mijjer of 4Cast, who was really helpful by getting the required information concerning the ToD module I used in the research.

From the University of Twente, I would like to thank Eric van Berkum for having a critical view on the draft versions of the report. Besides, I would like to thank my daily supervisor Tom Thomas, who really helped with managing the whole process of the research. Moreover, he was helpful by suggesting new ideas to improve the academic level of the research.

Finally, I like to thank my family, friends and fellow students for their support and by getting some relaxation during my life as a student.

At last, I would like to thank everyone again for being flexible during the outbreak of the COVID-19 virus. I understand that this situation was new for everyone, but everybody was supportive to me during the unpredictable last month of my thesis process.

Teun Borghuis,
Nijmegen, April 2020

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Samenvatting

Op economisch gebied is de regio van Eindhoven een van de snelst groeiende regio's van Nederland. De keerzijde van deze groeiende welvaart, is dat de druk op het verkeersnetwerk steeds groter wordt met doorstromings-en leefbaarheidsproblemen als gevolg. Naast deze verkeerskundige problemen, heeft de overheid ook een toekomstig probleem met het vergaren van inkomsten uit de verkoop van benzine en diesel. Door het steeds groter wordende aandeel van elektrische auto's, wordt er steeds minder benzine en diesel verkocht. Als mogelijke oplossing voor beide problemen, wordt vaak gesproken over het invoeren van rekeningrijden. In dit rapport is onderzocht, of rekeningrijden een van de oplossingen kan zijn voor de toekomstige verkeerskundige problemen in de regio van Eindhoven. De hoofdvraag die in dit rapport beantwoord is, is:

Wat zijn de effecten van rekeningrijden op de verkeersstromen in de regio van Eindhoven voor het jaar 2030?

Om deze hoofdvraag te kunnen beantwoorden, zijn drie vormen van rekeningrijden onderzocht. De vormen die onderzocht zijn de volgende:

1. Prijs per gereden kilometer (7 cent/km), inclusief een hogere prijs (11 cent/km) tijdens de spitsen
2. Prijs afhankelijk van de herkomst en bestemming (7 cent/km), inclusief een hogere prijs tijdens de spitsen (11 cent/km)
3. Prijs per gereden kilometer (7 cent/km), inclusief een hogere prijs tijdens de spitsen (11 cent/km) en een hogere prijs in bepaalde gebieden (plus 5.5 of 11 cent/km)

Uit eerder onderzoek bleek, dat de eerste vorm positieve effecten had op de verkeersdoorstroming. Echter het gevaar van deze vorm is, dat het gebruik van kortere routes wordt gestimuleerd omdat dit geld bespaart. Dit zou betekenen dat de leefbaarheid in sommige bebouwde gebieden achteruit zou gaan door een toename van sluipverkeer. Vorm nummer twee zou de problemen omtrent leefbaarheid moeten voorkomen, doordat een bedrag wordt bepaald onafhankelijk van de gereden route. Aan de hand van de herkomst en de bestemming wordt een bedrag betaald, wat het nemen van kortere routes dus niet stimuleert. In de derde vorm, net als in de eerste vorm, wordt de prijs van een rit bepaald op basis van het aantal gereden kilometers. Om verkeer te weren uit bepaalde gebieden, wordt in vorm 3 een extra prijs van 5.5 of 11 cent per kilometer in de stedelijke gebieden van Eindhoven geheven.

Om de vormen vervolgens te kunnen vergelijken, zijn vijf criteria opgesteld:

1. Verandering van vertrektijd van spits naar buiten de spits
2. Intensiteiten (leefbaarheid)
3. Totaal afgelegde afstanden per gebied (leefbaarheid)
4. Reistijden op de grotere wegen (congestie)
5. Voertuig verliesuren (congestie)

In het eerste criterium, zijn de aantal reizigers berekend die overstappen van vertrektijd tijdens de spits naar buiten de spits. Vervolgens wordt de leefbaarheid bepaald door het analyseren van de intensiteiten en de totaal afgelegde afstanden per gebied. Er is aangenomen dat de leefbaarheid in bebouwde gebieden afneemt wanneer de intensiteiten in die gebieden toenemen. Daarnaast is aangenomen dat de leefbaarheid afneemt wanneer de totale afgelegde afstand afneemt, omdat kortere routes worden genomen die leiden tot een toename van sluipverkeer en dus een afname van de leefbaarheid. Om te bepalen of de mate van congestie toe of afneemt, zijn de reistijden op de grotere wegen en de voertuig verliesuren per gebied bepaald.
Met behulp van een verkeersmodel zijn deze criteria per vorm onderzocht, afzonderlijk voor de ochtend en de avond periode voor het jaar 2030. Daarnaast is de basis situatie gebruikt als referentie scenario. In het

verkeersmodel, kunnen reizigers ervoor kiezen om een andere vertrektijd te nemen om de hogere prijs tijdens de spits te vermijden. Daarnaast, kunnen andere routes gekozen worden om eventueel geld te besparen.
Uit het verkeersmodel is gebleken, dat het aantal reizigers dat verandert van vertrektijdstip nagenoeg gelijk is voor de drie vormen, zowel voor de ochtend als avond periode rond de 2.35%. Wat betreft de effecten op de leefbaarheid, zit er meer verschil tussen de verschillende vormen. In vorm 2, worden geen kortere routes genomen en zorgt de betere spreiding van de piek ervoor dat de leefbaarheid omhoog gaat in stedelijke gebieden omdat de intensiteiten afnemen. In vorm 1, worden wel kortere routes genomen wat impliceert dat er een toename is van sluipverkeer en dus een verlaging van de leefbaarheid. Daarnaast zijn, in de ochtend periode de intensiteiten hoger in de stedelijke gebieden in vorm 1 dan in vorm 2. Vorm 3 is duidelijk effectief in het weren van verkeer uit de stedelijke gebieden. Maar omdat het bedrag afhangt van het aantal gereden kilometers, worden wel kortere routes genomen, wat een verslechtering van leefbaarheid veroorzaakt in bepaalde gebieden. Daarnaast, is er een verslechtering van leefbaarheid waarneembaar in de gebieden die net buiten de gebieden liggen met de extra locatie beprijzing.
Betreffende de congestievorming kan er geconcludeerd worden dat voornamelijk de betere spreiding in piekbelasting ervoor zorgt dat de mate van congestie afneemt. Toch is het zo, dat vormen 1 en 3 voor een hogere reductie van congestie zorgen dan vorm 2. Dit komt doordat meer kortere routes genomen worden waar geen doorstromingsproblemen zijn en dus geen voertuigverliesuren worden geregistreerd. Wat vorm 3 betreft, is het wel zo dat de mate van congestie in gebieden net buiten de gebieden met locatie component minder afneemt dan in de rest van de regio.
Afhankelijk van wat het precieze doel is van het invoeren van rekeningrijden, zijn er verschillende vormen die het meest effectief zijn. In Tabel 0-1 is weergegeven welke vorm van rekeningrijden het beste past bij welk doel. Om voor een geleidelijke spreiding van de piek te zorgen, maakt het niet uit welke vorm er gebruikt wordt. Het verschil in prijs tussen de spits en de niet-spits is hier wel van belang. Om verkeer te weren uit het stedelijk gebied, is vorm 3 het meest geschikt terwijl voor het ontmoedigen van het nemen van kortere routes vorm 2 meer geschikt is. Voor het verminderen van congestie, zijn vorm 1 of 3 het meest aan te raden. Vorm 3 zorgt er specifiek voor dat congestie in een gebied verminderd wordt, met als nadeel dat congestie in de aanliggende gebieden minder gereduceerd wordt. In vorm 1 wordt congestie in deze aanliggende gebieden meer gereduceerd.

Tabel 0-1 Aanbeveling per doel van rekeningrijden

Doel	Vorm	Opmerking
Geleidelijke spreiding piek	Vorm 1, 2 of 3	Het verschil in prijs tussen de spits en de niet-spits is cruciaal
Verkeer weren uit stedelijk gebied	Vorm 3	
Ontmoedigen van het nemen van kortere routes	Vorm 2	
Verminderen van congestie	Vorm 1 of 3	Vorm 3 is het effectiefst in het verminderen van congestie in een vooraf gedefinieerd gebied. Form 1 is het effectiefst in de andere gebieden.

Als eindconclusie op de hoofdvraag, is gevonden dat het aantal reizigers dat overstapt van vertrektijd niet afhankelijk is van de onderzochte vormen. Een prijs per gereden kilometer is effectief in het verminderen van congestie, maar is minder voor het verbeteren van de leefbaarheid omdat kortere routes (door bebouwd gebied) genomen worden. Wat betreft de leefbaarheid, is een prijs onafhankelijk van de gereden route geschikter omdat het nemen van korte routes niet gestimuleerd wordt. Daarnaast is er ook nog steeds een positief effect op congestie, maar is dit wel wat minder dan in de andere vormen. Een locatiecomponent per gereden kilometer is dus effectief in het verminderen van congestie, maar is wisselend effectief voor het verbeteren van de leefbaarheid. Aan de ene kant zorgt het ervoor dat verkeer een bepaald gebied vermijdt. Aan de andere kant, zorgt ervoor dat de leefbaarheid in aangrenzende gebieden verminderd en wordt nog steeds gestimuleerd om de kortere routes te nemen.

Gebaseerd op de verkregen resultaten in dit onderzoek, zijn de volgende vier aanbevelingen opgesteld:

1. Om voor een betere spreiding van de piek te zorgen, wordt geadviseerd om verschillende prijzen voor het reizen binnen de piek en buiten de piek te implementeren
2. Voor het weren van verkeer uit een (stedelijk) gebied, wordt geadviseerd om een locatiecomponent te implementeren
3. Om het nemen van kortere routes te ontmoedigen, wordt geadviseerd om een prijs te heffen die onafhankelijk is van de genomen route
4. Voor het verminderen van congestie, is de betere spreiding in piek essentieel. Voor nog meer effect, is een bedrag per gereden kilometer geadviseerd.

Voor vervolgonderzoek, zijn twee belangrijke aanbevelingen gemaakt. Als eerste, wordt geadviseerd om een vervoersmiddel en bestemmingskeuze component toe te voegen. Het invoeren van rekeningrijden kan mensen doen beslissen om andere vervoersmiddelen te gaan gebruiken en/of om bestemmingen te kiezen die dichterbij liggen. Daarnaast is het interessant om de effecten van een combinatie van een prijs onafhankelijk van de route en een locatiecomponent te onderzoeken. Hierin zou een prijs geheven moeten worden onafhankelijk van de route in combinatie met een prijs voor het binnenrijden van een bepaald gebied.

Abstract

Economically, the region of Eindhoven is one of the regions of the Netherlands with the highest growth. The downside of the growth in prosperity, is the increasing pressure on the traffic network causing problems as congestion and a reduction of liveability. Besides the problems in the context of transport, the government is also facing future problems with the generation of revenues by the use of fuel. Since the share of electrical vehicles is growing fast, less fuel is sold causing a reduction of earnings for the government. A possible solution for both problems, could be the implementation of road pricing. In this research, there is investigated whether road pricing could be a solution for the problems with the future traffic flows in the region of Eindhoven. The research question that is answered in this research is:

What are the effects of road pricing on the traffic flows in the region of Eindhoven for the year 2030?

To answer the research question, three different forms of road pricing are investigated. These forms are:

1. Charge per driven kilometre (7 cents/km), including a peak charge (11 cents/km)
2. Origin and destination based charge (7 cents/km), including a peak charge (11 cents/km)
3. Charge per driven kilometre (7 cents/km), including a peak charge (11 cents/km) and a location charge in two areas (plus 5.5 and 11 cents/km)

In a previous research is found, that form 1 has a positive effect on the traffic flows. However, this form could stimulate taking the shorter routes since this is rewarded by saving money. This would lead a reduction of liveability in some residential areas. The second form is made to avoid this problem with the decrease in liveability. Based on the origin and destination of a trip, a charge is paid independent of the exact route that is taken. In the third form, just as in the first form, a charge is levied based on the total number of kilometres that is driven. Besides, a charge of 5.5 or 11 cents per kilometre is levied in form 3 in the urban areas of Eindhoven to stimulate traffic to avoid these areas.
To compare the effects of the forms, five KPIs are composed:

1. Switch departure time peak vs off-peak
2. Intensities (liveability)
3. Total distance driven per area (liveability)
4. Travel times on main roads (congestion)
5. Vehicle loss hours (congestion)

In the first KPI, the number of travellers switching from a departure time in the peak to a departure time outside the peak is analysed. Subsequently, the liveability is considered by analysing the intensities and the total distance driven per area. There is assumed that an increase in intensities in residential areas leads to a reduction of the liveability. Besides, there is assumed that a decrease in total distance driven means that shorter routes are taken what implies an increase of rat running and thus a decrease of liveability. For assigning the degree of congestion, the travel times on main roads and the vehicle loss hours per area are determined.
By using a traffic model, the effects per criteria are investigated separately for the morning and evening period for the year 2030. Besides, the base situation is used as reference scenario. In the traffic model, travellers can switch from departure time to avoid the peak charge. Furthermore, other routes can be taken to save money.
Following the traffic model, the number of travellers that switched from departing in the peak hours to the peak-shoulders is similar for the three forms, both for the morning and evening period around 2.35%. Concerning the liveability, there are more differences across the forms. In form 2, no shorter routes are taken and due to the smoother spread in peak hours the liveability increases in the urban areas. In form 1,

shorter routes are taken implying an increase in rat running and thus a decrease in liveability. Besides, the intensities in area I and II increased in form 1 compared to form 2 in the morning period. Form 3 is clearly effective in stimulating traffic to avoid the urban areas. However, since the charge depends on the driven kilometres shorter routes are taken causing a reduction of liveability in some areas. Besides, liveability reduces in the areas that lay just outside the areas with the extra location charge.
Concerning congestion, there is concluded that mainly the smoother spread in peak hours cause a reduction of congestion. However, in form 1 and 3 the reduction of congestion is higher than in form 2. This is caused by the fact that shorter routes are taken on which less congestion problems arise and therefore less vehicle loss hours are registered. A disadvantage of form 3, is that the degree of congestion reduces less in the areas just outside the areas with the location charges than in the other parts of the region.
Depending on the aim of implementing road pricing, a government can decide which form is the most effective (see Table 0-2). For assuring a smoother spread in the peaks, the road pricing forms are of equal effectiveness. Crucial for this objective, is the difference between the peak and off-peak charge. For banning traffic from the urban area, form 3 is most effective. For discouraging the use of shorter routes, form 2 is most effective since there is no positive incentive for using the shorter route in this form. For reducing congestion, form 1 or form 3 are the most effective. Form 3 is the most effective in reducing congestion in a predefined area, causing a lower positive effect on the reduction of congestion in the areas next to the predefined area. In form 1, congestion is reduced more in these areas close to the predefined areas.

Table 0-2 Recommendations per objective of road pricing

Objective	Road pricing form	Comment
Smoother peak spread	Form 1, 2, or 3	The difference between the peak and off-peak charge is crucial
Banning traffic from urban area	Form 3	
Discouraging using shorter routes	Form 2	
Reducing congestion	Form 1 or 3	Form 3 is most effective in reducing congestion in the predefined area. Form 1 is more effective for the areas without location charge.

To reflect on the main research question, there is concluded that the number of travellers that switch form departure time is not influenced by the researched road pricing forms. When a charge per driven kilometre is levied, there is a positive effect on congestion, but the liveability is a point of attention. Shorter routes are stimulated sometimes crossing residential areas. In a form in which the charge is independent of the route that is taken, there is not stimulated to use shorter routes, what is positive for the liveability. On the other hand, the reduction of congestion is somewhat lower in this form compared to the others. When a location component per driven kilometre is implemented, congestion is reduced and traffic avoids the areas with the location charge. On the other hand, shorter routes are taken and the liveability in areas close to the areas with the location charge is reduced.

Following from the results found in this research, the following four recommendations are composed:

1. For assuring a smoother spread of the peak, there is advised to implement a different charge for the peak and off-peak hours
2. For banning traffic from an (urban) area, there is advised to implement a location charge in that area
3. For discouraging the use of shorter routes, there is advised to implement a charge that is independent of the route that is taken
4. For reducing congestion, the smoother spread is essential. For extra effect, a charge per driven kilometre is recommended

To continue on this research, two main recommendations are made. First, there is advised to implement both a transport mode and destination choice component. The implementation of road pricing could make travellers switch from transport mode and/or to choose a destination that is closer by. Besides, there is advised to investigate a form which is a combination a charge independently of the route and a location charge. In this form, a charge is levied independently of the route that is taken and an extra charge is levied for entering a predefined area.

Contents

List of Figures

List of Tables

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List of Abbreviations

DUE	Deterministic user equilibrium
EP	Evening peak
IC-ratio	Intensity/Capacity ratio
KiM	Kennisinstituut voor Mobiliteitsbeleid
KPI	Key Performance Indicator
LMS	Landelijk Model Systeem
MP	Morning peak
MSA	Method of Successive Averages
NRM	Nederlands Regionaal Model
OD	Origin-Destination
OViN	Onderzoek Verplaatsingen in Nederland
RC-function	Route Choice function
RoD	Rest of the Day
SUE	Stochastic user equilibrium
ToD	Time of Day
TPF	Turn Penalty Function
VDF	Volume Delay Function
Veh	Vehicle

1. Introduction

The region of Eindhoven is sometimes referred as the Silicon Valley of the Netherlands due to the innovative and sustainable character of the city (Groenen, 2018). It is the fifth biggest city of the Netherlands, with multinationals as ASML and Phillips located in the area, the high-tech campus and with its own growing airport. The downside of this booming trend, now and in the future, is the increasing pressure on the accessibility of the region. A few years ago, concrete plans were composed for constructing a new highway somewhat northern to Eindhoven to complete the ring road of highways around Eindhoven and Helmond. The plans were, however, rejected due to a lack of support in the involved city councils. As an alternative, a set of measures was composed which must assure the accessibility of the region of Eindhoven. This might improve the accessibility of the region, but there is also another problem arising. Currently, the government generates revenues by taxes on the purchase of fuel. However, the share of electrical cars increases fast nowadays, causing a gap in earnings of the government. Electrical cars do not need any fossil fuel, so the government does not earn any money on the use of these cars. A clear approach is required to deal with these problems. Among others, one can invest in public transport, construct more roads or try to change the travel behaviour However, the construction of new roads turned out to be a short-term solution rather than on the long base and the public transport system is almost at its maximum capacity. Therefore, there is a need for another solution.

A promising solution for both the congestion problems and the loss in revenues, is road pricing. The road users are stimulated to change their travel behaviour and the government also generates revenues from the use of electrical vehicles in this way. Besides, road pricing is labelled as being fairer, since road taxes and purchasing taxes will be abolished and thus using the car is charged instead of owning the car. In this way, the frequent car users, pay more taxes.

Concluding, road pricing is supposed to be a fairer way of paying taxes, the government does not miss out on earnings from electrical vehicles and at last it could be the solution for the increasing problems of congestion. In this research, on behalf of Royal HaskoningDHV, there is investigated whether the implementation of road pricing is the solution for improving the traffic flows in the region of Eindhoven.

1.1 Background

The idea of road pricing is not an idea that popped up recently. Back in 1920, there was proposed to impose toll on roads to finance the construction of new roads in the Netherlands. Instead of executing this idea, there was chosen to price the possibility of using the road. In other words, road taxes were implemented (Wegenwiki, 2018). The most aspects of this system are still in use, but through the years there were several moments that there was tried to revise the system. In 1988, there was suggested to charge the use of roads instead of charging the possibility of using the road. At that time, there was a lot of resistance against the plans, leaded by the ANWB (Dutch organization for road users). The ANWB doubted the efficiency and was afraid that the revenues were not used for improvement of the road network as was promised. Due to the fall of the cabinet, the debate about road pricing stopped and the plans were not executed.

It took until 2005 before road pricing was back at the political agenda. There was assumed that road pricing could be a solution for congestion problems, by for instance leading to smoother peak periods. The cabinet, leaded by Balkenende, was quite close at the implementation of a road pricing scheme. Nevertheless, also this cabinet felt and plans again were not executed. The years after, the economic crises started and the problems with congestion decreased. After the recovery of the economy, and therefore the demand for transportation, road pricing is a hot item again. As for a long time, the currently biggest politic party (VVD) was against any form of road pricing. However in the climate agreement revealed recently, there is stated that implementation of any road pricing is negotiable after a new government has been settled in 2026 (Nu.nl, 2019). This seems wise, since growing numbers of people have positive attitude against road pricing (I&O research, 2019).

1.2 Problem indication

Following the climate agreement, chances are high that sooner or later a new research is executed about the effects of road pricing on the national level. Following the climate agreement, a nationwide research is expected since road pricing is probably implemented for the Netherlands as a whole. However, a national research grades the performance of road pricing for the Netherlands as a whole, whereas regional differences conceivable. Due to differences in for example the road network, the one form could be more suitable for Eindhoven and another form for the Randstad.

In the region of Eindhoven there are a few aspects that makes it different from other cities. In Figure 1-1 and 1-2 (Google Maps Verkeer, 2020a, 2020b), the typical traffic on a Tuesday on respectively 08:30 and 17:30 are visualised. In the morning peak, the most problems occur on the A58 towards Eindhoven, A2 from Weert to Eindhoven, the A67 between Geldrop and Asten, the A270 and the ringroad. In the evening peak, the A58 both directions, the A50 from Eindhoven and the ringroad are the most congested. In general, most congestion is located on the highways to and from Eindhoven. But also in the city centre, presented in Figure 1-3 and 1-4, there is quite some congestion, what reduces the accessibility of Eindhoven. This problem is recognized by the municipality of Eindhoven, but the solution to ban traffic from the city centre is not found yet (Theeuwen, 2019). Due to the expected growth in traffic demand, the problems with congestion will be even more in 2030.

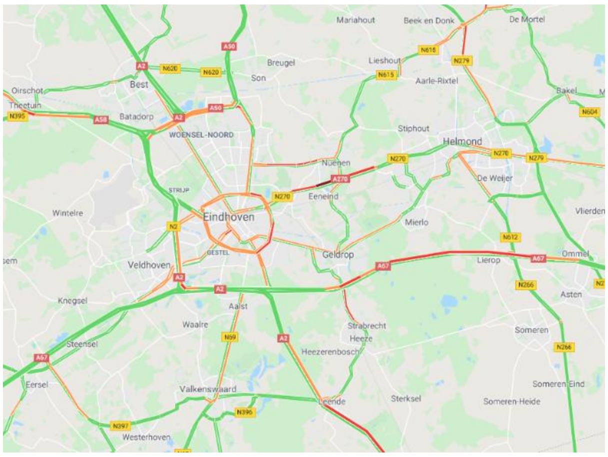


Figure 1-1 Typical traffic on a Tuesday 08:30

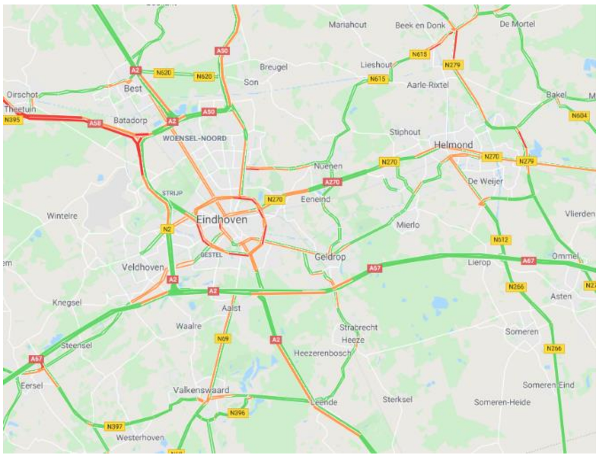


Figure 1-2 Typical traffic on a Tuesday 17:30

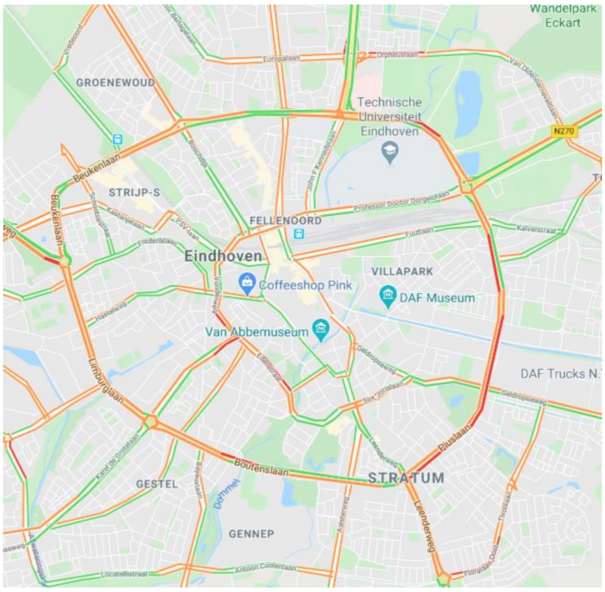


Figure 1-3 Typical traffic on a Tuesday 08:30

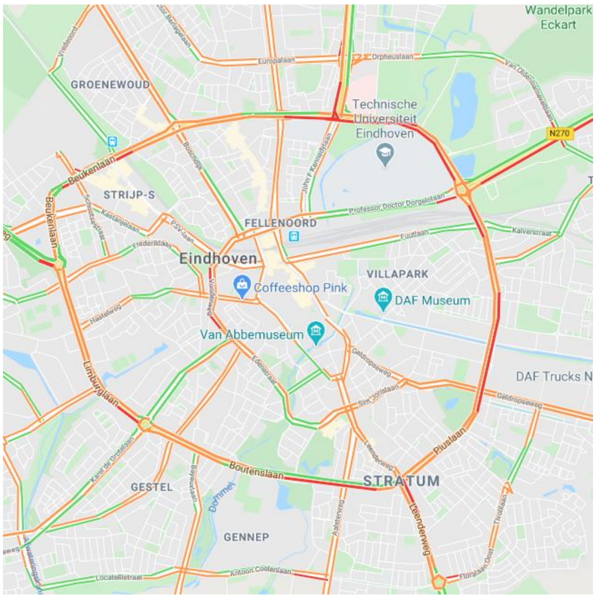


Figure 1-4 Typical traffic on a Tuesday 17:30

Although the problems with congestion in the city centre of Eindhoven are currently not that bad (Eindhoven is number nine of the Netherlands regarding congestion (TomTom, 2019)), the design of the road network of Eindhoven could increase future problems. First of all, most big cities as Amsterdam and Rotterdam have a ring road of highways around the city. As mentioned earlier, there were plans to accomplish this also for Eindhoven, but these plans were abolished. Therefore, Eindhoven only has a partially ring road of highways and a ring road called the 'robuuste rand'. This ringroad consists of the A50, A2, A67 and N279 (red roads in Figure 1-5). One of the consequences, is that traffic is more inclined to use secondary roads what could lead to rat running. This is unwanted, since rat running leads to accessibility and liveability. These problems are the most severe in the grey area of Figure 1-5, since this area is that far away from the 'robuuste rand' (ZO slim bereikbaar, n.d.). Furthermore, the interaction between the A2 and the N2 is unique. Over the complete length of the red route in Figure 1-5, the A2 is made for through traffic whereas the N2 serves traffic heading to the city centre. Many roads go to the city, making rat running

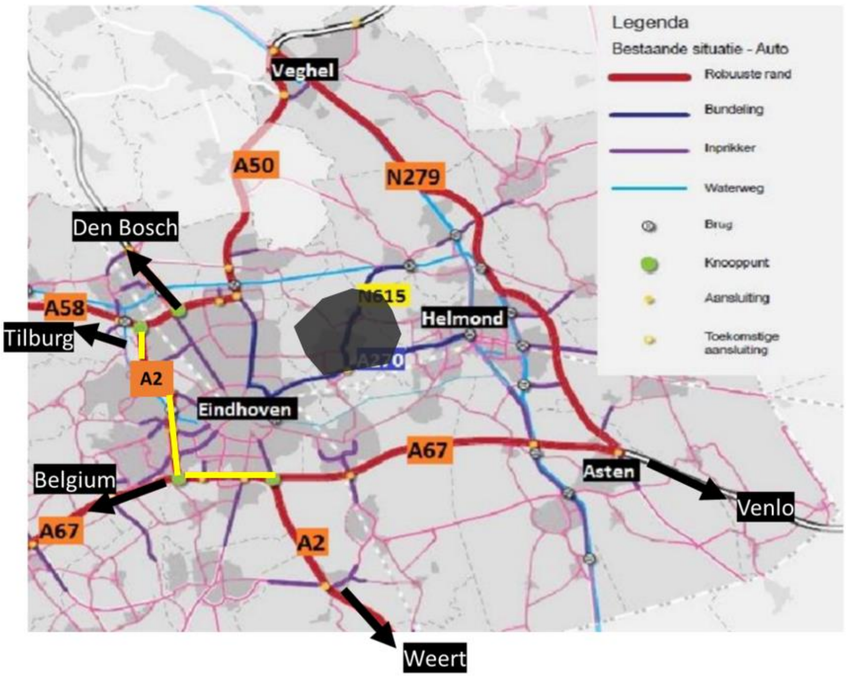


Figure 1-5 Road network Eindhoven

through the city simple. When a road pricing form is chosen that stimulates taking the shorter routes, this could become a serious problem for Eindhoven.

Thus, road pricing could be the solution against congestion but could increase the problems with rat running. In the past, as far as known never a research is conducted about the effects of road pricing specific for the region of Eindhoven. About fifteen years ago, a research was conducted by 4Cast about the nationwide effects of road pricing in the Netherlands (4Cast, 2006). Besides that this research is quite outdated, it was conducted for the whole Netherlands and therefore did not conclude anything about the liveability or degree of congestion in the region of Eindhoven. Since the effects could be different for each region, it is valuable to investigate this. Furthermore, the road pricing forms proposed in the research of 4Cast focus on paying a charge per driven kilometre, although this stimulates taking the shorter route (when travel times are of the same order) to save money and thus stimulates rat running. This decreases liveability, what is a negative effect of this form of road pricing. Using other forms of road pricing, this disadvantage is possibly solved.

Concluding from the previous chapters, thinking about road pricing is not new. However, it is unknown what road pricing form suits best for the region of Eindhoven and what the effects would be on the traffic flows. The problem statement is therefore formulated as:

Insight is missing in the effects of implementing road pricing on the traffic flows in the region of Eindhoven in 2030

1.3 Goal

In this research, there is aimed to solve the problem statement as described above. The goal is formulated as:

Provide insight in the effects of implementing various road pricing forms on the traffic flows in the region of Eindhoven in 2030

1.4 Research questions

To be able to achieve the goal, the following main research question is answered in this research:

What are the effects of road pricing on the traffic flows in the region of Eindhoven for the year 2030?

To be able to answer the main question, four sub-questions are composed. Below the questions are presented including a short explanation.

1. *Given the chosen road pricing forms, how to forecast the effects on the traffic flows?*

Since road pricing is not implemented yet in the region of Eindhoven or somewhere else in the Netherlands, there is no empirical data to investigate the effects. Therefore, a method is developed to forecast the effects of road pricing.

2. *What change of travel behaviour occurred after implementing road pricing?*

Road pricing is not only implemented to generate revenues or assuring that the tax system becomes fairer, but there is also attempted to change habits in travelling. One is for example stimulated to make its trip outside peak hours or to take another route to save money. For answering this sub question, two behaviour changes are analysed: (1) change in departure time (2) change in route choice. The change in departure time is analysed by calculating the percentage of trips that changed from departure time. The change in route choice is analysed by comparing intensities and the total distance driven on the network.

3. *What are the effects on traffic flows of the change in travel behaviour after implementing road pricing?*

When the implementation of road pricing caused a change in travel behaviour, the effects on the traffic flows are still unknown. So, in this sub question the degree of congestion is analysed for the base scenario and for the road pricing forms. This is graded by comparing the travel times on predefined trajectories and by calculating the vehicle loss hours in different areas.

4. *Which road pricing form is most effective for which objective of implementing road pricing?*

In total, the three forms of road pricing are assessed on five Key Performance Indicators (KPIs). In this sub question, related to the objective a government has for implementing road pricing, there is concluded which road pricing form is the most effective.

1.5 Scope

As followed from the introduction, this research is about the effects on the traffic flows of road pricing for the region of Eindhoven. In total, three different forms of road pricing are analysed. The first one, is a charge per driven kilometre, with an extra charge during the peak hours. In the second form, a charge is levied independent on the route that is taken including a peak charge. In the last form, a charge is paid per driven distance also including an extra peak charge. Besides, there is a location charge in the urban and sub-urban area of Eindhoven. In Chapter 2.1 & 2.2, there is elaborated how these choices are made.
Following these road pricing forms, there are two behavioural changes that are stimulated. First, travellers are stimulated to change their departure time, due to the higher charges during the peak hours compared to the off-peak hours. To forecast this effect, a Time-of-Day module is developed. As a second behavioural change, travellers are stimulated to take shorter routes when paying a charge per kilometre to save money. For this effect, route choice functions are adjusted in a way that the monetary charges are included in the process of choosing a route. Other behavioural changes could be the change from transport mode, or a destination change. These changes are not considered in this research, since the chosen road pricing forms do not specifically aim to influence these choices. See Chapter 2.2 for the discussion about why these choices are made.
For grading a possible behavioural change and the effects of the behavioural change, five different KPIs are composed. For grading the departure time change, the percentage of trips that change their initial departure time is analysed. For the route choice, the intensities are analysed including an analysis of the total distance driven on the network. The effects of these behavioural changes are investigated by calculating the travel times on predefined trajectories and by analysing the vehicle loss hours in specific areas. Furthermore, the emissions of greenhouse gases would be an interesting topic to investigate, but this is not addressed in this research since there is focussed on the effects on the traffic flows. See Chapter 4 for explanations of the chosen KPIs.
As a final important choice, there is decided to take 2030 as year to analyse, since there is assumed that road pricing will be implemented at the earliest around 2030. Following the climate agreement, thinking about road pricing should start after the government is settled in 2026. Afterwards, the potential implementation would take at least four years, making 2030 the earliest possible year. Compared to using 2020 as year to analyse, there is an increase of traffic in 2030. Besides, there are some adjustments on the road network compared to the current network. Since the same network and the same traffic demands are used in the base scenario and the different variant, the increase in traffic demand or the new infrastructure does not influence the results and conclusions. Besides, there is chosen to both analyse the morning and evening period, since there are differences in traffic demand and traffic flows. The evening period is more crowded than the morning period. In general, the main traffic flow goes toward Eindhoven in the morning

period and goes the other way around in the evening period. Due to these differences, road pricing could have a different effect on the morning period than on the evening period, making it necessary to analyse both periods.

1.6 Outline

In this paragraph, the structure of the report is discussed. In Chapter 2, the theoretical framework of this research is provided. Related researches are discussed, and more knowledge is provided in the topic of road pricing and the way of modelling it. In Chapter 3, the methods used in this research are elaborated. In the fourth chapter, there is explained how the performance of the different road pricing forms is graded. In Chapter 5, there is elaborated how the base scenario is simulated in the traffic model Aimsun. Subsequently, the implementation of the road pricing forms in Aimsun is explained in Chapter 6. In Chapter 7, the results of the simulations in Aimsun are presented. Chapter 8 provides conclusions on the hypotheses and the research questions and gives recommendations based on this research. In Chapter 9, the limitations of this research are discussed as well as the recommendations for further research.

2. Theoretical framework

Road pricing is a frequently researched topic. In this chapter, insight is provided into literature related to road pricing. First, an overview is provided of researches of different forms of road pricing including their objectives, effects and type of research. Subsequently, more insight is provided in two important aspects of road pricing, namely route choice and departure time choice. Finally, other conditions for a proper implementation of pricing are briefly discussed and five hypotheses are composed based on the introduction and literature review.

2.1 Overview road pricing schemes around the world

For sketching an overview of previous researches concerning road pricing, Table 2-1 is made. In this table, the location, form, objectives and effects are shortly presented. Besides, there is indicated whether it is a research that forecasts the effects of a (fictive) road pricing scheme using a model study, or whether it is a field study that evaluates the effects after it has been implemented (ex-post). Below the table, the reports are explained more extensive. The researches with similar types of road pricing are combined and are compared. There is started with the most basic form, followed by the more advanced ones.

Table 2-1 Overview related researches

Location	Form	Objective(s)	Effect	Ex-post/ model study	Reference
Wellington (New Zealand)	Cordon pricing, some variants with more cordons	Reduce congestion in peak periods	In the most beneficial option, among others the person kilometres can be reduces by 2-3 per cent and the delay at key bottlenecks is reduced with 10-15%	Model study	(Sinclair Knight Merz, 2005)
Singapore	Cordon pricing, based on real time congestion levels	Congestion management (keep average speeds inside pre-defined boundaries)	After introducing ERP, the traffic volume reduced by 15 per cent	Ex-post	(Olszewski, 2007; Xie & Olszewski, 2011)
Stockholm (Sweden)	Cordon pricing, time dependent	"reduce congestion on the most congested road—improve speed through the bottlenecks"	-Reduction in traffic flow of 22% -Travel time reliability increased	Ex-post	(Eliasson, 2008)
France	Time depend pricing of one road	Smoother spread in peak moments	Smoother traffic flows (no quantitative evidence given)	Ex-post	(de Palma & Lindsey, 2006)

Austria	Vignette for using the road network, trucks pay per driven kilometre	Revenues management, reduce truck intensity on some roads	-600 million Euros revenues -Overall percentage of diversion remained 2% (local differences)	Ex-post	(Schwarz-herda, 2005)
Netherlands (2)	1.Fixed fee per kilometre 2. Fee dependent on place and time including fixed congestion fee 3. Fee dependent on place and time including dynamic congestion fee	Congestion management, with requirement that revenues from road pricing are at least equal to the current revenues from road taxes.	No overall conclusion drawn, and effects are too different for each scenario	Model study	(4Cast, 2006)
Netherlands (3)	Charge per origin and destination, depending on time	Congestion management	Not investigated yet	-	(Ohazulike et al., 2013)

2.1.1 Cordon pricing

A road pricing form that is investigated extensively, is the one of cordon pricing. Drivers pay a fee for entering a pre-defined area (usually the city-centre), possibly depending on time and emissions of the vehicle. For example, in Singapore (Xie & Olszewski, 2011) and Stockholm (Eliasson, 2008) such a road pricing scheme is implemented. In Singapore, the aim of this scheme is to reduce congestion during peak hours. For Stockholm, a similar objective is composed: *'Reduce congestion on the most congestion road- improve speed through the bottlenecks'.* Although the objectives of both schemes are quite similar, the practise of both systems differs. In Stockholm, vehicles pay a fee between 10 and 20 SEK (respectively between €1 and €2) depending on the time of crossing the cordon. These charges are pre-defined and do not change in response on real-time congestion. This is different in Singapore, since the height of the charge depends on the real-time speed on important roads. The traffic managers aim, to keep the speeds any time between 45 and 65 km/h on expressways and between 20 and 30 km/h on arterials. When the observed speed is below the lower threshold, the charges will be increased, whereas when the observed speed exceeds the upper threshold, the charges will be reduced. A similarity between both systems, is that it had a positive influence on congestion. After the implementation of the Electric Road Pricing (ERP) scheme in Singapore, the traffic volume inside the cordon was reduced by 15% (compared to the situation before, where only a simple Area Licensing Scheme (ALS) was implemented). In Stockholm, a reduction of 22% in traffic flow combined with an observable success during rush hours occurred. These effects show the potential of a cordon pricing scheme.
A similar conclusion is drawn in a study about Wellington (New Zealand) (Sinclair Knight Merz, 2005). The difference here, is that the road pricing scheme is not implemented yet in Wellington and thus the effects are forecasted using the Wellington Transport Strategy Model. In total, eight scenarios of different road pricing schemes are forecasted, and their effects are analysed. Although no conclusion is drawn about what

form would be the best, there is concluded that the higher the charge, the higher the influence on among others the traffic flow and emissions. In Paris, another form of cordon pricing is evaluated (de Palma & Lindsey, 2006). Just as for Wellington, this form is not implemented yet and is therefore forecasted using a traffic model. In one of the forms evaluated, users pay a charge dependent on the time spent within a pre-defined area. There is concluded, that this form has the highest effect on the revenues and welfare gains (compared to the 'regular' cordon pricing forms).

The introduction of cordon pricing in Paris, Wellington, Singapore and Stockholm leaded in all cases to a (forecasted) reduction of congestion. Where the schemes in Stockholm and Singapore are already implemented, the studies of Paris and Wellington forecast the effects using a traffic model. Although the effects of the cordon pricing are described differently in the four studies, each concludes there is a significant effect. Therefore, the implementation of any form of cordon pricing seems to be promising. As far as known, this form is never considered for implementation in the Netherlands, although several studies demonstrate that cordon pricing is an effective way of reducing congestion.

2.1.2 Highway pricing

A form that focusses on the main road network instead of the urban areas, is the one of highway pricing. This form is already in use on the highway between Lille and Paris. On Sundays, this road was crowded by people returning home after a weekend off. At first, there was a flat toll over the whole day. Eventually, the toll was raised during the afternoon peak with 25% and lowered in the early afternoon and late evening with 25%. It turned out, that implementing such a variation in toll price leads to a smoother spread in traffic demand over the day. Although there is no quantitative evidence given, this case shows just as the Stockholm and Singapore case, that there is a potential in variating toll prices over time (de Palma & Lindsey, 2006). A similar approach can be found in countries where a vignette is implemented. For example in Austria, a vignette is implemented that people need to buy before being allowed to enter the highways (Schwarz-herda, 2005). Different from the French case, there is no differentiation over time. Besides, the goal of introducing a vignette is usually gaining revenues, whereas this was not the case for France. Both forms of highway pricing however are not interesting for the Netherlands. The highway pricing as implemented in France stimulates taking detours, what decreases the safety and liveability. The vignette form is not suitable, since the idea is that the frequent users pay more than the sporadic users. When implementing a vignette, this is not the case and therefore the system does not become fairer. Furthermore, a vignette only needed for highways, stimulated taking the other roads and thus leads to an increase in rat running.

2.1.3 Variants with charge per driven kilometre

Even more advanced road pricing forms are suggested for the Netherlands (4Cast, 2006). In these road pricing variants, one pays a charge for every single kilometre that is driven on the road network instead of only paying a charge for crossing a section or using the highway. The variants that are considered in the research of 4Cast are: (1) pay a fixed charge per kilometre (2) pay a charge per kilometre depending on location and time and including fixed congestion fee (3) pay a charge per kilometre depending on location and time, including a dynamic congestion fee.

Subsequently, scenarios are built that variate in the form of road pricing, but also in the percentage of abolishment of the road taxes and the purchase taxes. Based on the percentage of abolishment of the taxes, the charges per kilometre are determined (on average between 1.48 and 6.91 cents per driven kilometre). Overall there is found, that congestion decreased the most when the charge depends on the location (higher charge for highways with I/C ratio above 0.8) and time. The effects on the traffic flows were the highest when the maximal charge is implemented.

Although the form of paying per kilometre has the potential, it has a disadvantage. Road users are charged per kilometre, causing that the shortest trip in distance lead to lowest charge. There is expected that this stimulate detours to avoid long trips in distance, whereas this is not wanted from a traffic management point of view. Detours could lead to a reduction in liveability in some areas. Besides, after an accident happened on a highway, drivers are punished for leaving the highway since this detour involves more kilometres.

2.1.4 Origin-and destination-based charge

A road pricing form that could solve the problems of detours, is the one proposed in Ohazulike, Still, Kern & van Berkum (2013). In this form, road users pay a charge based on their origin and destination, irrespectively which route is taken. The charge depends on the departure time (peak versus non-peak) and on the distance between the origin and destination.
In general, there is expected that this form would have a positive influence on congestion and not a negative effect on the liveability. Since there is no positive incentive by reducing the number of kilometres driven, one is not stimulated to take the shortest route.

2.2 Conclusion road pricing forms

In the previous chapter, several road pricing forms are discussed with their advantages and disadvantages. Following these advantages and disadvantages, the following forms are selected to analyse in this research:

- Form 1: charge per driven kilometre, including a peak charge
- Form 2: origin and destination-based charge, including a peak charge
- Form 3: charge per driven kilometre, including a peak and location charge

The first form is chosen since the research of 4Cast (2006) showed that this form would have the most effect on traffic flows. The expectation is that indeed, this form has a positive effect on the traffic flow but has a negative effect on the liveability. The second form should overcome this problem with rat running. The route is not important in this form, only the time, origin and destination determine the charge of a trip. The third variant is almost the same as form 1, except for an extra location component. This form is evaluated to investigate whether a location component can be used to control the traffic flows. As stated in the introduction there is quite some congestion in the urban areas of Eindhoven, what can possibly be banned by a location component. The location component, an increasement of the charge per kilometre, is implemented on two different levels based on the priority of the roads. First, the urban road of Eindhoven gets the highest charge, since only local traffic should drive here and therefore there is tried to stimulate other traffic to take other routes. For the sub-urban roads, which have a double function, a lower charge than on the urban roads is implemented. On the one hand, these roads must be used by traffic to prevent them from unnecessarily entering the urban area. On the other hand, through traffic from north to south for example should not use the suburban area. Therefore, the roads in the urban area get the higher charge and the suburban roads a somewhat lower charge. The expectation is, that traffic will avoid the roads with the location components when it is possible. For this research, there is chosen to only implement this extra component for Eindhoven itself, but it is possible to do the same thing for any area, village or city.

2.3 Type of research

In the previous chapter, there is explained which road pricing forms will be investigated for the region of Eindhoven. Following from the literature study concerning road pricing, the effect of road pricing is either forecasted using a traffic assignment model or by conducting a stated preference survey. Furthermore, the effects can be evaluated ex-post by using traffic counts. Conducting an ex-post analysis is not possible for any phenomena that is not implemented yet. Besides, performing only a stated preference survey does not provide answers on the effects of a possible change of travel behaviour. Therefore, the choice for using a traffic assignment model is straightforward.
Another important choice to make, is which components of a traffic assignment model are included and which not. These choices depend on the aim a government has for implementing road pricing. In general, the aim of implementing road pricing is either managing congestion or assuring the generation of revenues (Litman, 2005). The aim of managing congestion, is accomplished by influencing the travel behaviour. This

is tried by influencing the departure time, the transport mode, destination location or the route choice. By considering the chosen forms, a change in departure time and route are the most interesting components to investigate. In all forms a peak charge is implemented, what solely aims to assure a smoother spread in peak hours. Besides, there is a risk that the forms in which a charge is paid per driven distance stimulate to take the shorter route. In other words, the chosen route can be adjusted. The choice for considering the Time-of-Day and route choice as possible components that can change, is supported by Ortúzar and Willumsen (2011). They claim, that adjusting the departure time is the second most likely response to a change in travel conditions after changing the route. Although the implementation of road pricing only indirectly changes the travel conditions, it indicates that changing route or departure time is an expected reaction.
In the following paragraphs, the route choice modelling and Time-of-Day modelling in a traffic assignment model are discussed.

2.4 Route choice modelling and traffic assignment

The route someone takes in a traffic model, are determined by using route choice functions. The basic idea of route choice modelling is that travellers act rational and choose the route which comprises the lowest individual costs. The definition of 'lowest individual costs' is quite subjective and can depend on among others the travel time, travel distance, monetary costs, congestion and queues, type of manoeuvres required, type of road, scenery, signposting, road works, reliability of travel time and habit (Ortúzar & Willumsen, 2011). In the most common route-choice functions, only the travel time and the monetary costs are included. Since the overall utility needs to be expressed in one unit, the concept of the generalized cost function is used. Usually this means that the values of all parameters are expressed in either monetary values or in minutes. Following this approach, there is usually one route found that incorporates the lowest generalized costs. However, this does not mean that 100 per cent of the trips follow this 'best route', due to the following three problems:

- Different types of people experience other definitions for the 'best route'. Some aim to minimize costs as much as possible, whereas others aim to minimize the travel time. This is usually solved by considering multiple user classes, which valuate costs and travel time differently.
- To what extend someone is familiar in an area, to be able to take alternative routes. Usually solved by considering stochastic effects.
- Congestion effects change the generalized costs of the routes. Usually solved by a congested assignment and a method which leads to an equilibrium.

Following the three reasons above, a distinction can be made in methods that forecast the routes that are taken (van Nes, 2018). In Table 2-2, the main traffic assignment types are presented. The problem of the difference in personal characteristics is not included in this table, since this could be solved in each method by using multiple user classes. The main differences between the methods are the questions whether multiple routes and/or congestion effects are included. When no multiple routes are modelled, it means that all travellers perceive the same 'best route' in one iteration, whereas there is a variety in 'best routes' in one iteration in the methods that model multiple routes. Depending on the objective of the traffic assignment, one chooses which method is most suitable.

Table 2-2 Main traffic assignment types

		Congestion effect modelled?	
		No	**Yes**
Multiple routes modelled (in one iteration)?	**No**	All-or-nothing assignment	Deterministic user-equilibrium assignment
	Yes	Stochastic assignment	Stochastic user-equilibrium assignment

2.4.1 All-or-nothing assignment

In this method of traffic assignment to the network, there is assumed that there is only one 'best route' between each OD-pair in an iteration. This means, that congestion and multiple routes are not considered and that all the traffic going from A to B uses the same route in an iteration. In a successive iteration, travel times on the routes changed causing that all traffic uses another route. After conducting several iterations, the average flow on each route is calculated. So, in the end there is a distribution in taken routes from A to B. The advantage of this method is the simplicity and the low required computational time. However, this method is only reasonably applicable in a small network where few alternative routes are available. In the bigger and congested networks, this method is not suitable since the results do not meet the reality.

2.4.2 Stochastic assignment

Whereas in the all-or-nothing assignment travellers take the best route, travellers in a stochastic assignment take the best perceived route. Since the perception of the best route is a personal thing, multiple routes for each OD-pair are considered. In other words, randomness and uncertainty is also included in this method. This method is more realistic and is less sensitive to small travel time changes on the network than the all-or-nothing assignment.

2.4.3 Deterministic user-equilibrium assignment

In a deterministic user-equilibrium (DUE) assignment, congestion effects are included but there are no multiple routes modelled in an iteration. In these types of assignment, there is aimed for an equilibrium as described by Wardrop (1952):

The journey times on all routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused road.

This means, that no traveller could reduce its generalized costs by switching to another route. To come to an equilibrium, multiple iterations are required. In most cases it takes too long to find an exact equilibrium and therefore there is usually stopped when a predefined level of convergence has been reached. The most used methods for the DUE are the method of successive averaging (MSA) and the Frank-and-Wolfe algorithm. In short, the main difference between both methods is the way traffic can move to another route in the successive iteration. In MSA, this is calculated by a predefined value ($\frac{1}{\phi}, \phi\ is\ the\ iteration\ number$) whereas this value is calculated in the Frank-and-Wolfe algorithm. Concluding, the Frank-and-Wolfe algorithm is more precise, but also requires more computational power and time.

2.4.4 Stochastic user-equilibrium assignment

In the stochastic user-equilibrium (SUE) assignment, both congestion and multiple routes are considered. Also in this method, the Wardrops equilibrium is used but it slightly changed. Whereas first no traveller could decrease its generalized costs, now the traveller cannot decrease its perceived generalized costs. The SUE assignment is the most realistic assignment and the computational time shorter than in a DUE assignment. This is because in a DUE assignment only 1 route between A and B per iteration is considered, whereas there are several routes between A and B considered in a SUE assignment. This causes that an equilibrium is faster reached in a SUE assignment. Although SUE is faster than DUE, there are still sometimes troubles with reaching convergence in a SUE. This is usually solved by considering a low predefined number of possible routes between each OD-pair.

2.4.5 Summary route choice modelling and traffic assignment

For the calculation of the route a traveller would take, the generalized costs of the possible routes are calculated. Most common, is to include the travel time and monetary costs as parameters. Due to congestion, different perceptions of the 'best route' and the unfamiliarity of an area, there is usually not one 'best route'. For dealing with these problems, several traffic assignment methods are available. Depending on the objective of the traffic simulation, one could choose to do an all-or-nothing assignment, stochastic assignment, DUE assignment or SUE assignment. In Chapter 5, the traffic assignment methods used in this research are explained.

2.5 Time of Day modules

When a peak charge is implemented, travellers are stimulated to adjust their departure time to a departure time outside the peak period. To make an estimation about the distribution in departure times of a population, Time of Day (ToD) modules help to forecast the future. Each ToD has the goal to forecast the distribution in departure times of a population, but there are differences in the approaches of different types of ToD modules. First, there is a difference between macroscopic and microscopic ToD modules. Macroscopic ToD modules involve the selection of broad time periods, say 2-3 hours (Ortúzar & Willumsen, 2011). In microscopic ToD modules, the time periods to choose are smaller, normally from 30 minutes to even just a minute. Furthermore, a distinction can be made between equilibrium scheduling theory (EST) and the discrete choice theory. A last frequent distinction in ToD approaches is the inclusion or exclusion of the concept of a preferred arrival or departure time. The idea of this concept is that one strives to arrive or depart within a certain time window. When arriving or departing within this time window is not achieved, from a theoretical viewpoint, one receives a penalty for arriving or departing late or early. Using these penalties, the departure time is chosen which leads to the maximum utility.
Besides the differences between ToD methods, there is also a similarity among almost all methods. The base of each ToD method is mostly the theory of the economical utility in combination with a discrete choice model. Also for most of the user equilibrium models, the theory of economical utility is the bases. This theory assumes that one always maximizes its utility and can only choose one of the possible alternatives. The utility per alternative, is calculated by the general formula:

$$V_i = ASC_i + \beta_1 X_{1,i} + \cdots + \beta_n X_{n,i} \quad (2.1)$$

In this formula, V_i is the utility of alternative i, ASC_i is the alternative specific constant of alternative i, β_n is the valuation of parameter n and $X_{n,i}$ is the value of parameter n for alternative i. In the ToD context, the alternatives are different departure time windows. The parameters can vary from total travel time, total travel costs till personal characteristics as income and educational level.

2.5.1 Summary Time-of-Day modules

In this research, five different forms of ToD modules are considered. In Table 2-3, the advantages and disadvantages of the different modules are presented. Following the advantages and disadvantages of the modules, there is chosen to use the LMS 7.0 in this research. Below the table, the explanation for this choice is provided and in Appendix A more information can be found about the considered ToD modules.

Table 2-3 Advantages and disadvantages ToD modules

	Disadvantage(s)	Advantage(s)
Kristoffersson & Engelson	-Integrated modal split and departure time model -Designed for specific case study area (Stockholm) -Only morning period	-Microscopic model
Hades	-Hardly an equilibrium can be found, leading to extreme computational times -No monetary cost parameter included	-Simplicity -Possible to adjust to microscopic model
Hilderink model	-Only morning period -No monetary cost parameter included -Outdated	-Designed for the Netherlands -Simplicity -Microscopic model
LMS 7.0	-Outdated -Macroscopic model	-Designed for the Netherlands -Simplicity -Renowned model
Groeimodel	-Complexity -Macroscopic model	-Designed for the Netherlands -Renowned model

For the ToD module that is used, the applicability of the method is important. The method of Kristoffersson & Engelson is no option due to this reason. The method uses an integrated time of day and transport mode choice method, with parameters specifically estimated for Stockholm. Besides, only the morning period is considered. In general, there are too many issues that need to be solved when this method would be used. The same goes for the method of Hilderink. Although this model is made for the Netherlands, again only the morning peak period is considered. Furthermore, there is no cost component included in this model, meaning that a parameter must be added for the travel costs. This is undesirable, since the model is estimated for the specific parameters and adding a new one would disturb the balance of the model.
This last point is also one of the reasons that the HADES method is not directly applicable in this research. The HADES method namely, only considers the travel duration and a penalty for arriving too early or too late. Furthermore, there is known that executing this method in large networks requires a lot of computational time making this method not workable in practise. This is also supported by Kristoffersson & Engelson, since they found out that hardly any equilibrium can be found using this method. Additionally, they state that the future of ToD forecasting lies in the discrete choice theory.
As remaining options, there are two methods used in the LMS. The first one is quite simple and based on a survey held in 1995 whereas the other one is way more complex and based on surveys held in the period 2007-2009. Both methods are made for the Netherlands, have the discrete choice theory as fundament and do not use the concept of a preferred arrival and/or departure time. However, the complexity of the latest version of the LMS is a disadvantage of this method. The ToD module in the latest version of the LMS, is an integrated transport mode, destination choice and departure time choice model. This means, that the choice for a departure time depends on the transport mode choice and the destination choice. Implementing this ToD in another model would therefore be complex. As a workaround, one could decide to use the LMS in combination with the NRM. However, forecasting rat running is not possible due to the coarse level of

detail of the LMS and NRM. Because this is an important aspect of this research, the use of the LMS and NRM is not desirable.
Compared to the latest version of the LMS, the ToD module in LMS 7.0 is less complicated and it is applicable as stand-alone process since it is not an integrated module. The travel time, travel costs and the base distribution determine the new departure period. However, there are some disadvantages of this method that must be solved. First, the monetary values used in estimating the model, are based on guilders instead of euros. Besides, it is a macroscopic model making only a distinction between the morning period, evening period and the rest of the day. In Chapter 6 there is explained is dealt with the disadvantages of this ToD module.

2.6 Other conditions for proper working road pricing

In the following chapters, other conditions for proper working of road pricing are discussed. The aspects discussed in this chapter are not directly investigated in this research but are kept in mind during the process of this research.

2.6.1 Acceptation/ understandability of road pricing

A road pricing scheme can be genius in theory, but when the people do not accept and/or understand the practise of the system, it does not have any chance of succeeding. Due to this aspect, a prudent consideration is needed between the effect and the complexity of the road pricing scheme.
A lot of research has been done on the acceptability of road pricing. For example, in Grisolía and López is stated (Grisolía & López, 2008) that the lack of transparency in the revenues management is the most heard complain of road pricing. As said, before the economic crisis, the implementation of a road pricing scheme was quite close. In this period, a research was done about the effect, efficiency and acceptation of road pricing in the Netherlands (Verhoef et al., 2004). There is found, that the acceptation increases when the freedom of movement is not reduced too much. This is either achieved when the road pricing is not effective, or when there are enough other options (another transport mode, another departure time or another route). Besides, the fairness of the system, individual advantages and disadvantages and to what extend the problems with congestion are solved, are important factors. At last, it is important to communicate clear what happens with the revenues, to make sure that the people know what they are paying for.
For the Dutch case, it is wise to have a simple and understandable road pricing form, especially important in the beginning phase to reduce the resistance against road pricing. For deciding which road pricing forms are promising for the Netherlands, this information must be kept in mind.

2.6.2 Equity

One of the objectives of implementing road pricing, is that road pricing lead to a fairer way of paying taxes. Since the road taxes and purchase taxes will be abolished, the frequent car users pay more tax than the ones that barely use the car. This issue addressed here, is often researched in the expertise of transportation. In Litman (2002), a distinction is made between three types of equity, namely horizontal equity, vertical equity with regard to income and social class and vertical equity with regard to mobility need and ability. As regards road pricing, the horizontal equity and the vertical equity with regards to income and social class are important. With horizontal equity, the distribution of the effects between individuals and groups concerning the ability and needs are described. In the scenario of road pricing with peak charges, the horizontal equity is in dispute since not everybody has the possibility to switch their moment of travelling. Besides, the vertical equity with regard to mobility need and ability, comprises the distribution of effects among groups with different income levels or social classes. In the case of road pricing, it is hardly possible to make a distinction in charges based on the social class or the income level. Instead, a generalized charge is implementing which applies to everyone. Both forms are not investigated in this research any further but needs to be kept in mind when drawing conclusions about the chosen road pricing forms.

2.6.3 Operational issues

For making the road pricing a success, it is necessary that the implementation of it does not cause a lot of problems. Depending on the road pricing form that is finally chosen, there are several different approaches of implementing the pricing scheme. The implementation of the technology will ask for large investments and therefore it needs to be though out precisely before it can be implemented. When there is chosen for a cordon pricing, the ERP system as implemented in Singapore is an option. All cars are equipped with an electronical device, which registers when a vehicle enters a predefined area. This option is easier and more cost friendly to implement instead of building physical toll booths. For highway pricing, the same technique can be chosen. Instead of registering a vehicle when it enters an area, there is registered when a vehicle enters the highway. The other option is using a vignette just as done in Austria, but this does not assure that the frequent car-users pay more than the ones that barely use the car.
When a charge per driven kilometre is chosen, a device insight the cars needs to trace the location in a frequent interval to determine the route that is taken. Technically this is possible, since the same information is required as for a navigation. In the OD-variant, the device only needs to trace the origin and the destination of the vehicle. This can possibly be accomplished by using the moment of turning on and off the engine as start and end point of a trip. All in all, the operational issues do not seem to be an insurmountable problem.

2.6.4 Privacy issues

One of the most heard worries of having an electronical device in the car, is that the government exactly knows when and where someone is driving. Followed by a research conducted by I&O Research (Mebius et al., 2019), 40 per cent of the Dutch inhabitants worry about privacy when implementing road pricing. Therefore, it is crucial that the government arranges clear agreements about who can use and see the data about the individual trips. Besides, a reliable security protection of the database in which the data is stored is required, which avoid the database from being hacked. Concluding, the privacy issue is something the government needs to investigate on beforehand.

2.7 Hypotheses

Following from the introduction and the literature review, there are five hypotheses that are tested in this research. These hypotheses are related to a comparison between the road pricing forms, but also to a comparison between the base scenario and the road pricing forms. The hypotheses are formulated as:

1. In all forms there is a decrease in traffic demand in the peak hours and an increase in the peak-shoulders
2. In form 2, there is no decrease in liveability compared to the base scenario in residential areas of the region of Eindhoven.
3. Form 1 reduces the liveability compared to form 2, especially in the city centre of Eindhoven
4. In form 3, the liveability in the urban areas improve compared to form 1 but decreases in areas just outside the urban areas
5. In all forms, a reduction of x% in traffic demand leads to approximately a fivefold reduction of vehicle loss hours.

By implementing a peak charge, there is aimed to stimulate travellers to avoid the peak hours. Linking this hypothesis to quantitative numbers is not possible, since as far as known there are no other researches with a comparable design. In the other researches it is possible to change from destination and/or of transport mode. Therefore, making a quantitative estimation is not possible for the first hypothesis.
The second, third, and fourth hypotheses relate to the liveability in the region of Eindhoven. Due to the differences in characteristics of the road pricing forms, there are different expectations. There is expected, that form 2 does not have negative effects on the liveability in residential areas of the region of Eindhoven, since the route choice is not affected in form 2 by the charge. Therefore, shorter routes are not stimulated.

Since in form 1 shorter routes are stimulated, there is expected that in form 1 the liveability is reduced compared to form 2. In form 3, there is tried to improve the liveability by implementing location charges in the urban area. There is expected that this causes an increase of liveability in the urban area, but a decrease in liveability in areas just outside the urban area compared to form 1.
The last hypothesis is based on a research conducted by De Baat & Suijs from Goudappel Coffeng (in Rottier, 2020) concerning the effects of the corona virus on traffic jams. They analysed the effect of the reduction in traffic intensity on the degree of traffic jams. There is found, that a reduction of 1% in traffic demand causes a reduction of 3% in traffic jams. For translating this to vehicle loss hours (see Chapter 4.2.1 for explanation why vehicle loss hours are used), the research of Jonkers et al. is used (2009). They stated, that the relation between the degree of traffic jams and the vehicle loss hours is between 1.43 and 2.18 for highways, mostly depending on the number of lanes on a highway. Taking an average value, leads to the hypothesis that a reduction of x percent in traffic demands leads to approximately a fivefold reduction of vehicle loss hours.

3. Methodology

In this chapter, the methodology of this research is explained. First, the chosen road pricing forms are discussed included the corresponding charges. Subsequently, the choices for a model and the ToD module are explained. At the end, the research framework is provided to provide a clear overview of the upcoming steps.

3.1 Road pricing forms

In Chapter 2.2, the three investigated road pricing forms are explained. In Table 3-1 they are summarised and there is indicated which choice-components are included in each variant. In the base scenario, only the default route choice function without monetary costs is included. In form 1 and 3, both the ToD-module and the route choice with monetary values are included. In the route choice functions, the monetary costs per kilometre are implemented. In the second form, the ToD module is included with the monetary costs, but in the route choice function the monetary costs are not used. This is because the total charge someone pays does not depend on the route that is taken. For all forms goes, that there is no distinction made between cars and trucks. The charges for trucks and car traffic are therefore equal.

Table 3-1 Components in road pricing forms

	ToD-module		Route choice function	
	Without monetary costs	With monetary costs	Without monetary costs	With monetary costs
Base scenario			x	
Form 1 (charge per driven kilometre including peak charge)		x		x
Form 2 (OD-variant including peak charge)		x	x	
Form 3 (charge per driven kilometre including peak and location charge		x		x

3.2 Road pricing charges

Essential for the success of road pricing, is the value of the charge. In Table 3-2, an overview of the charges per scenario per area are presented (in cents per kilometre). Below the table, there is explained why these charges are chosen.

Table 3-2 Final charges in cents per kilometre

	Base		Form 1		Form 2*		Form 3	
	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-Peak
Area I	0	0	11	7	11	7	22	18
Area II	0	0	11	7	11	7	16.5	12.5
Area III	0	0	11	7	11	7	11	7
Area IV	0	0	11	7	11	7	11	7

*Charge is per kilometre but does not depend on the route. I.e. it is a fixed charge.

The charge must be on point, since a too high charge could lead to a lot resistance among residents and a too low charge would not cause any effect on congestion. In earlier attempts to implement road pricing, the mentioned charges are 7 cents per kilometre outside peak hours and 11 cents per kilometre during peak hours. These charges were used as example for calculating the revenues of road pricing in 2016 (Giebels, 2016) and are in line with proposals of the election programs (Centraal planbureau, 2015). In the research

of 4Cast, an average charge of 6.91 cents is used when all taxes are abolished. Concluding, the charges of 7 cents per kilometre outside peak hours and 11 cents per kilometre during peak hours are in line with previous reports and are therefore also used in this research.
For form 3, the value of the location components is based on the research of 4Cast. In this research, location components are added on roads where an IC-ratio is above 0.8. The location components, variate from 5.5 till 22 cents per kilometre. Using this as reference framework, the location component is set at 5.5 cents per kilometre extra in area II, and 11 cents per kilometre extra in area I (see Figure 3-1). The first level addresses the area inside the ring road of Eindhoven and is meant for stimulating traffic to not enter the city centre of Eindhoven. The second area addresses the suburbs of Eindhoven and the main access roads of the city centre, which should also be avoided. The city centre area is not included in this area. Area III and IV do not get the location charge.

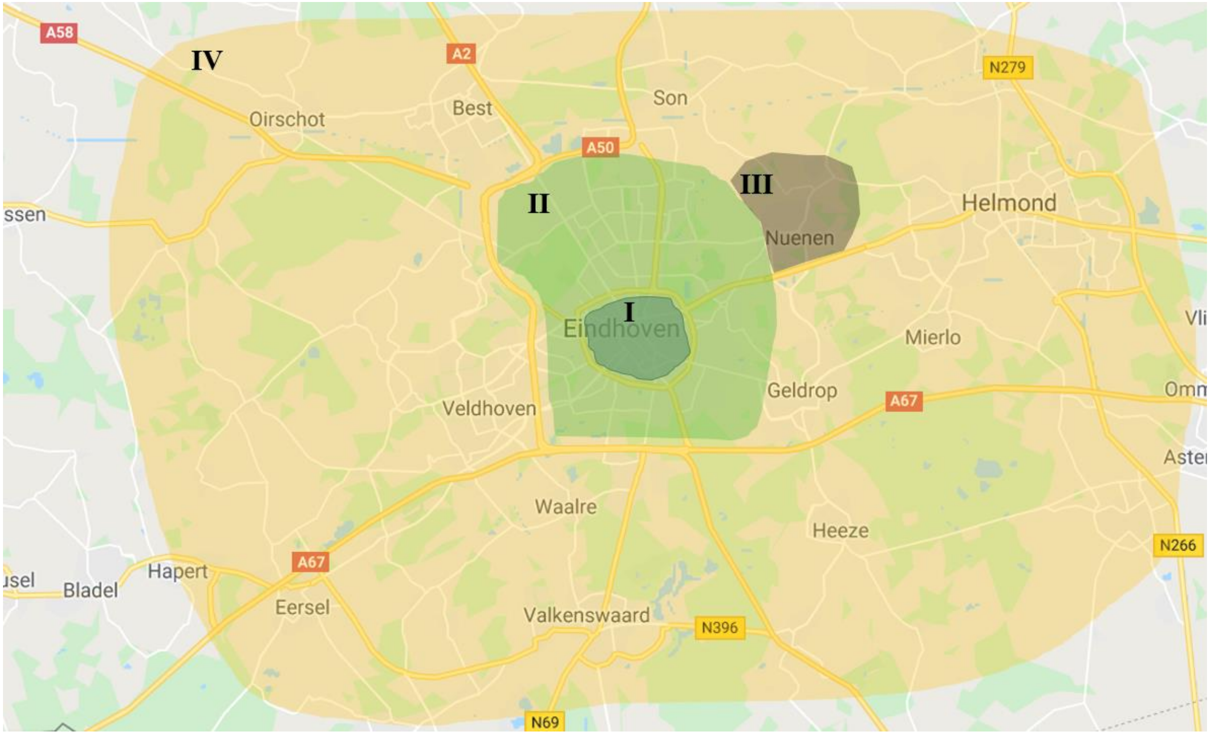


Figure 3-1 Areas in region of Eindhoven

3.3 Model choice

In the world of traffic forecasting, there are multiple approaches. The choice for which approach to follow, depends on the aim of the research and the research questions that needs to be answered. There is chosen between three types of traffic models: macroscopic, mesoscopic and microscopic. The simulation approach with the highest level of aggregation is a macroscopic simulation. Typical parameters measured by macroscopic models are speed, flow and density (Boxill & Yu, 2000). The main advantage of this approach is the efficiency and the ability to deal with greater networks in terms of a reasonable computation time. The main disadvantage is the loss of the level of detail (Ratrout & Rahman, 2009). The approach with the highest level of detail, is the microscopic simulation. In a microscopic simulation, the behaviour of each single vehicle is modelled. Although this leads to detailed results, it is not workable in the bigger network since it requires a lot of computational time. An approach that lies in the middle between the micro and macroscopic approach, is the mesoscopic simulation. The traffic characteristics are described on a high level of detail, but traffic behaviour and interactions are not designed on that high level of detail as in a microscopic simulation, to save computational power and time (Wilco Burghout, 2004). In a mesoscopic simulation, it is possible to accurately determine the level of congestion, whereas this is not possible in a macroscopic

simulation. Since investigating the degree of congestion needs to be investigated for the road pricing forms, there is chosen to use a mesoscopic assignment. This is supported by Burghout, Koutsopoulos and Andreasson (2006), who stated that mesoscopic models are accurate enough for modelling travel behaviour as route choice.
Next to the choice for a specific model, a choice is made between different software packages. The most relevant software packages for this case are Aimsun and Omnitrans. Nationally seen Omnitrans is most used and internationally seen Aimsun is most used (Calvert et al., 2016). Although both Aimsun and Omnitrans are quite similar, there are few important issues that places Aimsun above Omnitrans for this research. First, a model of the region of Eindhoven is directly ready for use. Furthermore, switching between a static and dynamic simulation does not need extra actions in Aimsun whereas this would be the case in Omnitrans. Thirdly, Aimsun has a dynamic mesoscopic model whereas this is missing in Omnitrans. At last, there is a lot of experience in working with Aimsun at Royal HaskoningDHV. Due to these practical issues, there is chosen to use Aimsun as software program.

3.4 Choice Time of Day module

Since the method used in LMS 7.0 is chosen as ToD module, this method is explained in detail in the following paragraphs. The module used in LMS 7.0 is just a discrete choice model, what is proved in Appendix B. In this module, the distribution between departing in an average morning peak hour, an average evening peak hour and an average rest of day hour is calculated, for each trip purpose and each OD-pair. The parameters that influence the choice for a departure time period are the travel time, travel costs and the distribution in percentages between the morning peak, evening peak and rest of day for a base scenario. The share of for example the morning period in a future year is calculated by the following formula:

$$P_{N+1}^{MP} = \frac{f_N^{MP} * e^{V_{N+1}^{MP}}}{f_N^{MP} * e^{V_{N+1}^{MP}} + f_N^{EP} * e^{V_{N+1}^{EP}} + f_N^{RoD}} \qquad (3.1)$$

Where:
P_{N+1}^{MP}=Share of morning peak in year $N+1$
f_N^{MP}=Share of morning peak in year N
V_{N+1}^{MP}=Utility of travelling in the morning peak in year $N+1$
f_N^{EP}=Share of evening peak in year N
V_{N+1}^{EP}=Utility of travelling in the evening peak in year $N+1$
f_N^{RoD}=Share of the rest of the day in year N

The utility of travelling in the morning peak (V_{N+1}^{MP}) for example, is calculated by the following formula:

$$v_{N+1}^{MP} = \beta_{Time}^{m} * \left((TT_{N+1}^{MP} - TT_{N+1}^{RoD}) - (TT_N^{MP} - TT_N^{RoD})\right) + \beta_{cost}^{m} * \left((Cost_{N+1}^{MP} - Cost_{N+1}^{RoD}) - (Cost_N^{MP} - Cost_N^{RoD})\right) \qquad (3.2)$$

Where:

$\beta_{Time}^{m}, \beta_{cost}^{m}$= Respectively the valuation of travel time and travel costs per trip purpose (m)
TT_{N+1}^{MP}, TT_N^{MP}= Travel time during the morning peak in year $N+1$ or N respectively
$TT_{N+1}^{RoD}, TT_N^{RoD}$ = Travel time during the rest of the day in year $N+1$ or N respectively
$Cost_{N+1}^{MP}, Cost_N^{MP}$ = Travel costs during the morning peak in year $N+1$ or N respectively
$Cost_{N+1}^{RoD}, Cost_N^{RoD}$ = Travel costs during the rest of the day in year $N+1$ or N respectively

What is stated in formula 3.2, is that the utility of travelling in the morning peak in year $N+1$ depends on the difference in travel time in the morning peak and rest of the day of year $N+1$ minus the difference in travel time between the morning peak and the rest of the day in year N. The same goes for the travel costs and the combined generalized costs determine the utility of travelling in the morning peak in year $N+1$. By executing formula 3.1 this process for both the morning peak, evening peak and the rest of the day, the distribution between the morning peak, evening peak and rest of day is found for year $N + 1$. In Appendix C.1 a detailed example for one OD-pair can be found and in Appendix C.2 the valuations of the travel time and travel costs per trip purpose are presented.

3.5 Research framework

To provide an overview of all the steps conducted in this research, Figure 3-2 is made. Roughly, the steps can be divided in seven main categories: (1) practical input, (2) theoretical input, (3) base scenario, (4) static macroscopic part road pricing forms, (5) dynamic mesoscopic part road pricing forms, (6) assessment framework, and (7) results, conclusions and discussions. In the following paragraphs, there is elaborated what is done in which step and where more information can be found about that step.
The practical input consists of two main components. The first one, is the delivered model of the region of Eindhoven. This model is delivered by Royal HaskoningDHV and is already used in previous studies. Secondly, OD-matrices are delivered both for cars and trucks for the year 2030. Both the delivered model and the delivered OD-matrices are used as input for the base scenario and for the road pricing forms. More information about the practical input can be found in Chapter 5.
The theoretical input comprises the literature review what can be found in Chapter 3. In this chapter, multiple road pricing forms are discussed and there is explained which ones are chosen and why they are chosen. Besides, several Time-of-Day modules are elaborated, and the concept of route choice functions and traffic assignment is discussed. At last, five hypotheses are composed which help to answer the research questions.
The third main category of this research is the simulation process of the base scenario. Before the delivered OD-matrices can be used, they are converted to matrices per trip purpose (OD-matrices for trucks are not changed). Subsequently, the static macroscopic assignment is executed. The output of this simulation is used as input for the dynamic mesoscopic assignment, just as the OD-matrices per 15-minute which are obtained by converting the delivered OD-matrices of cars and trucks for the year 2030. Following from the dynamic mesoscopic assignment, Key Performance Indicators (KPIs) are obtained. See Chapter 4 for the KPIs and Chapter 5 for the simulation process of the base scenario.
The fourth main category is the static macroscopic part of the road pricing forms. As input for the static macroscopic assignment, the OD-matrices per trip purpose (car) are used. For trucks, the delivered OD-matrices are used. Besides, the static route choice functions are adjusted in a way that road pricing is included in the route choice process (see Chapter 6.1). After the static macroscopic assignment is conducted, the output of this simulation is used for the ToD module. This step produces new OD-matrices, which are used in a new static macroscopic assignment. After this process is conducted four times, there is continued with the dynamic part of the road pricing forms. The information about the static part of the road pricing forms can be found in Chapter 6.1 and 6.2.
After the static part, the dynamic mesoscopic part of the road pricing forms is conducted. Firstly, the OD-matrices are converted to 15-minute matrices which are used for the dynamic mesoscopic assignment. This assignment is executed six times, to reduce the degree of randomness. The output of the assignment are the KPIs. Information about the dynamic mesoscopic assignment can be found in Chapter 6.4.
The sixth category comprises the assessment framework that is used in this research. To grade the performance of the road pricing forms, five Key Performance Indicators (KPIs) are composed. In Chapter 4, there is explained which KPIs are used and why these ones are chosen.
The last category of this research is the results, conclusions and discussions part. In the results part, all KPIs are compared between the road pricing forms and the base scenario (Chapter 7). Subsequently, conclusions are provided on the hypotheses and the research questions (Chapter 8). At last, the conclusions and results are discussed and recommendations for further research are provided (Chapter 9).

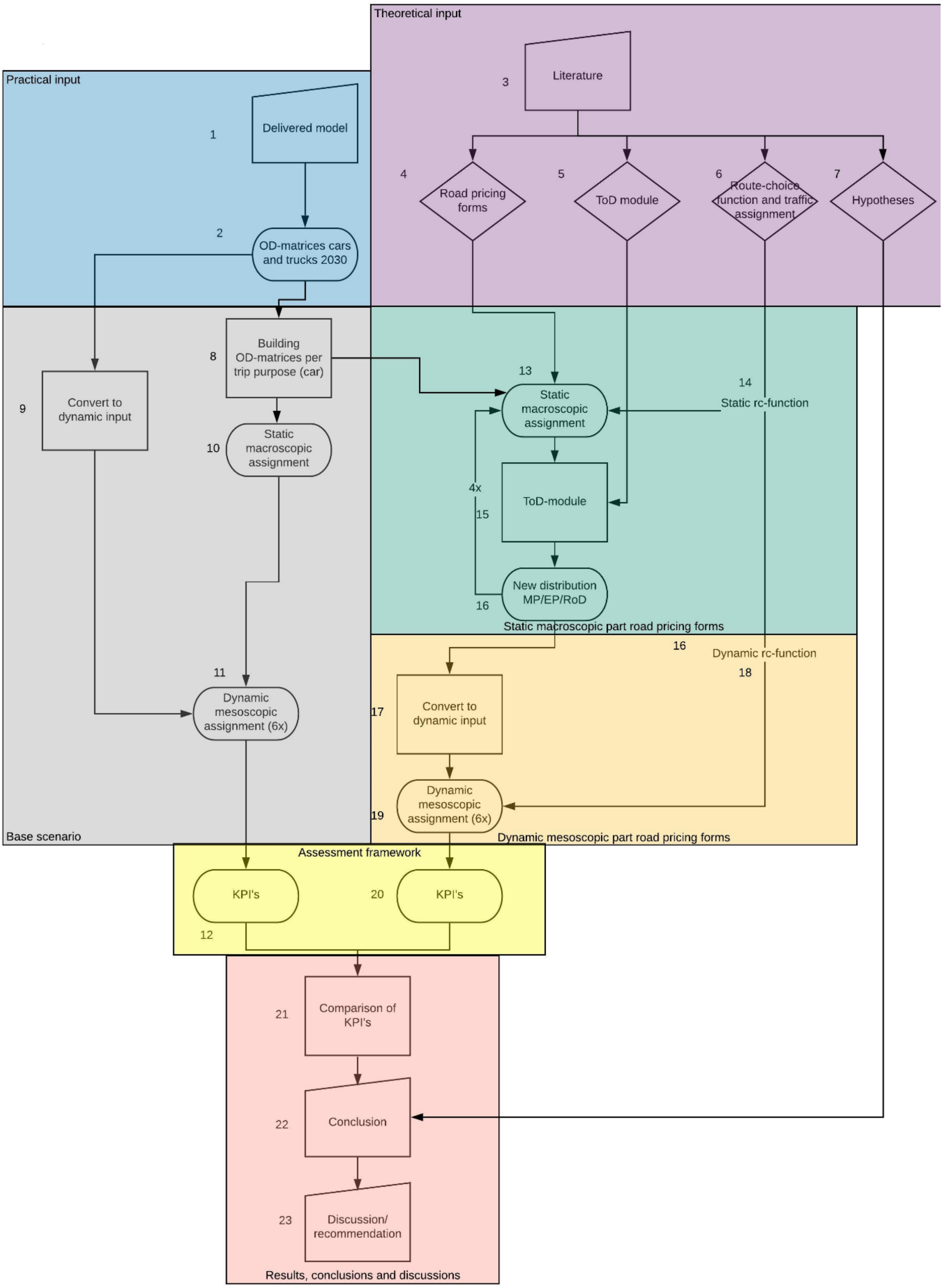


Figure 3-2 Research framework

4. Assessment framework

The goal of this research is to provide insight in the effects of implementing road pricing for the region of Eindhoven. This is done by composing Key Performance Indicators (KPI) that are used to grade the road pricing forms. The following five KPIs are used:

1. Switch departure time peak vs off-peak
2. Intensities
3. Total distance driven
4. Travel times on main roads
5. Vehicle loss hours

These KPIs are closely related to the goal a government wants to achieve by implementing road pricing. The main reason of implementing road pricing is to reduce the level of congestion (generating revenues and equity issue are not considered). To achieve this, a peak charge is implemented which should stimulate people to avoid the peak hours and to assure a smoother spread in peak hours. On the other hand, the implementation of road pricing should not induce any nuisance caused by people taking detours.
A distinction can be made between KPIs that determine a possible change in travel behaviour and KPIs that determine the effects of a possible change in traffic behaviour. All KPIs are analysed separately per period (morning peak, morning peak shoulder, evening peak, evening peak shoulder) and are compared among the other scenarios and the base scenario. In the following paragraphs the KPIs are explained.

4.1 Change in travel behaviour

In this research, a traveller could choose to take another departure time and/or can choose to take another route. The following KPIs explain how this change in travel behaviour is measured exactly.

4.1.1 Switch departure time peak vs. peak shoulders

As a first criteria, there is investigated whether travellers are really stimulated to change their departure time to an outside peak hour. For measuring this KPI, there is looked at the total number of trips made in the peak period versus the total number of trips in the peak shoulders, separately for the morning period and the evening period.

4.1.2 Liveability residential areas

As a possible disadvantage of one of the chosen road pricing forms (paying per driven kilometre), is that travellers could be stimulated to use the shorter route to save money, what could reduce the liveability in some areas. Although the liveability of an area addresses many aspects, there is chosen to grade the liveability using two KPIs which are described in the following paragraphs.

4.1.2.1 Intensities

Due to the absence of a ring road of highways in the region of Eindhoven, there is often spoken about the ‘robuuste rand’ in the region of Eindhoven. The red roads in Figure 4-1 belong to the robuuste rand. Besides, roads in the area inside the robuuste rand (blue and purple roads) are designated to lead traffic as fast as possible to the roads of the robuuste rand. This means, that an increase of traffic on these roads does not imply a reduction in liveability. However, an increase of intensities on the other roads does imply a reduction in liveability. To check whether this is the case after implementing road pricing, plots are used which present the differences in intensities between the scenarios with road pricing and the base scenario. First, a plot is made which presents the difference between the base scenario and form 2. In this way, the effect of only the smoother spread in peak can be analysed, since there is no route choice component included in form

2. Second, a plot is made between the difference in intensities between form 2 and form 1. In this plot, the effect of the route choice component can be evaluated. As last, a plot is made of the difference in intensities of form 1 and form 3. In this plot, the effect of the location charge is presented.

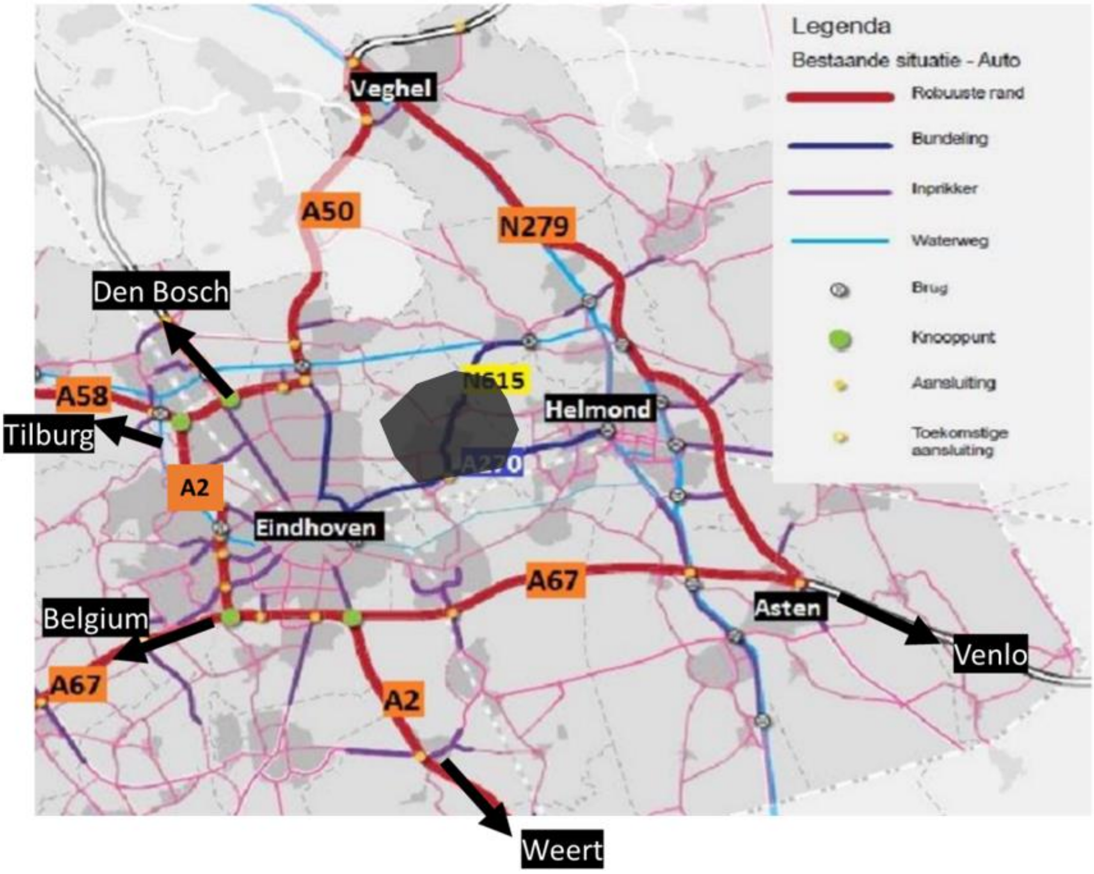


Figure 4-1 Road network region Eindhoven

4.1.2.2 Total distance driven

Since it is not possible to analyse each road section separately, there is also a KPI introduced which grades liveability on the broader scale. To do this, the total distance driven is analysed for four different areas (see Figure 3-1). The total distance driven per area is used to analyse whether there is an increase or decrease of traffic in each area. Area I is chosen since it is the city centre of Eindhoven and area II is the suburban area of Eindhoven. Area III is chosen since there are already liveability problems in this area which could increase in some road pricing forms. In this area, the N615 is not included since this is an important road for the complete network and therefore an increase of traffic demand on this road is not negative. At last, the complete area is analysed over the complete simulation period. Since the total number of trips is the same in each scenario, the total distance driven over the complete network indicates whether shorter routes are taken or not. A decrease in total distance driven could indicate that there is an increase of rat running traffic implying a reduction in liveability.

4.2 Effects of change in travel behaviour

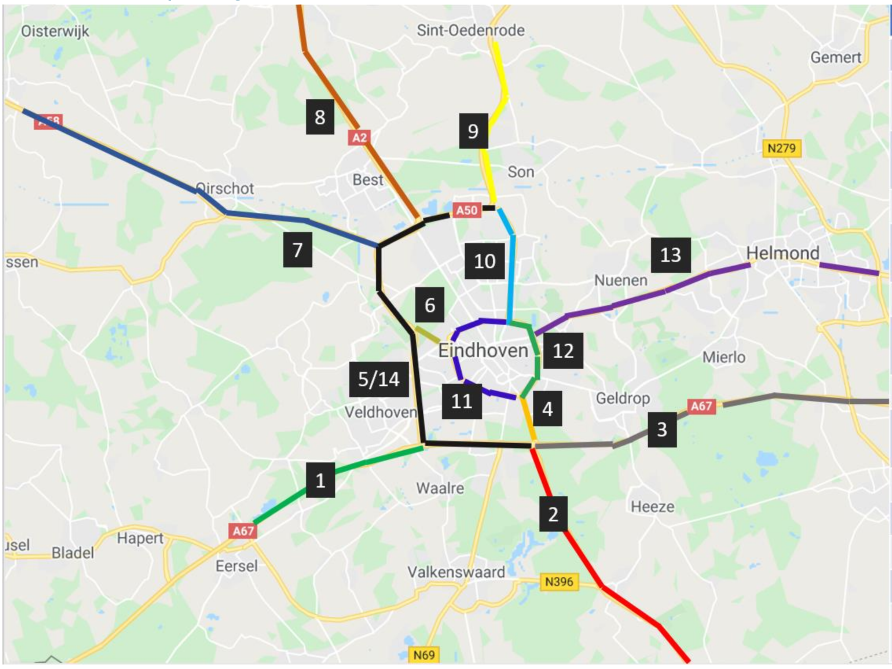
The implementation of road pricing could lead to a change in travel behaviour. For investigating the effect of a possible change of travel behaviour, the degree of congestion is analysed.

4.2.1 Congestion

As reduction of congestion being one of the main objectives of the implementation of road pricing, this is chosen as KPI. The degree of congestion is determined in two different ways as explained below.

4.2.1.1 Travel times

To assess the degree of congestion, the travel times on the main roads are used as indicator. The travel time is chosen since this is drivers most appreciated traffic information (Soriguera et al., 2010). It is not possible to analyse each possible route, therefore there is focussed on the most important ones, mainly on the highways. The routes that are considered, are presented in Figure 4-2. In total, 28 routes are analysed (both directions of each trajectory). The travel times are calculated per hour and are compared across the different road pricing forms and the base scenario.



Number	Trajectory
1	A67 Eersel-de Hogt
2	A2 Maarheze-Leenderheide
3	A67 Asten-Leenderheide
4	Leenderweg
5	A2 Ekkersrijt-Leenderheide
6	Tilburgseweg
7	A58 Moergestel-Batadorp
8	A2 Boxtel-Ekkersweijer
9	A50 Sint-Oedenrode-Ekkersrijt
10	John F. Kennedylaan
11	Ring Western route
12	Ring Eastern route
13	A270/N270 N279-Ring
14	N2 Ekkersrijt-Leenderheide

Figure 4-2 Trajectories for analyses travel times

4.2.1.2 Vehicle loss hours

Following the procedure described above, it is not possible to analyse the travel time on each single road section. A criterion that is often used to describe the degree of congestion of a whole network, is the parameter total vehicle loss hours (for instance in the yearly report of the KiM about mobility of the Netherlands (Kennisinstituut voor Mobiliteitsbeleid, 2019)). The vehicle loss hours provide a better indication of the delay on the network than analysing the degree of traffic jams. The vehicle loss hours are travel time hours that are lost in an area/on a road. 1 vehicle loss hour could be the delay of one vehicle of one hour, or e.g. the delay of 1 minute for 60 vehicles.

The previous KPI, the travel time on predefined trajectories, mainly focusses on the effects on the bigger roads. However, there can be differences between the development of congestion on the bigger roads compared to congestion on the smaller roads. Therefore, there is chosen to calculate the vehicle loss hours on four levels (see Figure 4-2). The first level addresses the area inside the ring road of Eindhoven and is meant for evaluating the effect on congestion in the city centre of Eindhoven. The second area addresses the suburbs of Eindhoven and the main access roads of the city centre. The city centre area is not included in this area. In area III, there is investigated whether a possible increase in intensities also means an increasement of vehicle loss hours. At last, the vehicle loss hours are calculated for all other roads in the network. Using the four different areas, conclusions can be drawn about the degree of congestion on different levels.

5. Base scenario in Aimsun

In this chapter, there is explained which steps are conducted to obtain the results of the base scenario. First, a general introduction of Aimsun is provided. Thereafter, there is explained how the required matrices are composed and how and why the static macroscopic assignment is executed. Furthermore, there is discussed how the transition from macroscopic to mesoscopic is completed. At the end, there is explained how the dynamic mesoscopic assignment is executed.

5.1 Introduction Aimsun

The traffic simulation model Aimsun (advanced interactive microscopic simulator for urban and non-urban networks), is designed in a long-term research project at the University of Catalonia. Nowadays the scope of Aimsun is broader than only being a microscopic simulator, since the software includes macroscopic, mesoscopic, microscopic and hybrid models (Casas et al., 2010). For this research, only the macroscopic and mesoscopic model are used due to the complexity of the microscopic and hybrid models.
The model that is used in this research, does not have to be built from scratch. A lot information is already available from previous projects done by Royal HaskoningDHV. The network visualised in Figure 5-1, is used as basis for this research. This network consists of around 4400 zones with a detailed road network especially in Eindhoven and Helmond. For this network, OD-matrices for both cars and trucks are available, for the morning period, evening period and for the rest of the day for the year 2030. For the peak periods, these matrices consist of the number of trips of an average peak hour. For example, the OD-matrix of the morning peak includes the trips of the hourly-average between 07:00 and 09:00. In total, there are six OD-matrices (three day-periods, two vehicle types) for the year 2030.

Figure 5-1 Base model

5.2 Composing matrices

As said in the previous chapter, matrices are available for both cars and trucks for an average morning peak, evening peak and rest of day hour for the year 2030. These matrices are corrected based on traffic counts in the following way:

For an OD-pair, the number of trips is determined at 10 based on the social economic data of the base year. After calibrating for this OD-pair using traffic counts, it turned out that the number of trips is 20, and thus there is a calibration factor of 2. For the year 2030, new social economic data is provided, and the new number of trips is set at 100 caused by a new business park. Using the calibration factor, the corrected *number of trips for this OD-pair is set at 200. However, using only the calibration factor, the number of trips in the future year is overestimated. Therefore, an extra restriction is used that the trips for the future year are corrected with at most three times the absolute difference of the base year. Concluding, the corrected number of trips for the OD-pair in 2030 is 130.*

The corrected matrices can be used directly, however there is a problem arising when the ToD module would be applied. In the ToD module, the valuation of travel time and travel cost depend on the trip purpose, thus matrices are required for each separate trip purpose. Although the ToD module is not used in the base scenario and therefore no matrices per trip purpose are required, matrices per trip purpose are composed to assure that the exact same input is used in the base scenario as in the road pricing scenarios. This process is explained in the following chapter for car traffic. Since the ToD module is not used for trucks, the corrected matrices of trucks can be used directly.

5.2.1 Matrices per trip purpose

For composing the matrices per trip purpose, a distinction is made between internal traffic and through traffic. For both the internal and through traffic, the base network is reduced to a network consisting of around 2200 zones to reduce the computational time. This is done, by excluding roads which are too small or too far away from the area of interest. In the following paragraphs, there is shorty described how the matrices per trip purpose are composed for the external and through traffic.

5.2.1.1 Internal traffic

In this research, internal traffic is the traffic that either departs or arrives in a zone which is inside the network. For each zone inside the network, social-economic data is available that is used as input for conducting the matrices per trip purpose. These matrices per trip purpose are conducted by executing the trip generation and distribution process in Aimsun. The output of this process, are matrices of an average morning peak, evening peak and rest of day hour with the following trip purposes:

- Home-Work
- Home-School
- Home-Shopping
- Home-Business
- Work-Home
- School-Home
- Shopping-Home
- Business-Home
- Business
- Other

For the detailed process of composing the matrices per trip purpose for the internal traffic, see Appendix D.1.

5.2.1.2 Through traffic

Since no social-economic data is available of the origin nor the destination of this traffic, it is not possible to use the trip generation and distribution method to invent the distribution in trip purposes. Instead, there is chosen to directly use the through traffic that is included in the delivered matrices. Following from the OD-matrices composed per trip purpose of the internal traffic, the ratio across the trip purposes can be calculated. Next, the ratios are somewhat adjusted based on expert judgement. Using these ratios, the through traffic is added to the matrices composed of the internal traffic per trip purpose. In Appendix D.2 the exact distribution among the trip purposes is shown for the through traffic.

5.2.1.3 Merging matrices

For the base scenario, it is not required to calculate something with the matrices per trip purpose. Therefore, all matrices are merged per time period both for the internal and through traffic. This provides matrices of an average hour in the morning peak and evening peak for the year 2030 consisting of both internal and through traffic. At last, the OD-matrices of trucks are added to the OD-matrices of the cars.

5.3 Static macroscopic assignment

Now the OD-matrices are composed, the traffic can be assigned to the network. As already discussed in Chapter 5.2, the results are obtained by using a dynamic mesoscopic simulation, of which the stochastic user equilibrium (SUE) assignment is the most reliable. However, in a SUE assignment the following problem is occurring:

Between two zones, it is possible to travel via route A of route B. On 08:00, there is much more congestion on route A, causing that almost all traffic departing on 08:00 uses route B. Therefore, route A is almost free of congestion at 08:15. As a response, almost all traffic departing at 08:15 uses route A. And so on.

In Aimsun, this problem can be tackled by first executing a static macroscopic simulation. The output of this simulation is a path-file in which the three most-used routes are stored for each OD-pair. Subsequently, this path-vis used as input for the dynamic mesoscopic simulation (in Chapter E more details are provided about the path-file as input for a dynamic mesoscopic simulation). For determining which routes are the three most-used per OD-pair, a static route choice function is used. The costs on the road sections is calculated by the VDF and the costs on a turn by the TPF. Both functions are required, due to the way the network is composed in Aimsun. Between two road sections, a turn is implemented to connect the road sections. The concept of both functions is similar, with the only difference that the VDF considers the road sections and the TPF the turns.

5.3.1 VDF

The form of the used VDF is as follows:

$$Cost_j = TT_j + 0.25 * D_j \qquad (5.1)$$

Where:
TT_j= Actual travel time on road section j in minutes
D_j= Distance of road section j in kilometres

The weights in this formula, are based on the default settings used by Royal HaskoningDHV. In other projects, the weight of the travel time is set at one and the weight of the distance on 0.25. Furthermore, the travel time on a road section is calculated by the following formula:

$$TT_j = \frac{D_j}{speed * reductFactor} \qquad (5.2)$$

Where D_j is the distance in kilometres, $speed$ is the speed in kilometres per minute and $reductFactor$ is a reduction factor. This reduction factor is implemented since the travel time is calculated under congestion-free circumstances, whereas this is not realistic. Therefore, the travel time is corrected by a factor based on the IC-ratio (intensity/capacity-ratio) on the road section. A reduction factor below one, means that the travel time becomes greater than the free flow travel time due to delay caused by the intensities on the road.

In Figure 5-2, the reduction factors on the main road are presented. The higher the IC-ratio, the lower the reduction factor and thus the higher the actual travel time. For example, an IC-ratio of 0.9 leads to a reduction factor of 0.852 (i.e. the real travel time is 1.17 times the free flow travel time).

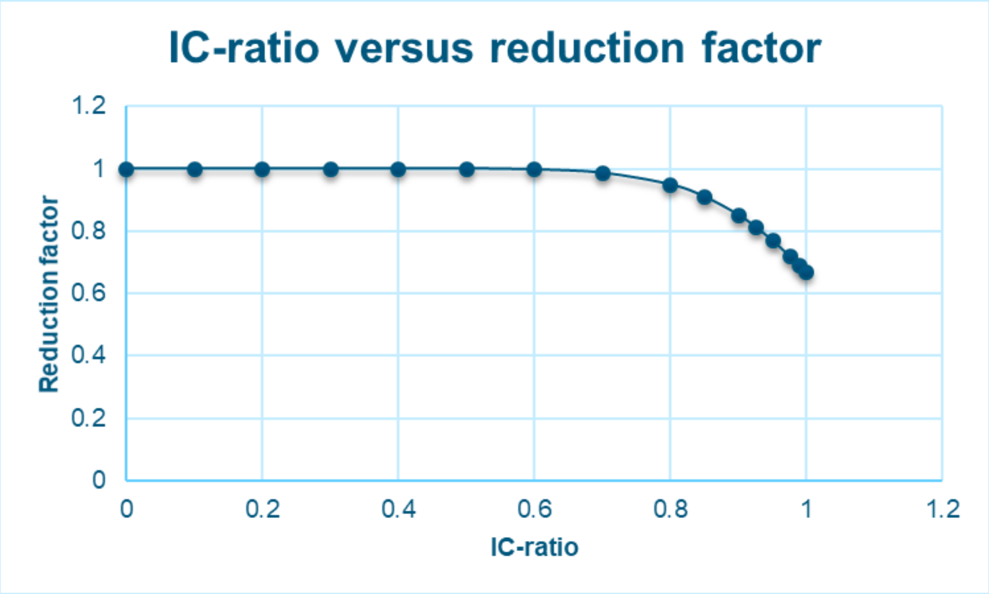


Figure 5-2 IC-ratio versus reduction factor on main roads

5.3.2 TPF

Road sections are connected to each other by turns, which also have a (small) length. Although most of the lengths of the turns are neglectable compared to the lengths of the road sections, it is correct to implement the cost charge also on the turns. This is done in the exact same way as for the VDFs, except that now the length of the turns is considered instead of the length of the road sections.

5.3.3 Assignment method

For executing the static macroscopic assignment, the MSA method is used. Although the Frank-and-Wolfe algorithm is somewhat more accurate, this advantage does not outweigh the disadvantage of the increasing computational time. In Appendix D.3, more technical details about the settings in Aimsun are presented.

5.4 Macroscopic to mesoscopic

To be able to draw relevant conclusion for in this research, a dynamic mesoscopic simulation is required since then all KPIs can be calculated.
The matrices composed in Chapter 5.2 consist of traffic of an average hour of the morning peak or the evening peak. For the dynamic mesoscopic assignment, matrices per 15 minutes are required. For the morning period the hours 05:00-11:00 are simulated and for the evening period the hours 14:00-20:00. For converting the hourly-matrices to 15-minute matrices, so-called 'departure profiles' are used. In Figure 5-3 and 5-4, the departure profiles of the morning and evening peak of the main roads leading to Eindhoven are presented. The percentages represent the number of trips that enter the network on a specific (fictive) location and are based on traffic counts of INWEVA. There are nine different profiles, since the number of trips departing is different for each location (for trucks there are different departure profiles, which are not presented here to keep the figure structured). An example:

A model is made in such a way that traffic enters the model on the highway A67 between Eersel and Eindhoven. In an average morning peak hour, the intensity on this road section is for example 3000 vehicles per hour. When the percentage for the time interval 08:00-08:15 is for example 30 per cent, it means that around 900 vehicles enter the network in the time window 08:00-08:15 on the road section A67 between Eersel and Eindhoven. In this way, the number of trips departing from each centroid, are converted from an average hour to a 15-minute interval.

As can be seen in Figure 5-3 and 5-4, the last hour of the simulations no traffic enters the network (respectively 10:00-11:00 and 19:00-20:00). This is done, since the last hour is used as cooldown period for the model. This is done to assure that all traffic that entered the network is also able to leave the network before the end of the simulation. Vehicles that are trapped in the network at the end of the simulation, are not considered in some simulation results and could therefore bias the obtained results. What furthermore stands out in Figure 5-3 and 5-4 is that, mainly in the evening peak, the profile of departures in Eindhoven and the rest differs quite a lot compared to the other profiles. This shows the usefulness of using different departure profiles.

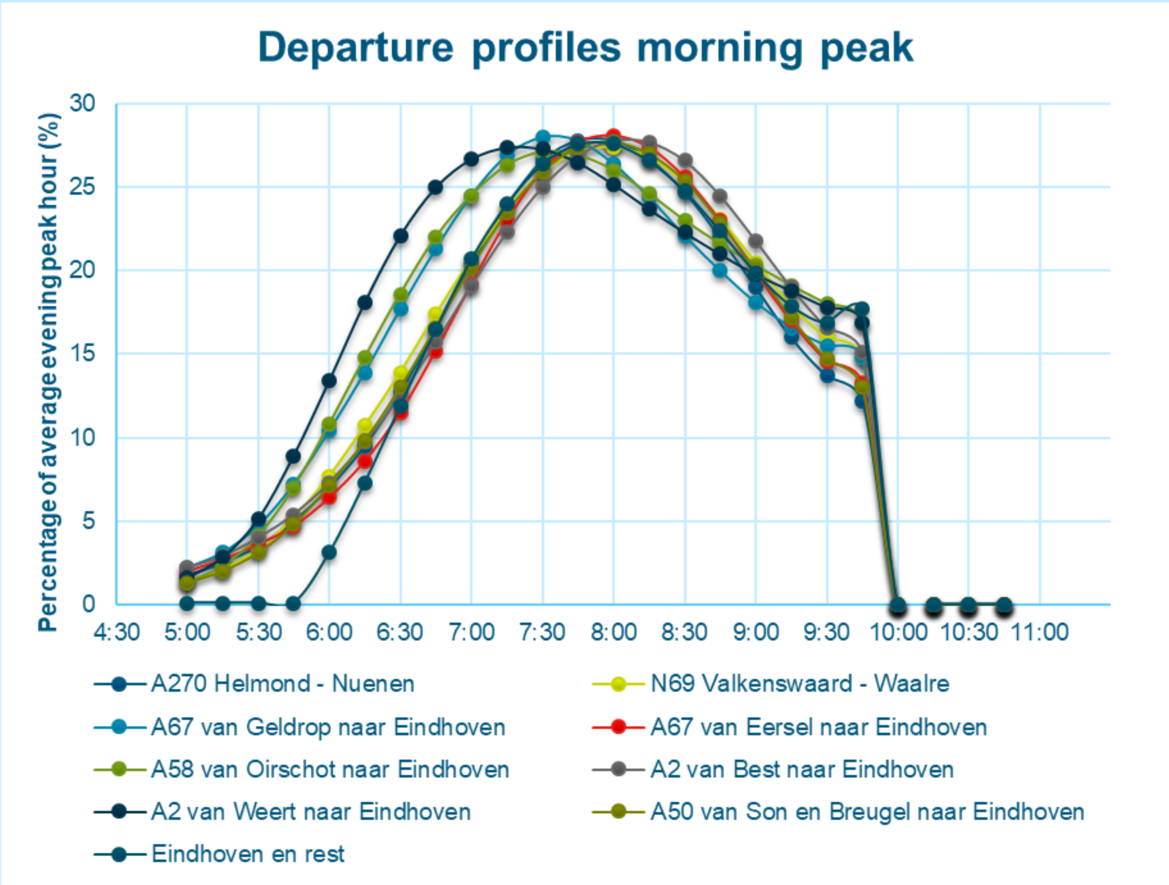


Figure 5-3 Departure profiles morning peak

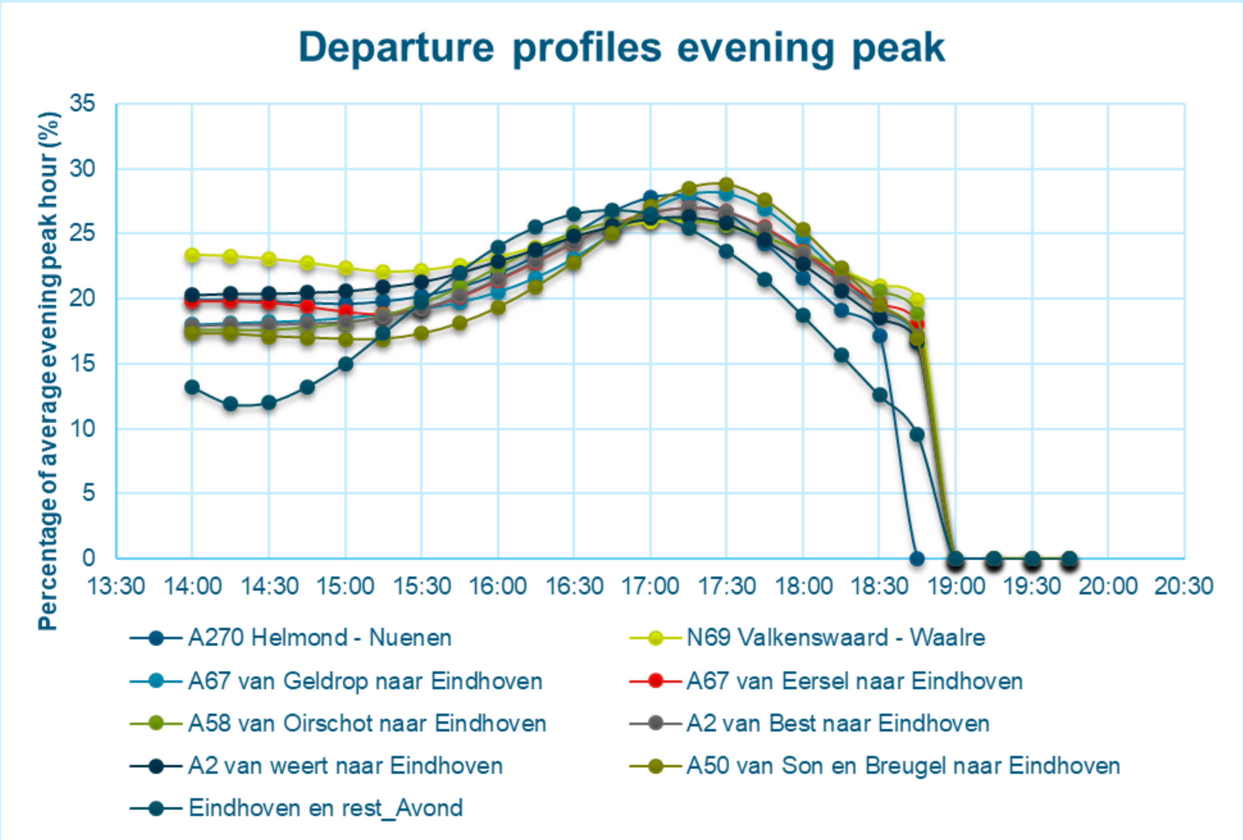


Figure 5-4 Departure profiles evening peak

The outputs of this step are 24 15-minute matrices both for the morning and the evening period. The matrices of the trucks are merged to the matrices of the car and can subsequently be used in the dynamic mesoscopic simulation as explained in the following chapter.

5.5 Dynamic mesoscopic assignment

As said, the SUE method is used for the dynamic mesoscopic simulation. The SUE method is chosen since it is the most realistic one and it is faster than a dynamic user equilibrium assignment (DUE). Compared to the static macroscopic assignment, the advantage of a dynamic mesoscopic assignment is that the congestion is included. This means, that realistic travel times and vehicle loss hours can be obtained by using a dynamic mesoscopic assignment.

5.5.1 Dynamic route choice function

Just as in the static macroscopic assignment, the taken routes are determined by a route choice function. In the base scenario in the dynamic assignment, the following default route choice function is used:

$$Cost_j = TTime_j \qquad (5.3)$$

In other words, the costs of a road section only depend on the travel time of that road section. For calculating the dynamic costs for a complete route, the same function as described above is used for the turns.

5.5.2 Interaction static and dynamic route choice function

Following from Chapter 5.2, a path-file as output from the static macroscopic assignment is used as input for the dynamic mesoscopic assignment. In this path-file, the three most-used routes between each OD-pair are stored. This path file is subsequently used as input for the route choice process in the dynamic mesoscopic simulation. However, when copying 100 per cent of the taken routes from the path-file, it means that the routes are not adjusted based on the dynamic route choice function as described above. This is unwanted, since the dynamic mesoscopic simulation is more accurate in considering congestion effects. It is also unwanted to base 100 per cent of the routes on the dynamic route choice function, since then the effect as described in Chapter 5.3 occurs what is not realistic. To solve this, the following distinction based on expert judgement is made for determining the routes:

- For 64% of the traffic the routes are determined on the path file of the static macroscopic assignment
- 16% of the traffic initially bases its route on the path-file of the macroscopic static assignment, but can change en-route based on the dynamic cost function
- 20% of the traffic uses the dynamic cost function for the initial route and can change it en-route based on the dynamic cost function

5.5.3 Number of replications dynamic mesoscopic simulation

Using the distribution explained above, the dynamic mesoscopic assignment can be executed. The results of a replication are quite reliable, but each replication of a mesoscopic scenario deals with some randomness. This is caused by the fact that there is a difference in how the 'best route' is experienced. Due to this randomness, the result of each replication is somewhat different. For minimizing the effects of randomness on the results, there is decided to execute six different replications (see Appendix D.4 for calculation of the required number of replications) for each scenario. For more details about the dynamic mesoscopic simulation in Aimsun, see Appendix D.5.

5.5.4 Executing dynamic mesoscopic simulation

After the matrices for cars are merged with the matrices for trucks, the dynamic mesoscopic simulations for the base scenario can be executed. Each scenario is executed in six replications after which the average is calculated. In this way, more reliable results of the KPIs can be obtained than when only one replication is executed.

6. Road pricing in Aimsun

In this chapter, there is explained how road pricing is implemented in Aimsun. Only the steps that are different compared to the base scenario are addressed in this chapter. There is started with the static macroscopic assignment, after which the ToD module is explained in Aimsun. Next, the transition from macroscopic to mesoscopic is explained and as last the execution of the dynamic mesoscopic simulation is discussed. For the detailed step process in Aimsun of the road pricing forms, see Appendix E.1, E.2 & E.3. In this appendix, there is explained step by step what is done in Aimsun per road pricing form.

6.1 Static macroscopic assignment

Just as in the base scenario, the static macroscopic assignment is executed. What is different from the base scenario, is the composition of the route choice functions. In the following paragraphs there is explained which route choice functions are used per road pricing scenario.

6.1.1 Static route choice function

The form of the used VDF in the road pricing variants is as follows (for the TPF the same principle is followed):

$$Cost_j = TT_j + 0.25 * VT_j + 0.25 * D_j \qquad (6.1)$$

Where:

TT_j= Travel time on road section j in minutes
VT_j=Variable toll on road section j in minutes
D_j= Distance of road section j in kilometres

Next to the travel time and distance, a component of the variable toll is added. The weight of the variable toll is set at 0.25, since the variable toll also increases over the distance. In the following paragraphs, there is explained per form how the variable toll is implemented.

6.1.1.1 Form 1

As is found in formula 6.1, the input of the variable toll is given in minutes. This means, that the monetary costs are converted to minutes using the value of Time (VoT). The VoT represent the value in euros that one is willing to pay to save one hour of travel time. The VoT depends on many personal characteristics as trip purpose, income, age for instance. In a research done by Significance, there is found that the average VoT of car users is €9/hour (Significance, 2012). By using the average VoT of €9/hour, the charge of 7 cents per kilometre is expressed in minutes:

$$\frac{€9}{hour} = \frac{9}{60} * 100 = \frac{15\ ct}{minute}$$

The outside peak charge is 7 cents/kilometre, so:

$$\frac{7}{15} = 0.47 \frac{minute}{kilometer}$$

For clarifying this:

Suppose a road section of exact 1 kilometre. In monetary values, one pays 7 cents for crossing this road section. When this monetary value needs to be expressed in minutes, 7 is divided by 15 as is done above, *leading to a charge of 0.47 minute for crossing this road section. In the same way the charge during peak hours is set at 0.74.*

6.1.1.2 Form 2

For form 2, the same VDF is used as described for the base scenario. In this form, the total charge of a trip does not depend on the actual route someone choses. Therefore, the monetary costs of road pricing do not influence the route someone is taking.

6.1.1.3 Form 3

In form 3, the same function is used as described in form 1. Subsequently, extra location components are added to the roads of area I and II presented in Figure 4-2 of respectively 11 and 5.5 cents per kilometre. Technically, these components are added by assigning an attribute value to all the road sections in area I and II. This value is set at 1 for the roads in area II, 2 for the roads in area I and a 0 for all other roads. Subsequently, the charge per road section is calculated by adding 0.37 (=5.5 cent) times the attribute value to the regular charge of 0.47. In this way, each road section gets the correct charge per kilometre.

6.2 Time of Day

The time of day module that is used in LMS 7.0, is implemented in Aimsun. The essence of this ToD module is that it calculated the number of departing trips separately for the morning peak, evening peak and the rest of the day. As described in Chapter 2.5, one of the disadvantages of this ToD module is that is dates from 1995. In the following paragraph, there is explained how this disadvantage is solved. Afterwards, the process of the ToD module in Aimsun is explained.

6.2.1 Updating the ToD module to 2030

Since the ToD module date from 1995, the parameters in are bases on guilders. However, in 2002 guilders were replaced by euros and due to inflation, the price level of 1995 is not the same as in 2030. The problem of the changed currency is solved, when the input in the ToD module is also in guilders just as is done in the research of 4Cast (2006). The only problem that remains here, is that the value of money in 1995 is different from the value of money of 2030. This is solved, by indexing the monetary values that are used as input.
The price per kilometre that is taken as starting point is 7 cents per kilometre outside peak hours and 11 cents during peak hours. After indexing these values from 2016 to 2030, the charges are 8 cents/kilometres outside peak hours and 12.6 cents/kilometre during peak hours (BerekenHet.nl, 2020). Without considering the increased value of money compared to 1995, the charges in guilders are (Omrekenen.nl, 2018):

$$€0.08 * 2.2 = ƒ\,0.18$$
$$€0.126 * 2.2 = ƒ\,0.28$$

However, $ƒ\,0.18$ now does not have the same value as it had back in 1995. Following from the international institute for social history, $ƒ\,0.18$ in 2018 has the same purchasing power as $ƒ\,0.12$ in 1995 (Internationaal instituut voor sociale geschiedenis, 2020). For the peak hours, the charge will be $ƒ\,0.19$ per driven kilometre. In Table 6-1, the final values per driven kilometre for both the peak and the off-peak periods are presented.

Table 6-1 Charges road pricing per kilometre

Period	Charge per kilometre
Peak	ƒ 0.19
Off-peak	ƒ 0.12

6.2.2 ToD module in Aimsun

In Figure 6-1, a schematic overview is given of how the ToD module is implemented in Aimsun (for a detailed explanation of the process in Aimsun, see Appendix E.1, E.2 & E.3). The procedure is similar for all road pricing forms, hence this process is explained once. There is started with a static macroscopic assignment (1) for the morning peak, evening peak and rest of day, just as is explained in Chapter 6.1. In this first simulation of the static macroscopic assignment, the route choice function as described in formula 5.1, thus without monetary costs component. The output of this simulation are the travel times per OD-pair (2) of the base scenario (since the monetary cost component is not included in the route choice function), separately for the morning peak, evening peak and rest of day. These travel times are used as input in the ToD-module (4), just as the travel costs per OD-pair (3). In the ToD-module step, per trip purpose per OD-pair, a new distribution between the morning peak (MP), evening peak (EP) and rest of the day (RoD) is calculated.

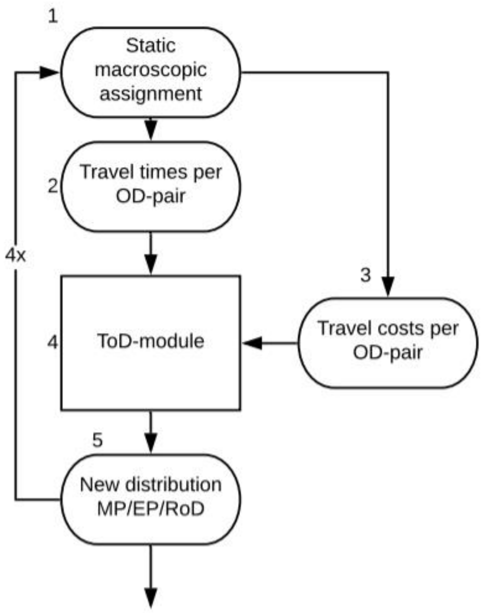


Figure 6-1 ToD module in Aimsun

This new distribution arises due to the travel costs that are added. The new distribution MP/EP/RoD (5), is used as input in three new static macroscopic assignments. In road pricing forms 1&3, the static route choice function with monetary cost component (formula 6.1) is used, whereas in form 2 still formula 5.1 is used. As output of the new static macroscopic assignments, new travel times per OD-pair separately per period are obtained, just as new travel costs per OD-pair per period. These new inputs are again used in the ToD-module, leading to new distributions between the MP, EP and RoD. This process is repeated four times (see Appendix F.1 for explanation), after which convergence has been reached. What happens with the new distributions MP, EP and RoD is explained in the next chapter.

6.3 Macroscopic to mesoscopic

A second disadvantage of the chosen ToD-module is that is only distinctions macroscopic day periods. For drawing conclusions about a possible smoother spread of a peak period, it is necessary to have smaller microscopic time intervals than just the morning peak, evening peak and rest of day. This is done, by treating the morning peak and evening peak as two individual periods and making a distinction between the peak periods and the peak shoulders. As an output of the ToD-module, the demand is provided for both the morning peak and the evening peak. An output could be, that after the implementation of road pricing, 1000 trips less are made in the morning peak compared to the scenario without road pricing. Now the assumption is made, that the traffic that is pulled away from the peak, will departure the hour before or after the peak. In this example, the 1000 trips will be redistributed in the hours 06:00-07:00 and 09:00-10:00. The redistribution of these trips is done proportionally to the number of trips per 15-minute interval presented in Figure 5-3 and 5-4. In Appendix F.2, an exact example is given of how the traffic is redistributed over the

15-minute intervals. In Appendix E.1, E.2 & E.3, the exacts steps conducted in Aimsun are explained in detail per road pricing form.

6.4 Dynamic mesoscopic simulation

Once the matrices are converted to 15-minute interval matrices, the dynamic mesoscopic simulation can almost be executed. First, for road pricing forms 1 and 3, the dynamic route choice function is adjusted what is explained below.

6.4.1 Dynamic route choice function

The dynamic cost function used in Aimsun for road pricing forms 1 and 3 is as follows:

$$Cost_j = TTime_j + VT_j \quad (6.2)$$

Where:

$Cost_j$= Generalized total costs of road section j, expressed in seconds
$TTime_j$=Travel time of road section j, expressed in seconds
VT_j=Variable toll of road section j, expressed in seconds

Compared to the base scenario, the variable toll component is added. Below, for form 1 and 3 is explained how the dynamic route choice function is used.

6.4.1.1. Form 1

Next to the travel time on a road section, also the monetary costs of the road section are considered in this road pricing form. For adding this, the variable toll is set at 28 seconds per kilometre (=0.47 minute) for the off-peak hours. For the peak hours, the user defined costs are set at 44 seconds/km.

6.4.1.2 Form 3

In this form, the same route choice function is used as in form 1. But next to the regular charges, the location component is added in the same way as is done in the VDF. The location charges are respectively 22 and 44 seconds per kilometre (corresponding to 5.5 and 11 cents per kilometre).

6.4.2 Executing dynamic mesoscopic simulation

Just as for the base scenario, the matrices of car and trucks are merged, and the simulation is executed in six replications. The average is calculated and the results of the KPIs are obtained.

7 Results

In this chapter, the results for the different road pricing forms are presented. The KPIs that are analysed are:

1. Switch peak vs off-peak
2. Intensities
3. Total distance driven
4. Travel times on main roads
5. Vehicle loss hours

These KPIs are presented separately for the morning and evening period. At the end, a sensitivity analysis of the ToD module is conducted to investigate the effects of the charge on the number of travellers that switch from peak to off-peak.

7.1 Results per KPI

For drawing conclusions about which form scores the best on which KPI, the results are combined and presented in several tables. The KPIs are analysed separately for the morning and evening period, since the traffic flow in the morning period are different from the evening period. In general, traffic drives towards Eindhoven in the morning period and in the evening period in the opposite direction.

7.1.1 Peak versus off-peak

As a first KPI, there is looked at the number of trips that will not depart in the peak hours anymore due to the implemented peak charges. In Table 7-1, the decrease/increase in departing trips compared to the base scenario is presented. As found in this table, there are no differences across the different forms. In each form, the percentage of trips leaving the morning peak is around 2.32% and around 2.38% for the evening peak. The fact that the effects across the different forms are comparable, is caused by the used ToD-module. In the ToD-module, the differences in costs and travel time between a peak hour and a rest of day hour for both the base year and the future year determine the change in departure time. In both form 1 and 2, the difference between a peak hour and rest of day hour in costs is 4 cents per kilometre (11 cents for peak hour, 7 cents for off-peak hour). For form 3, the differences are the same, even in the areas where the location component is implemented. For example in area I, the charge is 22 cents/km in the peak hours and 18 cents/km in the off-peak hours, leading to a difference of 4 cents/km. Therefore, the results are similar for the three forms.
The distributions in which traffic is assigned in the dynamic mesoscopic simulation to the network are presented in Figure 7-1 and 7-2. In these figures the distribution of form 1 is presented, but for the other forms the distributions are similar. As can be seen in these figures, less traffic departs in the peak hours and more traffic departs in the peak shoulders.

Table 7-1 Changes in departure times compared to the base scenario

	Form 1		Form 2		Form 3	
	Absolute difference	Percentage (%)	Absolute difference	Percentage (%)	Absolute difference	Percentage (%)
Morning peak	-3504	-2.32	-3508	-2.32	-3499	-2.31
Evening peak	-4335	-2.38	-4307	-2.37	-4326	-2.38
Rest of day	7831	6.76	7815	6.74	7825	6.75

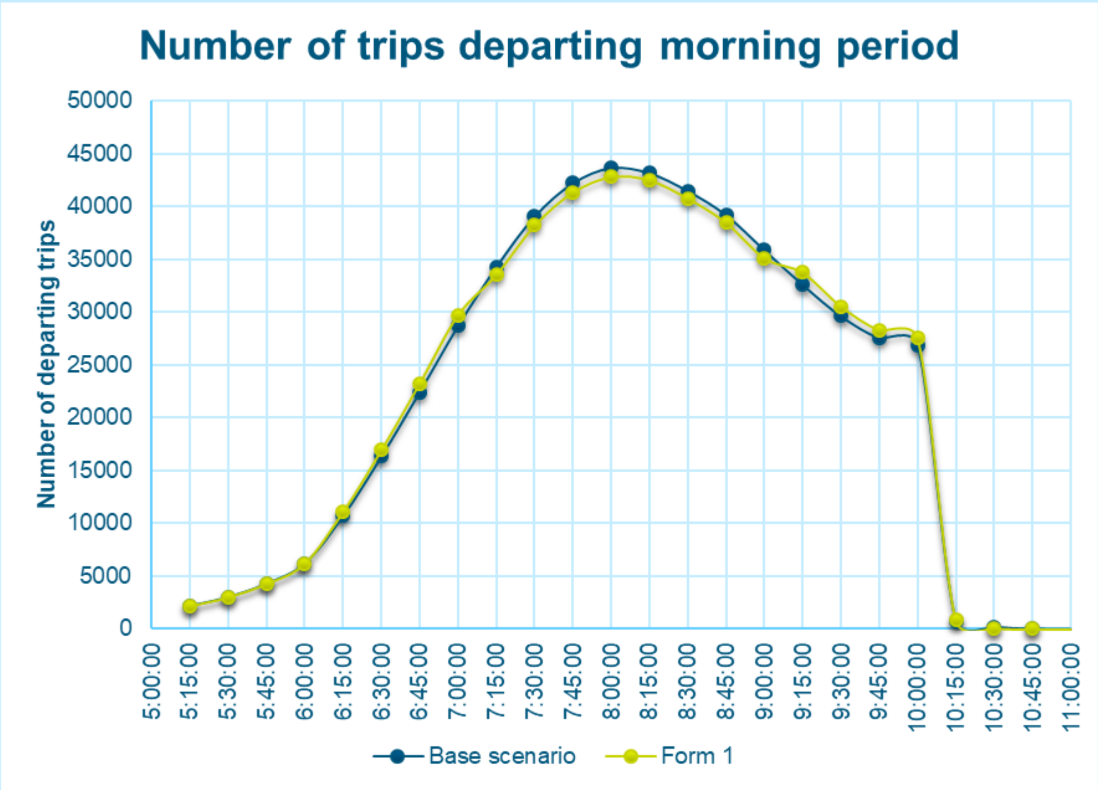


Figure 7-1 Distribution departing trips morning period base scenario and form 1

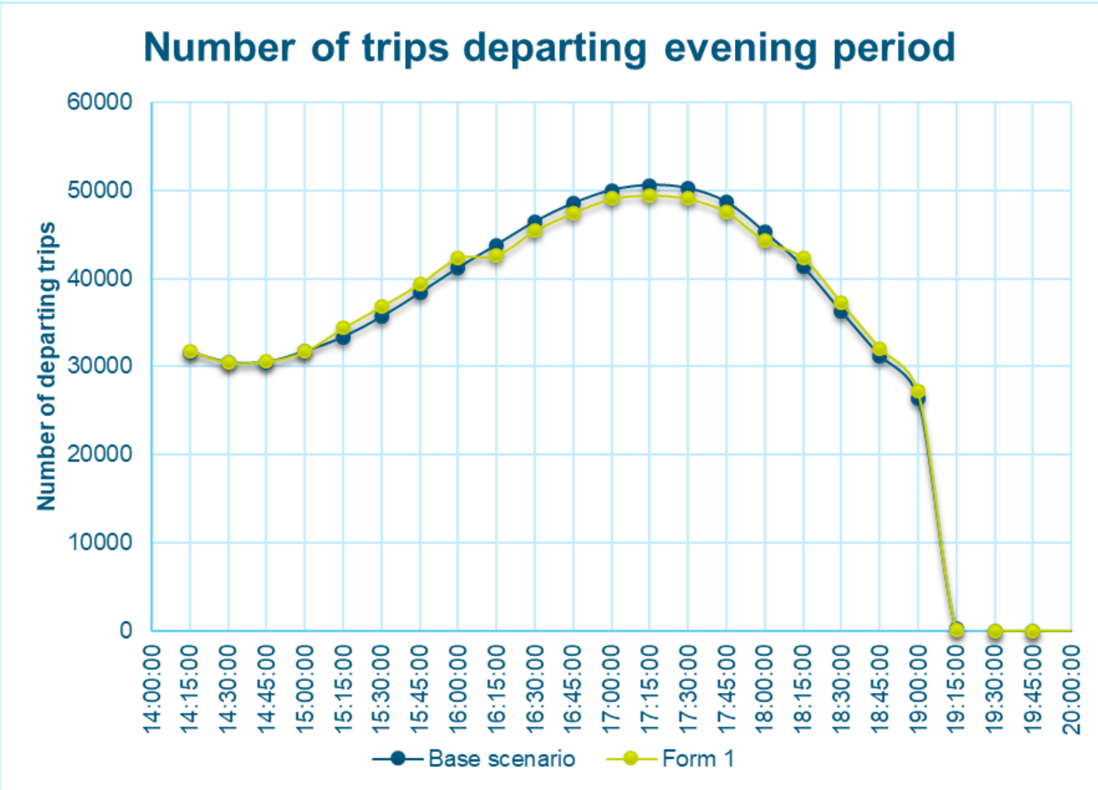


Figure 7-2 Distribution departing trips evening period base scenario and form 1

7.1.2 Morning period

For the morning period, the hours 06:00 until 11:00 are considered. The hours 07:00-09:00 are assumed to be the peak hours, and 06:00-07:00 and 09:00-10:00 are the peak shoulders. The hour 05:00-06:00 is included to present the difference with the evening period of the first simulation hour. The hour 10:00-11:00 is included since effects in the hours before could influence the travel flows in this hour and it is therefore fair to include this hour in the analyses. In Table 7-2, the number of departing trips is presented per variant and time period. The total number of trips is almost the similar for all variants. The numbers are not exactly the same, since there is some randomness included in the way traffic departs in the model. The traffic that departs in the hour 10:00-11:00, is traffic that was not able to depart in the previous hours.

Table 7-2 Number of departing trips per scenario and per time period

	Base	Form 1	Form 2	Form 3
05:00-06:00	15,763	15,763	15,763	15,763
06:00-07:00	78,167	81,056	81,035	81,038
07:00-09:00	318,858	312,665	312,801	312,632
09:00-10:00	116,637	120,081	120,315	120,037
10:00-11:00	1,016	942	568	1,030
05:00-11:00	530,440	530,506	530,481	530,499

7.1.2.1 Intensities

For providing insight in the intensities on traffic distributed over the network, plots are made. First, the difference is presented between road pricing form 2 and the base scenario. In this comparison, the effect of just the change in departure times is visible, since there is no route-choice component included in form 2. Another interesting comparison that is made is the one between road pricing form 2 and 1. Comparing both forms, the effect of solely the route choice effect is analysed. The input for both forms is similar, so only the effect of paying the charge per driven kilometre is considered. As a final comparison, form 3 is compared to form 1. The input is similar for both forms, but in form 3 an extra location component is levied in area I and II. Therefore, using this analysis there can perfectly be seen what the effect is of these location components.

Base scenario versus form 2

In Figure 7-3 (Appendix G for the differences in percentages), red means an increase in intensities in form 2 compared to the base scenario and green means the opposite. In this figure, the road sections with an absolute difference between -10 and 10 vehicles per hour are not presented. Besides, a change in percentages between -2 and 2% is also not presented to reduce the amount of numbers in this figure. As seen in this figure, there is an increase on nearly all highways of between 0 and 5 per cent. On the roads in area I, there is a decrease of intensities on most roads. On the bigger roads in area II, there mostly is a small increase in intensities (most parts of the ring road, Tilburgseweg towards Eindhoven, Leenderweg, A270/N270 and parts of the Kennedylaan). Also in area III, there is a decrease in intensities on most of the roads. The explanation for this effect is the fact that the smoother spread of the peak causes travel time savings on the bigger roads, making them more attractive in form 2 than in the base year. In other words, driving on the smaller roads is discouraged since the bigger roads become more attractive.

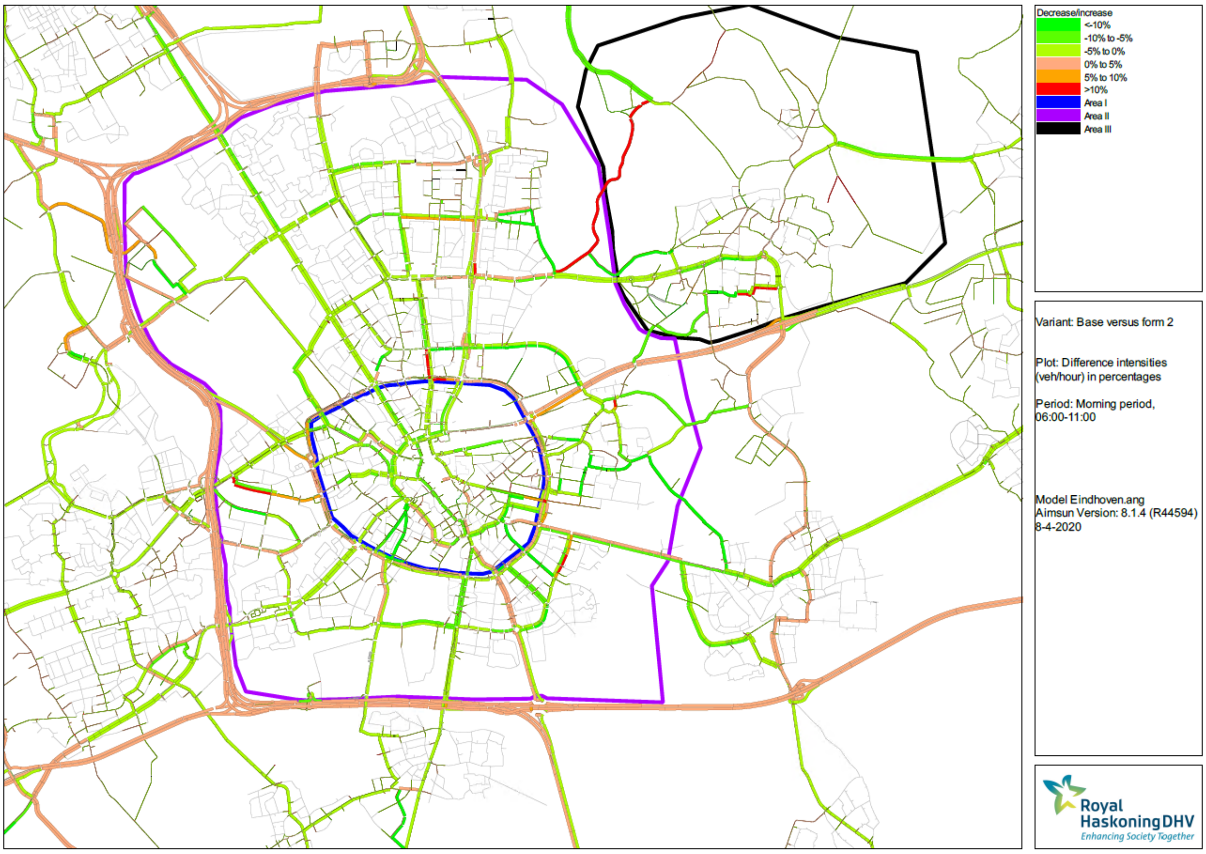


Figure 7-3 Difference in intensities (veh/hour) morning period (06:00-11:00) base scenario versus form 2 (red= increasement in form 2, green= reduction in form 2 compared to base scenario)

Form 2 versus form 1

In Figure 7-4 (Appendix H for the differences in percentages), the difference in intensities between form 2 and form 1 is presented. In this figure, red means an increase in intensities in form 1 and green a decrease in intensities in form 1. As seen in this figure, on most highway sections there is a decrease in intensities in form 1 compared to form 2. Also on most parts of the bigger roads in area II (Tilburgseweg, Leenderweg and most parts of the ring road), intensities dropped in form 1. Furthermore, there seems to be an increase in intensities on most roads in the urban area (area I) and on some roads in area III. Following this analysis, less traffic uses the bigger roads and instead uses the smaller roads in the urban areas. In other words, intensities increase in the urban areas in form 1, causing a reduction in liveability.

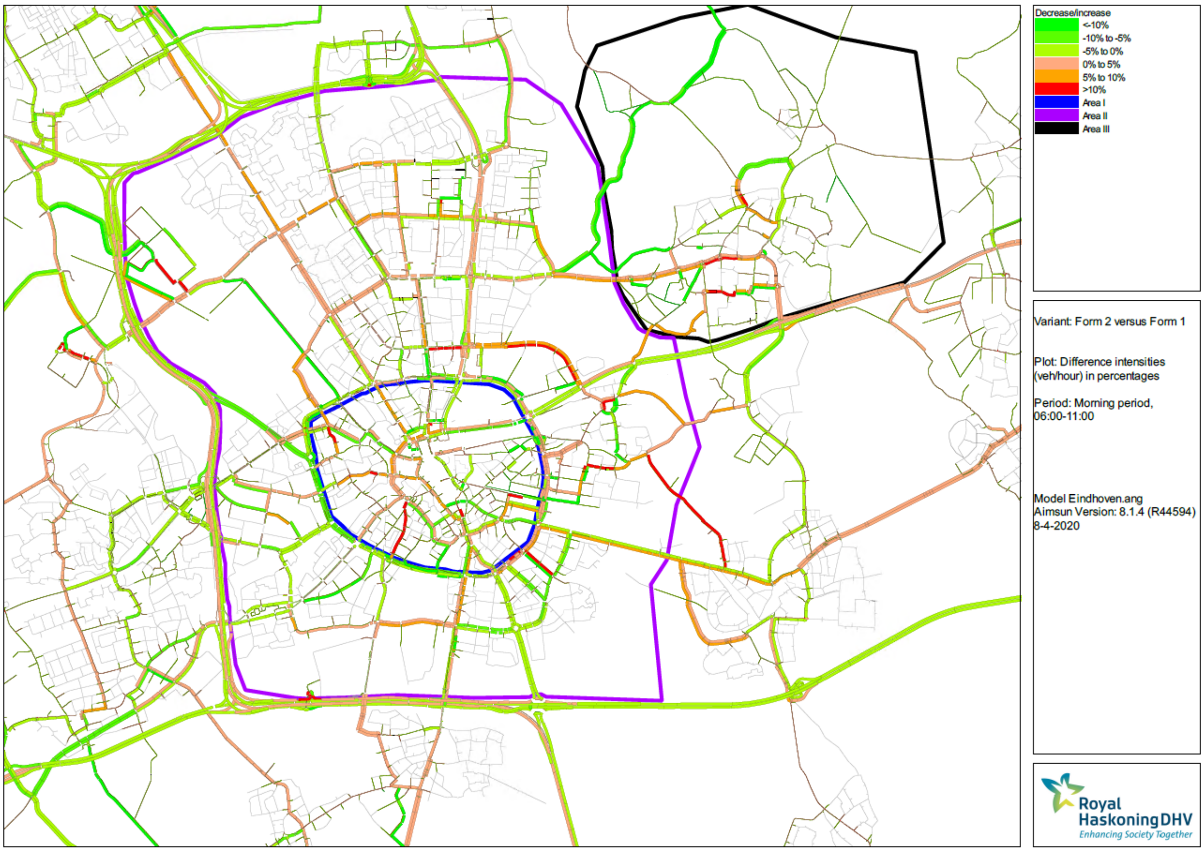


Figure 7-4 Difference in intensities (veh/hour) morning period (06:00-11:00) form 2 versus form 1 (red= increasement in from 1, green= reduction in form 1 compared to form 2

Form 1 versus form 3

In Figure 7-5 (Appendix I for differences in percentages), green determines a decrease in intensities in form 3 and red means an increase in form 3. As follows from this figure, there is a decrease in intensities on nearly all roads in the urban area (area I). Also on most of the roads in area II, the intensities are lower in form 3 than in form 1. On most highways, the opposite effect occurs. For area III, there is no overall conclusion possible based on this figure. Following these observations, there can be concluded that the location charges are effective for banning traffic from the urban areas. Instead, more traffic uses the highways to avoid the areas with the location charges. However, there must be kept in mind that roads that are situated just outside the areas with the location charge, possibly must deal with an increasing demand of traffic.

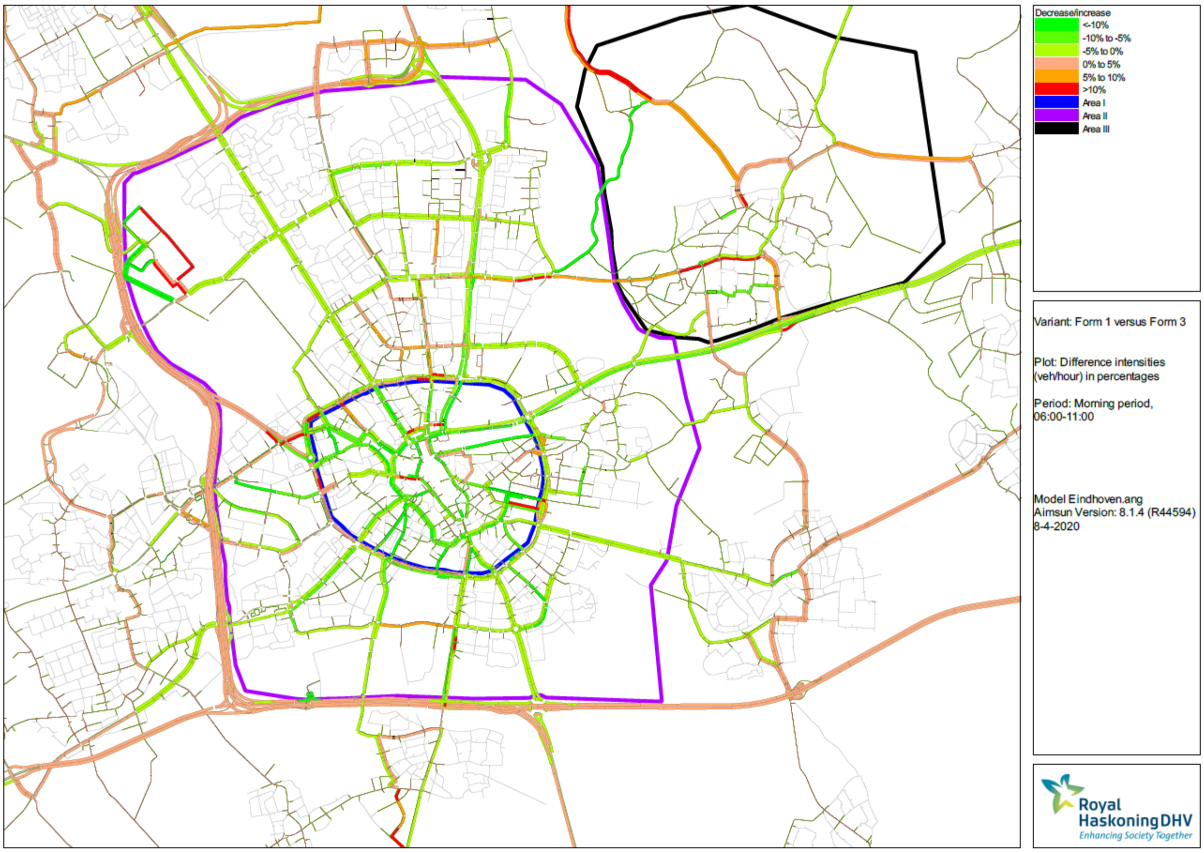


Figure 7-5 Differences in intensities (veh/hour) morning period (06:00-11:00) form 1 versus form 3 (red= increasement in form 3, green=reduction in form 3 compared to form 1)

7.1.2.2 Total distance driven

By analysing the intensities on roads, there is tentatively concluded that form 1 leads to a decrease of liveability in areas I and II, what does not happen in forms 2 and 3. Besides there was found, that in form 3 traffic avoids the areas with the location components. To connect these findings to a score per area, the total driven distance is analysed for the different forms per area. Besides, the total distance driven is analysed for the total network. Here the assumption is, that a decrease in total distance driven compared to the base scenario implies that traffic takes the shorter routes leading an increase of rat running and thus a reduction of liveability. In Table 7-3 the differences in percentage between the base scenario and the forms are presented.

Total network

Seen over the total period and the total network, there is an increase in total distance driven in form 2 (+0.2%), whereas there is a decrease in form 1 (-0.3%) and 3 (-0.2%). This implies, that both form 1 and 3 stimulate that shorter routes are taken leading to more rat running and therefore a reduction in liveability. Since there is a small improvement in form 2, this does not happen in this form.

Area I

In all forms, there is a reduction in total distance driven in area I. Judging on Figures 7-3, 7-4 and 7-5, there are different explanations for these observations. As found in Figure 7-3, there is less traffic in area I in form 2 compared to the base scenario. In form 1, there is an increase in intensities in area I compared to form 2 (Figure 7-4). Therefore, the reduction in total distance driven implies that shorter routes are taken in area I. In form 3, there is a higher reduction in total distance driven, mainly caused by the lower intensities in area I (see Figure 7-5).

Area II

In area II, the similar effects as in area I occur. The total distance driven in form 2 reduces due to the lower intensities and in form 1 due to the shorter routes that are taken. In form 3, traffic is avoiding area II due to the location component causing a reduction in total distance driven.

Area III

In area III, the differences across form 1 and 2 are negligible. In form 3, the total distance driven remains almost the same as in the base scenario, whereas there is a reduction of 2.3% in form 1 and 2.4% in form 2. This is caused by the traffic that avoids area I and II in form 3, now among other drives through area III. There is still a small reduction (-0.1%), since still the shortest routes are taken.

Area IV

In area IV, there are only minor differences among the road pricing forms. Since the road network is less detail in this area (except for Helmond), there are less alternative shorter routes that can be taken causing that the differences across the road pricing forms do not vary a lot. Overall, the total distance driven decreases in form 1 since there shorter routes are taken (-0.2%) to save money. In form 2, more distance is driven (0.3%) since the intensities on the highways increase what are the longer routes in general. In form 3, there is more traffic in area IV causing an increase in total distance driven (0.1%).

Table 7-3 Total distance driven per area and per time period compared to the base scenario

	Area I			Area II			Area III			Area IV			Total		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
06:00-07:00	0.0%	0.5%	-4.5%	2.2%	3.0%	0.0%	1.5%	0.8%	4.3%	6.6%	6.8%	6.9%	6.2%	6.5%	6.3%
07:00-09:00	-3.5%	-4.0%	-8.5%	-2.4%	-2.1%	-4.0%	-3.9%	-3.7%	-1.9%	-3.0%	-2.6%	-2.7%	-2.9%	-2.6%	-2.9%
09:00-10:00	-0.7%	-1.7%	-6.5%	0.8%	0.7%	-1.4%	-0.3%	-0.9%	1.7%	2.1%	2.4%	2.3%	2.0%	2.2%	1.9%
10:00-11:00	-4.1%	-0.7%	-9.9%	-0.4%	1.9%	-3.7%	1.4%	1.7%	8.0%	2.9%	5.8%	4.0%	2.6%	5.5%	3.4%
06:00-11:00	-2.5%	-2.8%	-7.6%	-1.0%	-0.7%	-2.9%	-2.3%	-2.4%	-0.1%	-0.2%	0.3%	0.1%	-0.3%	0.2%	-0.2%

7.1.2.3 Travel times

Following from the previous analysed KPIs, there is concluded that there is a change in departure times and on the routes that are taken. By analysing the travel times on the main roads, there is investigated what the effect is of these changes. In Table 7-4, the differences the travel times compared to the base scenario on the trajectories of Figure 4-2 in the different time periods are presented. As can be seen, there are few differences across the different forms. In general, there is a small increase of travel time during the hour 06:00-07:00 due to the increase in departing trips in this hour. During the peak hours, there are travel time savings of up to 1.5 minutes. In all forms, the travel time savings are the highest for the A67 between Asten and Leenderheide. Also in the hour 09:00-10:00 there are quite some travel time savings, of up to 1.5 minute on the A67 between Eersel and Eindhoven. In the hour 10:00-11:00, there are some minor increasements in travel times in all forms. Seen over the total period, the implementation of road pricing either has a positive or neutral effect on the travel times.

The most significant differences across the road pricing forms, are found on the secondary roads. In particular in form 3, there are more travel time savings on among others the ring roads, the A270/N270 and the N2 in the South direction. These roads are located either in the areas with the location charge, or directly lead to these areas explaining the differences in travel times. Although the intensities on the highways increase somewhat in form 3 and 2, there is no reduction in travel times perceptible in these forms. The smoother spread in departure times assures the travel time savings.

At last, there can be seen that the degree of congestion reduces in the hour 09:00-10:00 but increases somewhat in the hour 10:00-11:00.

In all forms, there are travel time savings in the hour 09:00-10:00 and some small travel time losses in the hour 10:00-11:00. This indicates that some more traffic is left in the model at 10:00, causing somewhat more congestion. This is also what happens in form 2 between 10:00 and 11:00, explaining the fact that there is driven more whereas less traffic is added to the network (less traffic can leave the network at the end of the hour 09:00-10:00).

Table 7-4 Changes in travel times morning period compared to the base scenario (in minutes) including colour scale

Difference ≤ -1 minute	-1 minute < Difference ≤ -0.5 minute	-0.5 minute < Difference ≤ 0.5 minute	0.5 minute > Difference ≤ 1 minute	Difference > 1 minute

	06:00-07:00			07:00-09:00			09:00-10:00			10:00-11:00			06:00-11:00		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
1: A67 Eersel-Eindhoven	0.0	0.0	0.0	-0.3	-0.4	-0.4	-1.5	-1.2	-0.8	0.0	0.0	0.0	-0.6	-0.5	-0.5
1: A67 Eindhoven-Eersel	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
2: A2 Maarheze-Eindhoven	0.1	0.2	0.1	-0.3	-0.2	-0.3	0.1	0.1	0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1
2: A2 Eindhoven-Maarheze	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3: A67 Asten-Leenderheide	0.0	0.0	0.1	-1.5	-1.2	-1.4	-1.0	-0.8	-0.9	0.1	0.1	0.1	-1.2	-0.9	-1.1
3: A67 Leenderheide-Asten	0.0	0.1	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
4: Leenderweg towards Eindhoven	0.0	0.0	0.0	-0.8	-0.6	-0.8	-0.1	-0.1	-0.1	0.0	0.0	0.0	-0.5	-0.3	-0.5
4: Leenderweg towards A2	0.0	0.0	0.0	-0.8	-0.6	-1.0	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.5	-0.4	-0.6
5: A2 Ekkersrijt-Leenderheide	0.1	0.1	0.1	-0.1	-0.2	0.0	0.1	0.3	0.5	0.2	0.2	0.2	-0.1	0.0	0.1
5: A2 Leenderheide-Ekkersrijt	0.1	0.1	0.1	-0.1	-0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
6: Tilburgseweg towards Eindhoven	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6: Tilburgseweg towards A2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7: A58 Moergestel-Eindhoven	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0
7: A58 Eindhoven-Moergestel	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0
8: A2 Boxtel-Eindhoven	0.0	0.0	0.0	-0.5	-0.5	-0.5	-1.2	-1.2	-1.1	0.1	-0.1	0.1	-0.6	-0.6	-0.6
8: A2 Eindhoven-Boxtel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9: A50 SintOedenrode-Eindhoven	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9: A50 Eindhoven-SintOedenrode	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0
10: Kennedylaan towards Eindhoven	0.0	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10: Kennedylaan towards A50	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1
11: Ring West right	0.0	0.0	-0.1	-0.9	-0.4	-1.1	-0.3	-0.2	-0.5	-0.1	-0.1	-0.2	-0.6	-0.3	-0.8
11: Ring West left	0.0	0.0	0.0	-0.2	-0.1	-0.3	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.1	-0.1	-0.2
12: Ring Oost right	0.0	0.0	0.0	-0.3	-0.5	-1.1	0.0	-0.1	-0.1	0.0	0.0	0.0	-0.2	-0.3	-0.7
12: Ring Oost left	0.0	0.0	0.0	-0.3	-0.1	-0.5	0.0	0.0	0.0	0.0	0.1	0.0	-0.2	-0.1	-0.3
13: A270 N279-Eindhoven	0.0	0.0	0.0	-0.4	-0.2	-0.7	-0.6	-0.7	-1.1	0.0	0.1	0.1	-0.4	-0.3	-0.7
13: A270 Eindhoven-N279	0.1	-0.1	0.0	-0.1	-0.2	-0.2	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	-0.1	-0.1
14: N2 going South	0.0	0.0	0.0	-0.2	-0.3	-0.1	-0.3	-0.5	-0.7	0.0	0.0	0.1	-0.3	-0.3	-0.3
14: N2 going North	0.0	0.0	0.0	-0.2	-0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	0.1
Total	0.6	0.8	0.6	-7.4	-5.9	-8.6	-5.1	-4.5	-5.1	0.6	0.4	0.7	-5.8	-4.8	-6.5

7.1.2.4 Vehicle loss hours

The travel times on the trajectories of Figure 4-2 only partly provide insight in the degree of congestion in the region of Eindhoven. Therefore, the vehicle loss hours are calculated for four different areas (see Figure 3-1 for the areas) for the different periods in the morning period. In Table 7-5, the differences in percentage between the base scenario and the road pricing forms are presented.

Total area

Across the road pricing forms, there are barely differences. Seen over the total period, the highest reduction in vehicle loss hours is obtained in form 3 (-9.6%), thereafter in form 1 (-8.6%) and as last in form 2 (-7.5%). Furthermore, there is a clear increasement of vehicle loss hours in the hour 06:00-07:00 and clear reductions in the hours 07:00-09:00 and 09:00-10:00. In form 2, there is a small increase in vehicle loss hours in the hour 10:00-11:00 over the total network, what is caused by an increase in congestion at the end of the hour 09:00-10:00. In Figure 7-6, the total vehicle loss hours of the complete network are presented per 15-minute interval for form 2 and the base scenario. Despite the increase in departing trips from 09:00 to 10:00, there is a decrease in vehicle loss hours until around 09:40 in form 2. Afterwards, the increasing departing trips increase the congestion and thus the vehicle loss hours in form 2. This effects the vehicle loss hours until around 10:15 and therefore causes an increasement in vehicle loss hours in form 2 in the hour 10:00-11:00.

Table 7-5 Changes in vehicle loss hours morning period compared to the base scenario including colour scale

Difference≤-5%	-5%<Difference≤0	0%>Difference≤5%	Difference>5%

	Area I			Area II			Area III			Area IV			Total		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
06:00-07:00	0.2	0.7	-4.2	3.3	3.4	1.9	3.2	3.0	11.5	11.1	11.8	11.3	7.9	8.4	7.3
07:00-09:00	-6.8	-10.3	-17.3	-7.7	-9.1	-12.2	-4.5	-6.6	-3.0	-12.6	-10.6	-11.6	-10.9	-10.2	-12.0
09:00-10:00	-1.3	-3.8	-9.6	-2.2	-5.0	-5.1	0.8	-1.3	4.5	-9.4	-5.6	-9.1	-7.4	-5.4	-8.2
10:00-11:00	-2.4	-1.8	-10.1	2.3	2.6	1.1	25.2	7.3	27.7	-0.7	1.0	-2.9	-0.3	1.1	-2.5
06:00-11:00	-4.9	-7.7	-14.3	-5.6	-7.2	-9.5	-2.6	-4.8	-0.3	-10.0	-7.6	-9.4	-8.6	-7.5	-9.6

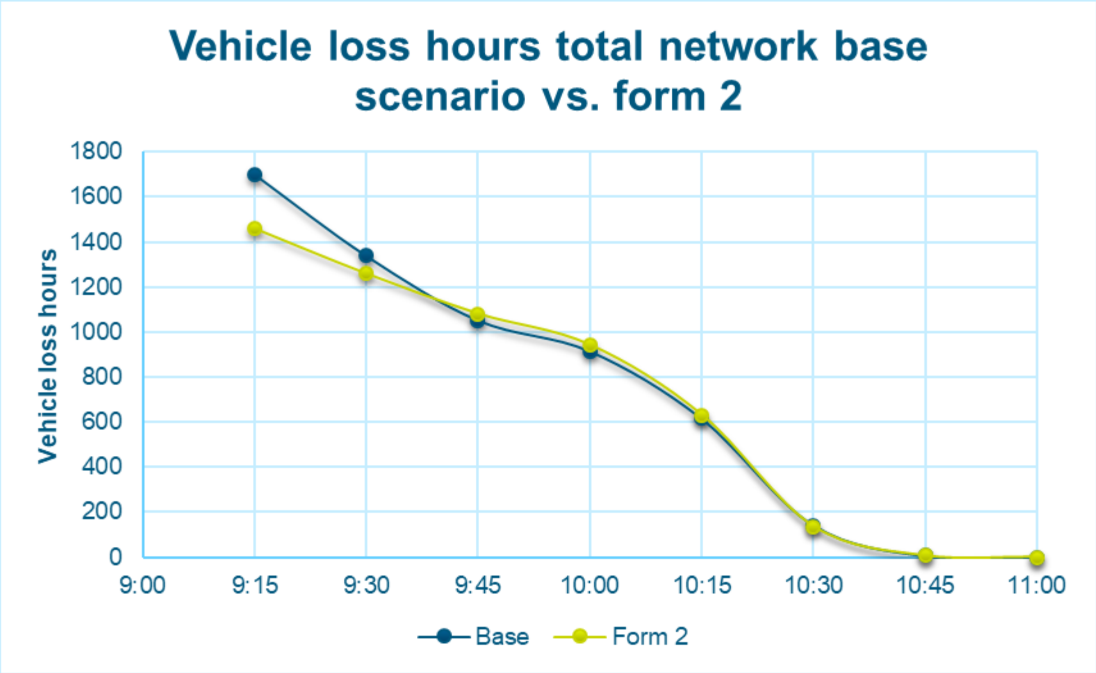


Figure 7-6 Vehicle loss hours on the total network in the base scenario and in form 2

Area I

For area I, form 3 leads to the highest reduction in vehicle loss hours (-14.3%) followed by form 2 (-7.7%) and form 1 (-4.9%) over the complete morning period. In form 3, this is caused by the fact that traffic avoids this area due to the extra charge. When comparing form 1 and 2, there is confirmed that more traffic uses area I in form 1 than in form 2. This is because the shorter route is stimulated in form 1, which often crosses area I.

Area II

For area II, the same phenomena appears as in area I. The highest reduction is obtained in form 3 (-9.5%), since traffic avoids area II. In form 2 the vehicle loss hours are reduced by 7.2% due to the smoother spread in peak hours. In form 1 the reduction is somewhat lower (-5.6%), since more traffic drives through area I.

Area III

What stands out for area III, is that there is a reduction of vehicle loss hours in form 1 (-2.6%) and 2 (-4.8%) over the complete morning period, whereas it is only -0.3% in form 3. Since area III is just outside the area which has a location component, this difference is explainable. Traffic avoids areas I and II, and now drives through among others area III causing a lower reduction of the vehicle loss hours.

Area IV

In area IV there are no big differences found among the road pricing forms. Compared to the total network, the differences are almost similar. The only difference is that in this area form 1 (-10.0%) is the most effective in reducing the vehicle loss hours over the complete morning period, whereas form 3 is most effective over the total network. This is caused by the fact that more traffic drives through area IV in form 3, since traffic avoids areas I and II.

7.1.3 Evening period

For the evening period, the same analyses are conducted as for the morning period. Since the evening period is more crowded and has other traffic flows, the effects of road pricing could be different for the evening period. In Table 7-6 the assigned number of departing trips are presented for the road pricing forms and the base scenario. As can be seen, in form 3 there are around 750 more trips assigned to the network as in form 1. This means on average that around 0.3 extra trips are assigned per zone (around 2200 zones) and therefore there is assumed that the effect is negligible.
Compared to the morning period, it is remarkable that less trips depart in the last hour of the simulation (10:00-11:00 and 19:00-20:00 respectively). Since originally no traffic is assigned in these hours, this is traffic that was not able to enter the network in hour before. This difference is caused by the difference in characteristics of the traffic flows in the morning and evening period. In general, traffic drives towards Eindhoven in the morning period and drives away from Eindhoven in the evening period. So in the morning period, traffic enters the model on the highways whereas in the evening period traffic enters the model in the urban areas of Eindhoven. On the locations where traffic enters the network, virtual queues can arise. In these virtual queues, traffic is waiting to enter the network. The intensities of traffic that enters the network on a highway are much higher than the intensities of traffic that enters the network somewhere in an urban area. Therefore, more virtual queues arise in the morning peak leading to more traffic that still needs to enter the network in the last hour of the simulation.

Table 7-6 Number of departing trips evening period

	Base	Form 1	Form 2	Form 3
14:00-15:00	124,474	124,532	124,475	124,517
15:00-16:00	148,636	152,950	153,046	153,135
16:00-18:00	383,525	375,118	375,225	375,542
18:00-19:00	135,211	138,918	139,233	139,041
19:00-20:00	262	198	155	211
15:00-20:00	792,109	791,716	792,134	792,446

7.1.3.1 Intensities

Just as for the morning period, three plots are made which compare the road pricing scenarios and the base scenario. First, the base scenario is compared to form 2. Secondly, form 2 is compared with form 1 and as last form 1 is compared with form 3.

Base scenario versus form 2

Just as for the morning period, the comparison between form 2 and the base scenario is made to solely investigate the effect of the changes in departure time (see Figure 7-7 and Appendix J for the differences in percentages). Compared to the morning period, there are few differences. The intensities on the highways increase, just as on the main secondary roads. On the traffic relation Kennedylaan-A270/N270 there is a clear increase in intensities, whereas intensities on the Tilburgseweg and Leenderweg decrease. Besides, on most roads in the urban area (area I) there is a decrease of intensity. All in all, there can be concluded that form 2 assures a higher attractivity of the highways and the main secondary roads. Besides, intensities on the urban roads decrease, meaning an improvement of the liveability.

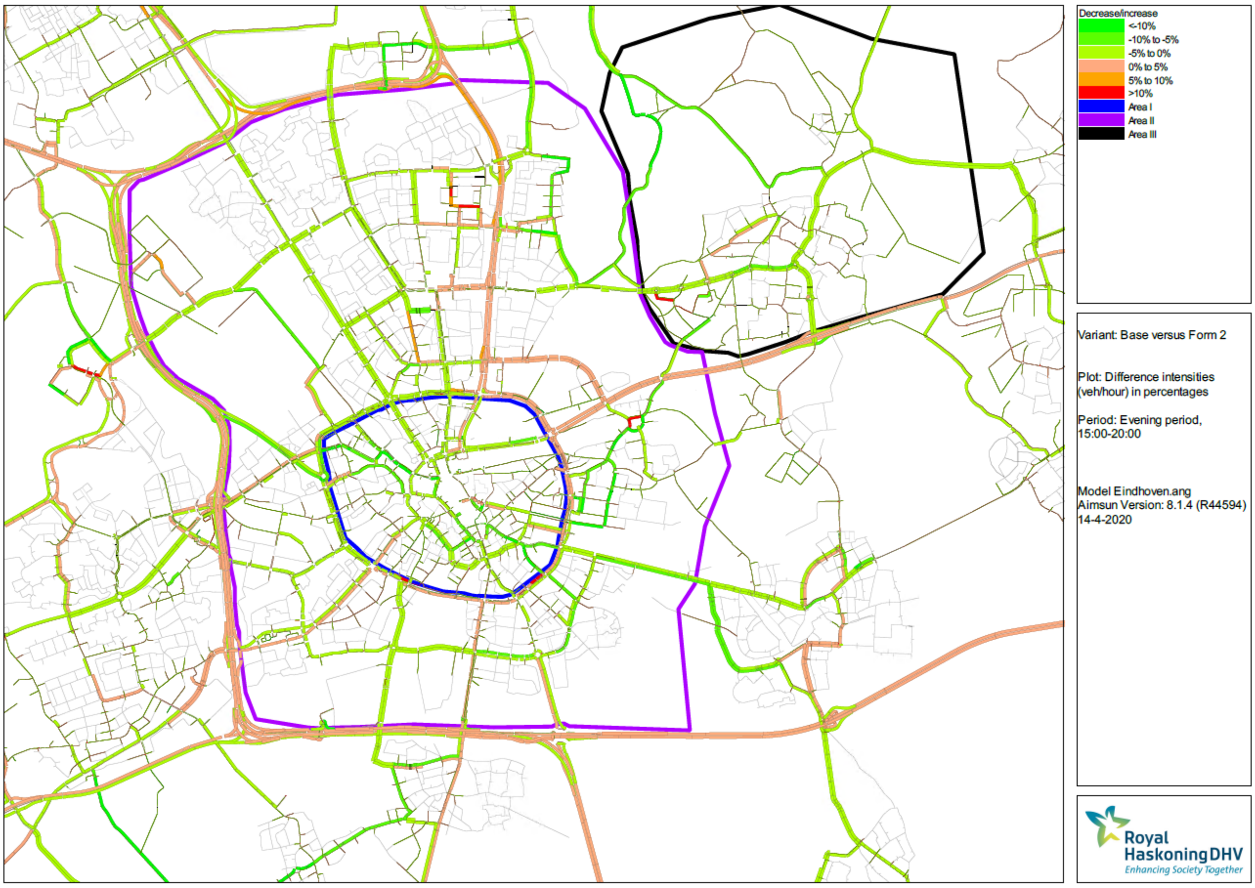


Figure 7-7 Difference in intensities (veh/hour) evening period (15:00-20:00) base scenario versus form 2 (red= increasement in form 2, green= reduction in form 2 compared to base scenario)

Form 2 versus form 1

Subsequently, the comparison between form 2 and form 1 is made to find out the effect of the charge per kilometre in the route choices. In Figure 7-8 (Appendix K for the difference in percentages), this comparison is presented. There is no clear conclusion possible in one of the areas nor on the highways. For all areas, there are seems to be a reasonable equal distribution in roads with an increase and a decrease of intensities. Following Figure 7-8, there cannot be concluded whether there is an increase or decrease in liveability in form 1 compared to form 2.

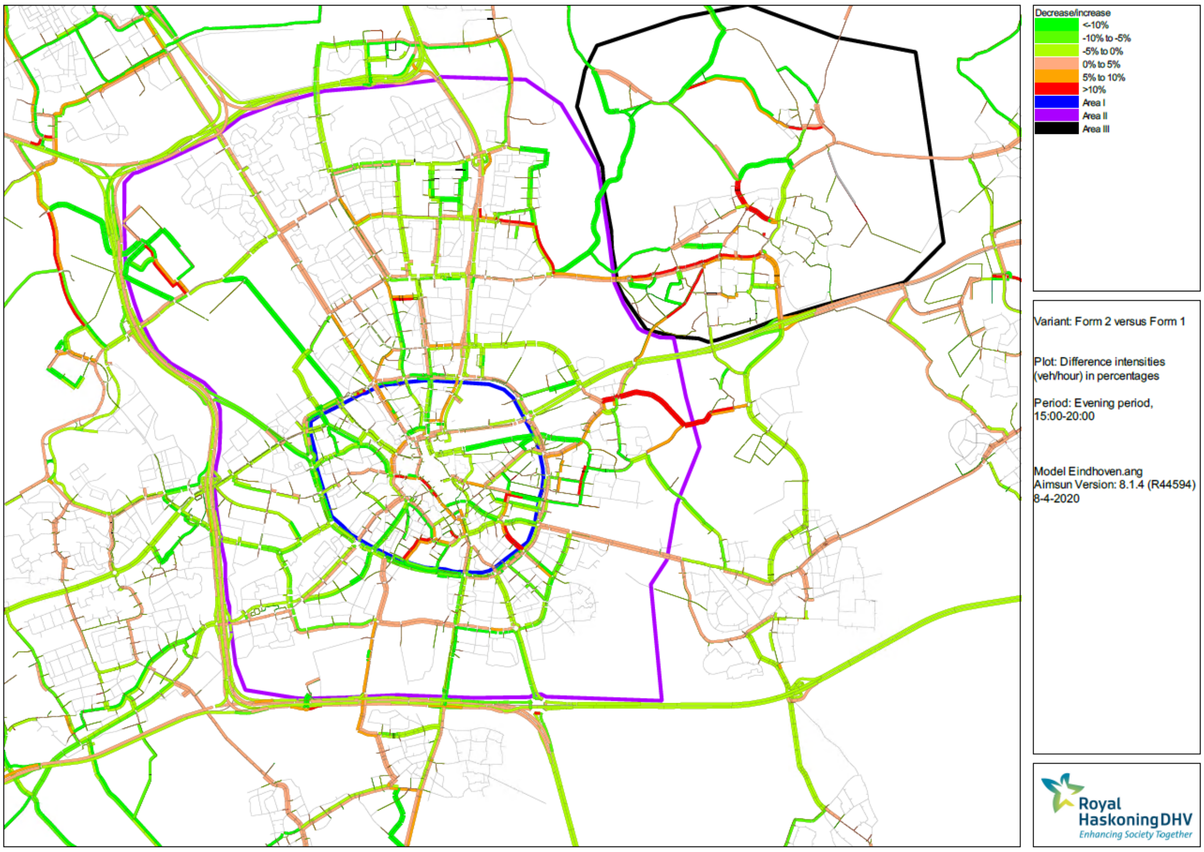


Figure 7-8 Difference in intensities (veh/hour) evening period (15:00-20:00) form 2 versus form 1 (red= increasement in form 1, green= reduction in form 1 compared to form 2)

Form 1 versus form 3

The last comparison is made between form 1 and form 3. This comparison is presented in Figure 7-9 (Appendix L for the difference in percentages) and emphasizes the effect of the location charges in form 3. As can be seen, there is a clear decrease in intensities on the roads where the location component is implemented. Besides, there is an increase in intensities in areas that are just outside the areas with the location charge, causing a reduction in liveability. These conclusions are in line with what is found in the morning period.

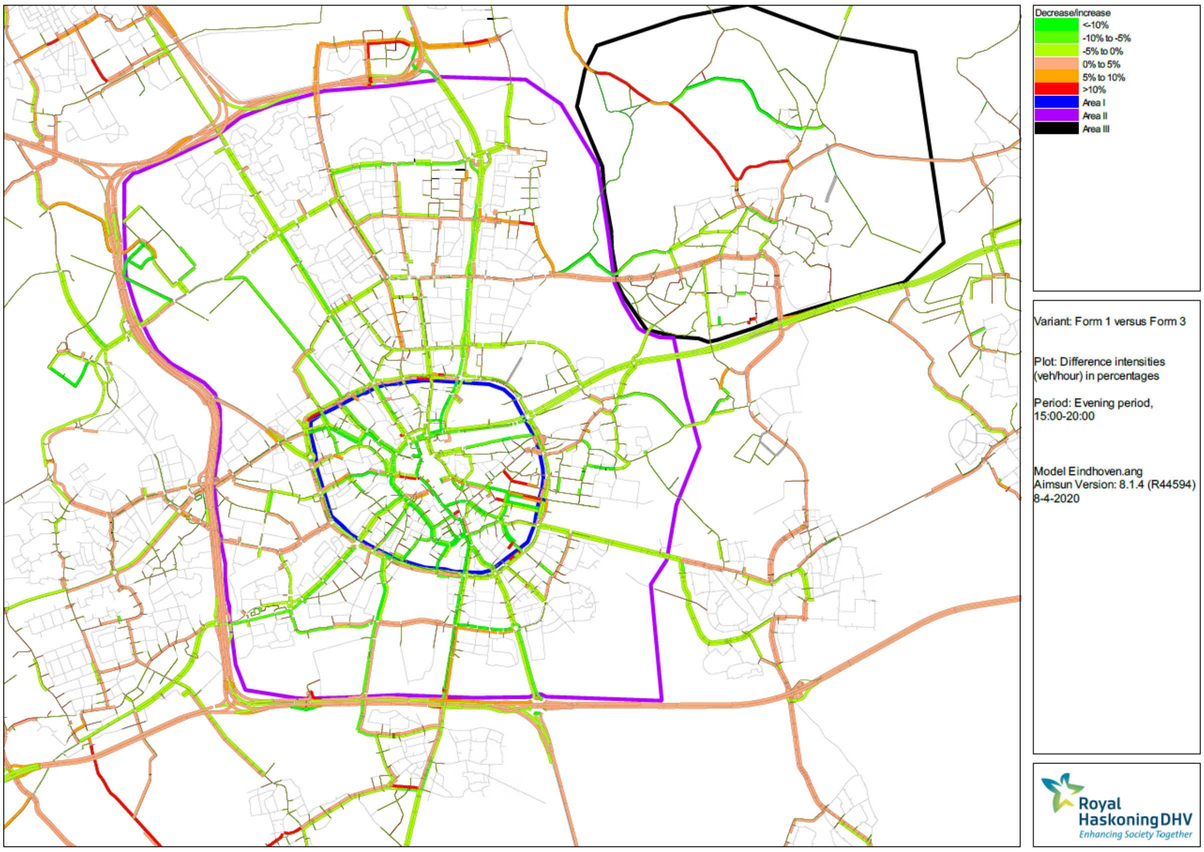


Figure 7-9 Difference in intensities (veh/hour) evening period (15:00-20:00) form 1 versus form 3 (red= increasement in form 3 green= reduction in form 3 compared to form 1)

7.1.3.2 Total distance driven

Following from the analysis of the intensities, it seems to be that form 1 increases rat running, whereas this does not happen in form 2 and 3. To check this presumption, the total distance driven is calculated and presented in Table 7-7. In this table, the differences in percentage compared to the base scenario are presented.

Total network

Seen for the total network and over the total evening period, there is a reduction of 0.8% in form 1 and 0.5% in form 3 whereas the total distance driven remains the same in form 2. This is in line with the morning period and indicates that shorter routes are taken in form 1 and 3. This leads to an increase in rat running and therefore a decrease in liveability.

Area I

For area I in the evening period, the same happens as in the morning period. In form 3, the total distance travelled reduced with 7.1% since traffic is avoiding this area. In form 1, the total distance driven reduced by 2.1% since traffic is taken the shorter route, but also because traffic avoids this area. In form 2, traffic is using the highways more causing a reduction of 1.5%.

Area II

In area II the same is happening as in area I, just as happened in the morning period. In form 3, traffic avoids area II causing a reduction of -3.1%, whereas in form 1 shorter routes are taken in combination with traffic that avoids this area, causing a reduction of -1.7%. In form 2, the highways are more often used causing a reduction of -0.2%.

Area III

In form 1 there is a reduction of 1.3% whereas there is a reduction of 2.1% in form 3. In form 3, there is only a reduction of 0.2%. This is because more traffic drives through area III, since they avoid the areas with the location component (area I and II).

Area IV

Over the total evening period, the total distance travelled remained the same in form 2. In form 1 and 3 (respectively -0.7% and -0.2%), there are reductions of the total distance travelled. This is in line with the morning period.

Table 7-7 Distance driven per form in the evening period compared to the base scenario

	Area I			Area II			Area III			Area IV			Total		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
15:00-16:00	0.7%	1.7%	-4.0%	1.3%	3.6%	-0.2%	1.6%	1.6%	2.9%	4.7%	5.1%	5.1%	4.3%	4.9%	4.5%
16:00-18:00	-3.3%	-2.8%	-7.8%	-2.6%	-1.5%	-4.0%	-2.8%	-3.2%	-1.6%	-3.4%	-2.9%	-3.1%	-3.3%	-2.8%	-3.2%
18:00-19:00	-2.2%	-1.5%	-8.0%	-1.9%	-0.4%	-3.3%	-0.2%	-2.6%	0.3%	1.2%	1.6%	1.7%	0.9%	1.4%	1.2%
19:00-20:00	4.9%	2.4%	-10.8%	-4.2%	0.5%	-6.5%	0.6%	-5.7%	4.3%	-3.4%	3.4%	-1.0%	-3.4%	3.2%	-1.4%
15:00-20:00	-2.1%	-1.5%	-7.1%	-1.7%	-0.2%	-3.1%	-1.3%	-2.1%	-0.2%	-0.7%	0.0%	-0.2%	-0.8%	0.0%	-0.5%

7.1.3.3 Travel times

Due to the changes in departure time and route choice, the travel times on the trajectories of Figure 4-2 can change. In Table 7-8, these changes in travel times for the evening period compared to the base scenario are presented. As follows from this table, there are high travel time savings especially in the hour 18:00-19:00 (up to -8.3 minutes). So due to the few numbers of trips departing in the peak hours (16:00-18:00), there is less congestion which especially has positive effects for the hour 18:00-19:00. Across the different forms of road pricing, there are only minor differences. The biggest ones can be found on the A2 between Leenderheide and Ekkersrijt. In form 1, there is a travel time saving of 8.3 minutes, whereas this is only 3.6 and 4.8 minutes in respectively form 2 and 3. The most plausible explanation for this difference is that more traffic choses to drive through the urban area in form 1, whereas this effect is smaller in form 2 (since it does not save money to use the urban area) and form 3 (there is a location charge for the urban area). This presumption is further investigated using the vehicle loss hours in the previous paragraph.
At last, there are two remarkable differences visible in Table 7-8. First, there is an increase of 0.8 minute on the A67 Eindhoven-Eersel in form 1 between 16:00-18:00. Since there is also an increase of 0.4 minute in form 3 at the same time, it is probably just a somewhat higher increasement due to randomness. What furthermore stands out, is the increase of 1.3 minute between Asten and Leenderheide on the A67 in form 2 between 19:00-20:00. It turned out, that this small increasement is caused by a temporarily increasement of vehicles entering the A67 nearby Leenderheide at 19:15 in form 2. Therefore, the overall travel time of the hour 19:00-20:00 increases, whereas this effect occurs only for 15 minutes.
All in all, there are no big differences between the road pricing forms found on the analysed trajectories. The travel time savings are the less in form 2, followed by form 3. The most travel time savings are gained in form 1, but as said these differences are only minor.

Table 7-8 Differences in travel times evening period compared to the base scenario (in minutes) including colour scale

Difference ≤ -1 minute	-1 minute < Difference ≤ -0.5 minute	-0.5 minute < Difference ≤ 0.5 minute	0.5 minute > Difference ≤ 1 minute	Difference > 1 minute

	15:00-16:00			16:00-18:00			18:00-19:00			19:00-20:00			15:00-20:00		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
1: A67 Eersel-Eindhoven	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1: A67 Eindhoven-Eersel	0.1	0.1	0.1	0.8	0.0	0.4	0.3	-0.1	-0.1	-0.4	-0.1	-0.2	0.5	0.0	0.2
2: A2 Maarheze-Eindhoven	0.1	0.1	0.1	-0.1	-0.1	-0.1	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0
2: A2 Eindhoven-Maarheze	0.1	0.0	0.0	-0.5	-0.5	-0.4	-2.1	-2.1	-2.1	-0.9	-0.8	-0.9	-0.8	-0.8	-0.8
3: A67 Asten-Leenderheide	0.1	0.1	0.1	-0.1	-0.1	-0.1	-1.2	-0.8	-1.2	-0.2	1.3	-0.2	-0.4	-0.2	-0.3
3: A67 Leenderheide-Asten	0.1	0.1	0.1	-0.1	0.1	0.1	-0.5	-0.1	-0.1	0.0	0.0	0.1	-0.2	0.0	0.0
4: Leenderweg towards Eindhoven	0.0	0.0	-0.1	-0.6	-0.2	-0.8	-0.4	-0.5	0.4	0.0	0.0	-0.1	-0.4	-0.2	-0.3
4: Leenderweg towards A2	0.0	0.1	0.0	-2.1	-0.8	-1.9	-0.5	-0.5	-0.5	0.0	-0.1	0.0	-1.2	-0.6	-1.2
5: A2 Ekkersrijt-Leenderheide	0.2	0.2	0.3	-1.3	-1.2	-1.1	-1.8	-1.8	-1.8	0.2	0.2	0.2	-1.1	-1.0	-0.9
5: A2 Leenderheide-Ekkersrijt	0.2	0.1	0.2	-2.3	-1.9	-1.8	-8.3	-3.6	-4.8	-1.2	-0.3	-1.2	-3.0	-1.8	-2.0
6: Tilburgseweg towards Eindhoven	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6: Tilburgseweg towards A2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7: A58 Moergestel-Eindhoven	0.1	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
7: A58 Eindhoven-Moergestel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8: A2 Boxtel-Eindhoven	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8: A2 Eindhoven-Boxtel	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.2	0.0	-0.2	0.0	0.0	0.0	-0.1	-0.1	-0.1
9: A50 SintOedenrode-Eindhoven	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
9: A50 Eindhoven-SintOedenrode	0.1	0.0	0.1	-1.6	-0.8	-0.9	-7.9	-8.2	-6.3	-2.6	-5.6	-4.6	-2.4	-2.1	-1.8
10: Kennedylaan towards Eindhoven	0.0	0.0	0.0	-1.2	-0.6	-0.6	-2.7	-1.9	-2.4	-0.6	-0.6	-0.6	-1.3	-0.8	-0.9
10: Kennedylaan towards A50	0.0	0.0	0.0	-0.2	-0.2	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1
11: Ring West right	-0.2	0.3	-0.3	-1.3	0.0	-1.3	-0.4	-0.3	-0.3	-0.1	0.0	-0.2	-0.8	0.0	-0.8
11: Ring West left	0.0	0.3	-0.1	-0.3	-0.7	-1.1	-0.7	-0.7	-0.9	-0.1	0.1	-0.1	-0.4	-0.5	-0.8
12: Ring Oost right	0.1	0.1	0.1	0.2	-0.3	-0.5	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	0.1	-0.1	-0.3
12: Ring Oost left	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
13: A270 N279-Eindhoven	0.0	0.0	0.0	-0.5	-0.2	-0.8	-0.3	-0.2	-0.2	0.0	0.0	-0.1	-0.3	-0.2	-0.5
13: A270 Eindhoven-N279	0.0	0.0	0.0	-0.2	-0.1	-0.3	0.1	-0.1	-0.1	0.0	0.1	0.0	-0.1	-0.1	-0.2
14: N2 going South	0.1	0.1	0.1	-1.6	-0.9	-0.9	-2.3	-2.0	-2.0	0.0	0.0	0.0	-1.4	-1.0	-0.9
14: N2 going North	0.0	0.0	0.0	-0.5	-0.5	0.0	-2.6	-2.6	-1.8	0.0	0.1	0.1	-0.9	-0.9	-0.4
Total	1.2	2.1	1.0	-13.8	-9.4	-12.7	-31.7	-25.2	-24.2	-6.0	-5.7	-7.9	-14.4	-10.4	-12.4

7.1.3.4 Vehicle loss hours

Since the travel times on the trajectories only locally grade the degree of congestion, also the vehicle loss hours of the areas presented in Figure 3-1 are calculated and presented in Table 7-9. The difference in percentage with the base scenario is presented for each form. Just as in the morning period, the results are separated per area.

Total network

Seen over the total evening period, the reduction in vehicle loss hours is the highest in form 1 (-15.9%), followed by form 3 (14.4%) and form 2 (11.7%). What furthermore stands out, is that the vehicle loss hours increase in the hour 15:00-16:00 in all forms, due to the increase in demand in this hour. In the hour 18:00-19:00, there is also an increase in demand but there is no increase in vehicle loss hours. This is caused by the strong reduction vehicle loss hours in the hours 16:00-18:00. Due to this reduction, also less congestion is occurring in the successive hours.

Area I

Across the different road pricing forms, form 3 causes the highest reduction (-15%) in vehicle loss hours in area I. This is caused by to the fact that traffic avoids area I in this form. The reduction in form 2 is somewhat higher (-5.5%) than in form 1 (-4.5%), since in form 1 shorter routes are taken which sometimes cross area I.

Area II

Also in area II, traffic in form 3 is avoiding this area causing a reduction of 13% in vehicle loss hours. In form 1, there is a reduction of 11.5% whereas the reduction in form 2 is 6.1%. This is in line with what is found in in Table 7-7 and Figure 7-8, that some of the traffic is avoiding area II in form 1.

Area III

For area III, there are quite remarkable results obtained. In form 2 there is a reduction in vehicle loss hours of 3.9%, whereas there is an increase of 3.6% in form 1 and 4.2% in form 3. In form 1 traffic takes the shorter routes that cross area III, whereas in form 3 traffic avoids area I and II and uses instead among others area III. In form 2 there is no positive incentive to take shorter routes or avoid other areas, causing a reduction of vehicle loss hours in area III.

Area IV

The results found for area IV are in line with the total network and with the morning period. The highest reduction is obtained in form 1 (-18.5%) followed by form 3 (-14.9%) and form 2 (-14.3%).

Table 7-9 Difference in vehicle loss hours evening period compared with the base scenario including colour scale

Difference≤-5%	-5%<Difference≤0	0%>Difference≤5%	Difference>5%

	Area I			Area II			Area III			Area IV			Total		
	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3	Form 1	Form 2	Form 3
15:00-16:00	2.6	3.7	-4.1	2.3	6.5	0.6	12.3	6.6	15.2	9.4	10.1	9.2	6.6	8.4	5.4
16:00-18:00	-6.1	-7.3	-17.2	-12.3	-7.0	-14.8	0.7	-6.2	1.6	-17.3	-13.8	-13.3	-15.1	-11.4	-14.0
18:00-19:00	-5.2	-7.6	-17.1	-18.5	-12.3	-16.6	6.4	-5.0	3.0	-28.2	-22.1	-23.5	-25.8	-19.9	-22.1
19:00-20:00	-2.3	1.5	-12.8	-21.8	-9.2	-18.3	8.4	-12.7	17.5	-31.9	-24.7	-33.8	-29.8	-21.9	-31.1
15:00-20:00	-4.5	-5.5	-15.0	-11.5	-6.1	-13.0	3.6	-3.9	4.2	-18.5	-14.3	-14.9	-15.9	-11.7	-14.4

7.2 Sensitivity analysis Time of Day module

Essential for the effectiveness of road pricing on the degree of congestion, is the smoother spread of the peak hours. This is achieved, by levying a higher charge during the peak hours compared to the off-peak hours. In this research, there is chosen to follow the often-heard charges of 7 cents per kilometre during off-peak hours and 11 cents per kilometre during peak hours. However, it is interesting to investigate what would happen when other charges are chosen. For the ToD-module, the difference between the peak and off-peak charge is essential for the number of trips that change from peak hours to off-peak hour. In the base scenario this difference is 4 cents, but there is also tested what happens when this difference is reduced to 2 cents or increased to 8, 16, 32 and 64 cents. This means that the effect of peak charges of 9, 15, 25, 41 and 73 cents are tested. In Figure 7-10, the results of the variety in peak charges are presented. What can be seen in the figure, is that there seems to be a linear relationship in the left part of the graph. However, when levying higher charges, the number of travellers that change from departure time are not doubled anymore. This is logic, since the occurrence of congestion causes that some travellers switch back to their original departure time.
Following this figure, it seems to be that the higher the difference in charge, the higher the number of travellers switching from departure time. This is logic by the way it is modelled in this research, but practical seen this is not realistic. At some point, the peak shoulders become more crowded than the peak hours, causing that travellers switch back to the peak hours. This figure shows, that there are improvements possible for the ToD module. In Chapter 9.5.1 is explained how this problem can be solved.

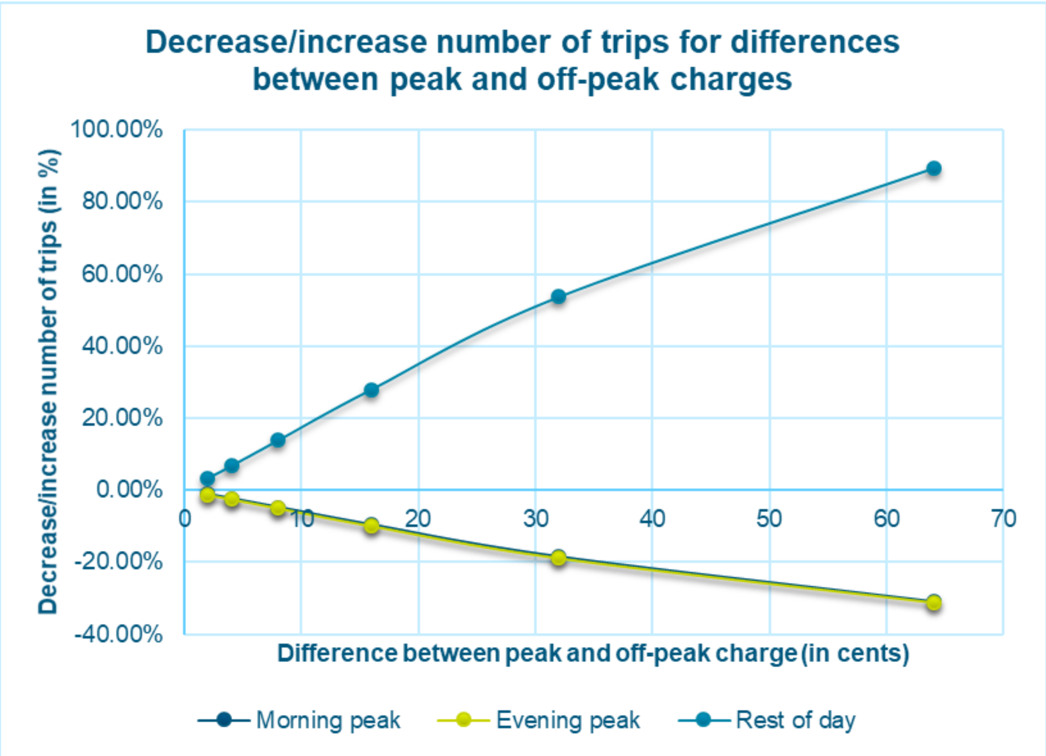


Figure 7-10 Results sensitivity analysis peak charge

8 Conclusion and recommendation

In the region of Eindhoven, congestion is an increasingly growing problem. Besides, the government is missing out on earnings due to the rise of electrical vehicles which do not contribute to the revenues obtained by selling fuel. As solution for both problems, road pricing, is an often-heard solution. In this research, there is investigated whether road pricing is a possible solution for the congestion problems in the region of Eindhoven. Furthermore, there is investigated whether road pricing does not unintentionally decrease the liveability in residential areas. For investigating this, the following three forms are analysed:

1. Charge per driven kilometre (7 cents/km), including a peak charge (11 cents/km)
2. Origin and destination based charge (7 cents/km), including a peak charge (11 cents/km)
3. Charge per driven kilometre (7 cents/km), including a peak charge (11 cents/km) and a location charge in two areas (plus 5.5 and 11 cents/km)

Using a traffic model, all forms are graded on the following five KPIs:

1. Switch departure time peak vs off-peak
2. Intensities (liveability)
3. Total distance driven per area (liveability)
4. Travel times on main roads (congestion)
5. Vehicle loss hours (congestion)

Using these KPIs, first the hypotheses are accepted or denied and subsequently the research questions are answered. Subsequently, an overall conclusion concerning road pricing is drawn and the findings are compared to other researches. At last, a recommendation is made concerning the findings of this research.

8.1 Hypotheses

1. *In all forms there is a decrease in traffic demand in the peak hours and an increase in the peak-shoulders*

Due to the higher charge during the peak hours compared to the off-peak hours, there is expected that some people change their departure time to off-peak hours. This hypothesis is tested by evaluating the number of trips in the three time periods (morning peak, evening peak and rest of day) for the road pricing forms and the base scenario. Following the results of Table 7-1, there can be concluded that the percentage of trips departing outside peak hours in response to the peak charge is equal for all road pricing forms. For all forms a difference of 4 cents between the charge in the peak and the charge in the off-peak, leads to a decrease of trips in the morning peak of around 2.32% and in the evening peak of 2.38%. As found in the sensitivity analysis, an increase in difference between the peak and off-peak charge lead to an increase in travellers that switch from departure time. However, this effect is not linear since the growth in congestion causes that travellers switch back to their initial departure time. This point is elaborated more extensively in the discussion (Chapter 9.5.1). All in all, this hypothesis is accepted.

2. *In form 2, there is no decrease in liveability compared to the base scenario in residential areas of the region of Eindhoven.*

This hypothesis cannot be accepted, despite the liveability increases in almost all areas in the region of Eindhoven. The hypothesis is graded based on the differences in intensities between form 2 and the base scenario (see Figure 7-3 for the morning period and Figure 7-7 for the evening period) and on the differences in total distance travelled. By analysing the intensities, there is a decrease of intensities in area I and II what improves the liveability in these areas both in the morning and evening period. Besides, there is an increase of intensities on the highways, what is as wanted since the highways are made for high intensities of traffic.

Following the total distance travelled, there is concluded that overall no shorter routes are taken (increase of 0.2% on the complete network over the morning period, whereas it remained the same in the evening period). When looking at the separate areas, there is concluded that in the areas where liveability problems could occur (areas I, II and III), there is a reduction of total distance driven leading to an improvement of liveability. However, in area IV there is an increase in total distance driven in the morning period (+0.3%), but this does not by definition imply a reduction in liveability since all highways are located in area IV. But since also residential areas are located in area IV, it is not possible to conclude that the liveability certainly not decreases in form 2. Therefore, the hypothesis cannot be accepted although it is likely that the liveability increases in all residential areas.

3. *Form 1 reduces the liveability compared to form 2, especially in the city centre of Eindhoven*

The second hypothesis is accepted. For the morning period, the total distance driven in area I (-2.5% form 1, -2.8% form 2) and II (-1% form 1, -0.7% form 2) is more or less equal for form 1 and 2, whereas following Figure 7-4 there seems to be an increase of intensities in form 1 compared to form 2. Both findings together, conclude that there is more traffic in area I and II in form 1 compared to form 2, what takes shorter routes and therefore not leads to an increase in total distance driven. This leads to a reduction of liveability.
For the evening period, there is no clear conclusion found on the intensities in area I and II in form 1 compared to form 2 (Figure 7-8). Concerning the total distance driven, there is a reduction of -2.1% in form 1 and -1.5% in form 2 in area I and a reduction of -1.7% and -0.2% in form 1 and 2 respectively in area II. Combining both findings, there can be concluded that shorter routes are taken in form 1 compared to form 2 in the urban areas, leading to a reduction of liveability.
All in all, this hypothesis is accepted both for the morning and evening period.

4. In form 3, the liveability in the urban areas improve compared to form 1 but decreases in areas just outside the urban areas

The fourth hypothesis is accepted. As follows from Figure 7-5 and 7-9, there is a clear decrease in intensities in area I and II. Besides, there is an increase in intensities in the areas just outside area II, just as in area III. These findings are confirmed by the total distance driven in these areas. In the morning period, there is a reduction of -7.6% and -2.9% in area I and II in form 3 whereas this is only -2.5% and -1% in form 1. In area III there is a reduction of -0.1% in form 3, whereas this is -2.3% in form 1. This seems to be an increase in liveability in area III in form 3, but this is caused by the fact that shorter routes are taken what has negative effects on the liveability. In the evening period, there is an increase of total distance driven in form 3 of +4.2 %, what is more than in form 1 (+3.6%). In form 1 this is caused by traffic that takes the shorter routes and now crosses area III, and in form 3 by traffic that avoids area I and II and now crosses area III. Concluding, the hypothesis is accepted.

5. *In all forms, a reduction of x% in traffic demand leads to approximately a fivefold reduction of vehicle loss hours.*

This hypothesis is accepted. In the morning period, there is a reduction of 2.32% of traffic after implementing road pricing, what thus should lead to a reduction of vehicle loss hours of around 11.5% according to the hypothesis. By analysing the vehicle loss hours during the morning peak, there is found that in form 1 there is a reduction of 10.9%, in form 2 of 10.2% and in form 3 of 12.0%. So, in all forms the reduction of vehicle loss hours is close to the expected value. For the evening period, the same conclusion is drawn. The vehicle loss hours reduce respectively by 15.1%, 11.4% and 14.0% in form 1, 2 and 3. Also these results are around the expected 11.5% reduction of vehicle loss hours. The reason that the reduction of vehicle loss hours is somewhat higher in the evening peak, is that this period is more crowded than the morning peak. In a more crowded period, there is more room for improving the degree of congestion. All in all, this hypothesis is accepted.

8.2 Research questions

In the following chapters, the answers on the research questions are provided. At the end, the main question is answered, and an overall conclusion is given.

1. *Given the chosen road pricing forms, how to forecast the effects on the traffic flows?*

In this research, a traffic assignment model of the region of Eindhoven is used to forecast the effects on the traffic flows. To be able to implement the effects of the different road pricing forms, a ToD module is developed to forecast the change in departure times. Besides, the route choice functions are adjusted so that the monetary costs are included in the route choice process in form 1 and 3 Subsequently, the effects on the traffic flows are forecasted by using a dynamic mesoscopic simulation in Aimsun.

2. *What change of travel behaviour occurred after implementing road pricing?*

The possible changes in travel behaviour are a change in departure times and a change in used routes. For the change in departure time there is a unanimous conclusion: a difference of four cents per kilometre between the peak and off-peak charge leads to a decrease of around 2.35% in trips in both peak hours, irrespective of the form of road pricing. As regards the route choice, there are differences across the different road pricing forms. For the forms with a charge per driven kilometre (form 1 and 3), the total distance driven reduces compared to the base scenario. When a location charge is added in an area, there is a reduction of traffic intensities inside that area. So, rat running increases and therefore liveability decreases with a charge per driven kilometre, but this can be discouraged in an area by implementing a location charge. Furthermore, a form in which the charge does not depend on the used route does not reduce the liveability. Concluding, independent on the road pricing form, travellers change their departure time from peak hours to off-peak hours. Besides, liveability reduces in residential areas when a charge per kilometre is levied. This can either be solved for that area by implementing a location charge, or by taking a road pricing form in which the charge does not depend on the route. In the area where in the current situation already liveability problems are arising (area III), a form with location components in the urban areas of Eindhoven has negative effects. A form in which a charge is levied independently of the routes that are taken, is more effective for this area.

3. *What are the effects on traffic flows of the change in travel behaviour after implementing road pricing?*

The changes in travel behaviour cause an overall decrease of congestion in all road pricing forms. This is measured by analysing the travel times on the main roads and by calculating the vehicle loss hours in three different areas. Although all forms have a positive effect on the degree of congestion, a charge per driven kilometre (form 1 and 3) is more effective than a form with a charge independently of the route (form 2). This is because in a form with a charge per kilometre, routes are taken that are shorter and are less congested. In the morning period, the vehicle loss hours on the complete network are reduced by 8.6% in form 1, 7.5% in form 2 and 9.6% in form 3. In the evening period, this is 16.5% in form 1, 11.7% and 14.4% in form 3. The travel time savings on the main roads are in line with the reductions in vehicle loss hours. For the urban area, there is found that form 3 has a way more positive effect on the vehicle loss hours than form 1 and 2 (15.0% against 4.5% and 5.5% respectively for the evening period). Also the travel time savings are higher for form 3 on the roads located in the area with the location charge. On the other hand, the reduction in vehicle loss hours in the areas without location charge in form 3 are lower than in form 1.
All in all, the three investigated road pricing forms have a positive effect on the travel times and vehicle loss hours in the region of Eindhoven. Form 1 and 3 reduce the travel times and vehicle loss hours the most, followed by form 2. Specific for the urban area, form 3 reduces congestion the most followed by form 2 and form 1 as last.

4. Which road pricing form is most effective for which objective of implementing road pricing?

Since it is arbitrary to come to an overall score of the road pricing forms, there is presented per objective which road pricing is recommended. These recommendations are presented in Table 8-1.

Table 8-1 Recommendations per objective

Objective	Road pricing form	Comment
Smoother peak spread	Form 1, 2, or 3	The difference between the peak and off-peak charge is crucial
Banning traffic from urban area	Form 3	
Discouraging using shorter routes	Form 2	
Reducing congestion	Form 1 or 3	Form 3 is most effective in reducing congestion in the predefined area. Form 1 is more effective for the areas without location charge.

When the government has the objective to assure a smoother peak spread by moving traffic to the peak shoulders, the effects of the three road pricing forms are similar. By taking higher differences between the peak and off-peak charge, more travellers adjust their departure time from peak hours to off-peak hours.
Following the analysis of the intensities, there can be concluded that form 3 is the most effective in banning traffic from the urban areas. The disadvantage of form 3, is that intensities increase in the areas that lay just outside the areas where the location charges are levied. When the government has the objective to discourage using shorter routes, form 2 is most effective. This found difference is caused by the fact that in form 2 there is no negative incentive of taking longer routes. The total distance driven per area sometimes gives a distorted view, since it could either imply that there is less traffic in that area or that the traffic takes shorter routes. For example in form 3, traffic is banned from the urban areas, but it is still stimulated to take the shorter routes to save money.
When the government has the objective to reduce congestion as much as possible, forms 1 and 3 are the most effective. Both on the travel times and the vehicle loss hours, form 1 and 3 are more effective in reducing congestion than form 2. Whether form 1 or 3 is the most effective, depends on the area someone is interested in. Form 3 is most effective in reducing congestion in a predefined area, but the disadvantage is that congestion increases in the area that lays next to the predefined area with location component. When form 1 is chosen, congestion is reduced smoother over the areas.

What are the effects of road pricing on the traffic flows in the region of Eindhoven for the year 2030?

The three road pricing forms are analysed on the degree of changing the departure times, liveability and the degree of congestion. Across the road pricing forms, the effect on the change of departure time is similar since the chosen differences in charges for the peak and off-peak hours are similar. When implementing a charge per driven kilometre, a positive effect on the degree of congestion is found. Both for the morning and evening period, the vehicle loss hours (8.6% and 16.5% respectively) and the travel times reduce compared to the base scenario. As regards the liveability, a charge per driven kilometre is less suitable. Shorter routes are taken, and more traffic drives through the urban area compared to the other forms. The effects of the

more rat running however, does not lead to an increase in vehicle loss hours in the urban area, caused by the smoother spread of the peak hours.
A charge independently of the route that is taken, has somewhat lower effects on the reduction of congestion than a charge per driven kilometre but compared to the base scenario there is still an improvement. For discouraging travellers to take shorter routes, a charge independently of the route is more effective than a charge per driven kilometre (+0.2% versus -0.3% in the morning period and -0.7% and 0.0% for the evening period). A charge independently the route that is taken is, does not actively aim to ban traffic from the urban area, but due to the smoother spread in peak hours and therefore less congestion, the main roads of the network become more attractive. This causes that less traffic drives through the urban area and therefore a reduction of vehicle loss hours of 7.7% and 5.5% in the morning and evening period is achieved.
Combining a charge per driven kilometre with a location charge per driven kilometre in the urban areas lead to a decrease in congestion. Both in the morning and evening period, the vehicle loss hours (-9.6% and -14.4% for the morning and evening period) and the travel times on the main roads reduces compared to the base scenario. For discouraging rat running, a charge per driven kilometre including location charge is not by definition effective. When the explicit goal is to ban traffic from a predefined area, the location components performs effectively. However, since the charge is still per driven kilometre, travellers are still stimulated to take the shorter routes (reduction of 0.2% and 0.4% in total distance driven in the morning and evening period), meaning an increase in rat running and thus a decrease in liveability. Besides, the liveability in areas just outside the areas with the location charge reduces.

8.3 Overall conclusion road pricing

Concluding, the implementation of road pricing has positive effects on the degree of congestion. Due to the smoother spread in the peak hours, less congestion occurs. What must be kept in mind, is that the degree of congestion increases somewhat in the early peak-shoulders. It is essential that the demand of traffic does not increase too much in these hours, since otherwise congestion arises in these hours also causing negative effects on congestion in the successive hours. Therefore, levying higher charges in the peak hours does not by definition reduce congestion seen over the complete peak period. To discourage rat running through the city centre, a location charge is effective since travellers avoid the areas with the location charges if possible. This is in line with the researches concerning cordon pricing (de Palma & Lindsey, 2006; Eliasson, 2008; Sinclair Knight Merz, 2005; Xie & Olszewski, 2011), who all concluded that cordon pricing leaded to a (forecasted) reduction of congestion. When the objective is to discourage using the shorter routes, it is more effective to assure that the charge does not depend on the number of kilometres someone is driving. This conclusion is in line with Ohazulike et al. (2013), who claimed that such a form does not influence the route choice process.
For analysing whether the results of this research are in line with other researches, the one of 4Cast (2006) is most relevant. In this research, among others the effects of an average charge of €0.067 per driven kilometre are investigated for the Netherlands, the Randstad and the rest of the Netherlands. For the reduction of congestion, the vehicle loss hours are calculated both for the main road network and the underlying road network. There is found, that in the morning peak there is a reduction of 45.5% on the main road network and 37.9% on the underlying road network. In the evening peak, there is a reduction of 47.7% and 47.3% on the main and underlying road network respectively. Although this research for the region of Eindhoven does not address the vehicle loss hours on the main or underlying road network, it is clear that in the research of 4Cast larger reductions of congestion are found. This difference is caused, by the fact that the research of 4Cast considers the destination and transport mode choice as possible choice options. Therefore, comparing the absolute results of the research of 4Cast with this research for the region of Eindhoven is hard. What however is also found in the research of 4Cast, is that the reduction of congestion is higher for the evening peak than for the morning peak. This is in line with what is found in this research. Furthermore, in the research of 4Cast there is also found that a location charge (extra charge on roads with an IC ratio above 0.8) causes that traffic avoids the roads with the location charge. The other regional findings cannot be compared with the research of 4Cast or any other research. Hence, the results of this

research contribute to the knowledge concerning road pricing in the Netherlands, and especially for the region of Eindhoven.

8.4 Recommendation

In this research, there is investigated whether road pricing could be a solution to the increasing problems with congestion. Following the results obtained in this research, the following four main recommendations for the region of Eindhoven are made:

1. For assuring a smoother spread of the peak, implement a different charge for the peak and off-peak hours
2. For banning traffic from an (urban) area, implement a location charge in that area
3. For discouraging the use of shorter routes, implement a charge that is independent of the route that is taken
4. For reducing congestion, the smoother spread is essential. For extra effect, a charge per driven kilometre is recommended

Crucial for assuring a smoother spread, is that there is a different charge for the off-peak periods and the peak hours. In this way, there is a positive incentive to travel in an off-peak hour. For the second recommendation, there must be said that implementing a location charge decreases the liveability in areas close to the areas with the location charge. In the close areas, there is an increase in intensities reducing the liveability. To discourage the use of shorter routes, there is recommended to implement a charge independent of the route that is taken. In this way, there is no positive incentive to take a shorter route. As said in recommendation four, the implementation of road pricing is effective in reducing congestion when a smoother peak is assures. A charge per driven kilometre is even more effective in reducing congestion since most of the congestion occurs on the main roads, which are partly avoided when a charge per driven kilometres must been paid. A reduction in liveability however is a negative effect of the charge per driven kilometre.
All in all, road pricing has the potential to reduce the problems with congestion, but possible negative side effects as a reduction in liveability could occur depending on the exact composition of the road pricing form.

9 Discussion

This research is based on certain assumptions and simplifications, which were crucial to keep the research feasible but might influence the found results. In this chapter, these assumptions and simplifications are discussed. A distinction is made between points comprising the traffic model and points comprising the design of the research. Furthermore, road pricing is discussed in general and recommendations are made for other governments than just Eindhoven. At last, recommendations for further research are provided.

9.1 Model assumptions and simplifications

The first point to discuss here, is the ToD module. In the ToD module used, it is possible that someone changes its departure time from the morning peak to the evening peak (or the other way around), whereas this is not realistic. In this research this effect did not occur, since equal peak charges were chosen for the morning and evening peak. However, it is something that must be kept in mind when someone uses this method in further research.

Another point of discussion of the ToD module, is the fact that only the difference between the peak and off-peak charge influences a possible change of departure time. In other words, a peak charge of 11 cents combined with an off-peak charge of 7 cents leads to the same number of travellers adjusting their departure time as an off-peak charge of 100 cents combined with a peak charge of 104 cents. This is not realistic, since the perception of paying an extra 4 cents is much worse when the original charge is 7 cents than with an original charge of 100 cents. The effect on this research is, that the higher the charges, the higher the change that the effect of the number of travellers adjusting their departure time is overestimated.

Next to the ToD-module, there are more points of discussion concerning the traffic model. Since the computational time of the traffic simulation needed to be workable, there was decided to make a cut-out of the normal network. This reduces the number of zones and the number of roads, but therefore also the level of detail of the network is reduced. This causes that, mainly outside the centre of Eindhoven, there are less roads that can possibly be used by rat runners. Therefore, the effect of rat running could possibly be underestimated in this research, mainly in the rural areas outside Eindhoven.

The last point of discussion of the traffic model, are the corrected OD-matrices for the year 2030. These matrices could not be calibrated by using empirical data and therefore calibration factors of the current year were used to correct the synthetic matrices. Despite this method is often used, it leaves a certain amount of uncertainty in the matrices of a future year. Besides, matrices are used for an average working day, whereas the effects on a crowded working day could be different. Although the same matrices are used as base for all the scenarios, it is a point that must be kept in mind.

9.2 Assumptions and simplifications in research design

First, the destination and transport mode choice are not addressed in this research, although road pricing influences them. For the destination choice, it becomes more attractive to choose locations which are closer, since this saves money. Although most trips have a more or less fixed origin and destination (e.g. home-work and educational trips), the destination for trips as shopping is more flexible. Therefore, it is possible that other destinations will be chosen after the implementation of road pricing. This effect is for example found in the research of 4Cast (2011), where is stated that travellers choose locations closer to home (even for the home-work relation on the longer term). This would positively influence the degree of congestion, since less kilometres are driven. Also for the liveability, a change in destination choice would have a positive effect. Closer destinations are chosen, leading to a decrease in intensities on some roads. When the transport mode choice would be considered, the expectation is that some travellers would switch from car to public transport, bike or no travel at all. This would influence the degree of congestion and liveability, but the number of switchers would probably be similar for form 1 and form 2. For form 3, there can be argued that more travellers leave the car since origins and destinations in area I and II become less attractive for car-users. This would reduce congestion and rat running even more. On the other hand, a decrease in congestion leads to an increase in demand for car traffic. This would flatten the positive effect on congestion and liveability. As a final remark, the KPI of the total distance driven cannot be used anymore to investigate whether shorter routes are taken. The number of trips made is not similar anymore, causing that the total distance driven automatically changes as well whereas it is not caused by a change in routes. This issue can be solved by using the average distance driven per vehicle instead.

Another important assumption made, is that the travellers that change their departure time from peak hour to peak shoulders, depart the hour before or after the peak hours. This is assumed since it is likely for most of the trips, that the new chosen departure time is as close as possible to the initial departure time. However, this is not by definition always the case since someone could also postpone its trip to somewhere in the afternoon for instance. Especially for not work-related trips this is a conceivable effect. Concluding, the traffic in the hours that are not considered as peak-shoulders (except the peak hours) is somewhat underestimated, but this is not expected to be much since one wants to stay as close as possible to its initial departure or arrival time.

Besides, analysing the intensities on a road section is in some cases not that reliable. In this research, a reduction in intensities is assumed to be a reduction in rat running, but this could also be the opposite. When the flow is low on a road section, it either means that there is no traffic on this section, or it means that there is so much congestion that driving is nearly impossible. This effect is minimized in this research, by using the complete morning and evening period by the analyses of the intensities. In the last hour of the simulations, no extra traffic is assigned to the network and at the end of the simulation all traffic has left the network. This means, that there are no traffic jams which are that extreme that traffic could not leave the network before the end of the simulation. Therefore, all traffic is counted in the intensity analyses causing that a reduction in intensity means that there is a decrease in demand on that road section.

9.3 Discussion road pricing in general

Found in this research, is that some forms are effective in reducing rat running and that all forms are effective in reducing the degree of congestion. In the previous paragraph there is already discussed that determining the degree of rat running is only an indication, but also for the degree of congestion some things must be kept in mind. First, it is crucial that the early peak shoulder does not become too crowded, since this would significantly influence the degree of congestion during the rest of the peak period. For the late peak shoulder this problem does not arise, since the demand of traffic reduces anyhow in the successive hours. In other words, the difference between the peak and the off-peak charge cannot be too high, since then the early peak shoulder could become too crowded.

Furthermore, the practise of the location charge is discussed. There is found that the location component is efficient for banning traffic from an area, but there are also dwellings and businesses located inside the area. For them it is unfair to also suffer from the location charge since they do not have the choice to avoid the area. Besides, the location charge is not meant for them, since the aim is to reduce rat running and not bullying the local traffic. Therefore, it is advised to arrange an exemption for the location charge for the residents and businesses in these areas. Instead, they pay the charge that is in operation in the outside area.

As final remark, it is unreasonable to think that road pricing solves all the problems with congestion. Next to the daily traffic jams, around 25% of congestion is caused by incidents (Ministerie van Infrastructuur en Milieu, 2016). These traffic jams will not be solved by road pricing, although a smoother spread in peak hours contributes to a reduction of incidents. On the other hand, an increasement of rat running could cause more incidents on secondary roads.

9.4 Recommendation other governments

In this research, the effects of road pricing are investigated for the region of Eindhoven. However, it is interesting to know whether the same results would be found for other cities or areas. What about the reduction of congestion in Amsterdam and Rotterdam after implementing road pricing for example, it is

questionable whether the same effects can be reached. The roads in the Randstad are more crowded also outside the peak hours, causing that banning traffic from the peak hours probably causes more congestion in the peak shoulders. Therefore, there is advised to make another distinction between the peak hours and the off-peak hours. There must be investigated in which hours there is room for a higher traffic demand and these hours must get a lower charge than in the peak hours.
For concluding something about the liveability in other cities, the road network is analysed. For Rotterdam and Amsterdam, there is noticed that both cities have a complete ring road of highways whereas this is missing in Eindhoven. Having this ring road, causes that the need for driving through the city centre is reduced. For through traffic from North to South for example, there is an option to take the Eastern direction or the Western direction. Next, it does not matter from which direction someone is approaching, the ringroad can always be used. Furthermore, the city centres of Amsterdam and Rotterdam are more crowded than the city centre of Eindhoven (Eindhoven is on the tenth place of the Netherlands, whereas Amsterdam and Rotterdam respectively are on the fifth and seventh place (TomTom, 2019)). Therefore, the expectation is that rat running in Amsterdam and Rotterdam is less rewarded than in Eindhoven. When a charge per driven kilometre would be implemented in Amsterdam or Rotterdam, the problem of a reduced liveability is probably less than in Eindhoven. The advantage of levying a charge independently of the route that is taken, would therefore be less valuable.
For banning traffic from the city centre, a location charge was the most effective. For Eindhoven the choices for where to implement the location charges was straightforward, since there is a clear urban area and sub-urban area. For Amsterdam and especially Rotterdam, there is no clear ringroad of secondary roads around the city centre. For the location charge to be effective, it is needed that the roads just outside the area with the location charge can handle an extra traffic demand. This is important to investigate for determining where the location charge must be implemented. Besides, there must be kept in mind that the roads just outside the area with the location charge probably need to handle an increase in traffic intensities.

9.5 Recommendations further research

To continue on this research, several recommendations are made. These recommendations are divided in recommendations concerning the traffic model and concerning road pricing in general.

9.5.1 Recommendation for the traffic model

In Figure 7-10, there is found that the higher the difference between the peak and off-peak charge, the higher the number of travellers switching from departure time. This however is not realistic, since the peak shoulders become more crowded than the peak hour at some point, causing that travellers switch back to the peak hours. This effect is insufficiently considered in the ToD module. For the number of travellers switching to the off-peak hours, the travel times and travel costs are used in the ToD module. However, what is calculated is the number of travellers that switch from peak hour to the peak shoulder. For calculating the average travel times of the peak shoulders, the traffic demand of an average rest of day hour is used meaning that all hours except the peak hours (07:00-09:00 and 16:00-18:00) are averaged. The traffic demand of an average rest of day hour is much lower than the traffic demand of an average peak-shoulder hour, causing that way lower travel times are obtained. When the switch towards the peak shoulders is estimated, it is more reliable to use the traffic demand of an average peak shoulder hour. In other words, an average OD-matrix must be composed of the hours 06:00-07:00, 09:00-10:00, 15:00-16:00 and 18:00-19:00. In this way, reliable travel times of the peak shoulders can be calculated, which can be used as input for the ToD module. When this was done in this research, higher travel times would have been obtained for the rest of day causing that less traffic switched from peak hours to off-peak hours.
Second, more research is recommended on which weights must be chosen in the static volume delay function. In this research, there is chosen to weight the monetary cost parameter as high as the distance travelled. These weights are important for the results of the research, so therefore it is worth investigating this more extensive. The most accurate way of doing this, is to execute a stated preference survey in which

car users are asked to choose between hypothetical alternatives. In these alternatives, the travel distance, time and costs variate. In this way, there is investigated how each component is valued relative to the other components.
The third recommendation concerning the traffic model, enhances the ToD module. In this research, the calculations of the travel times required in the iterations of in the ToD module are done in a static macroscopic assignment. Although a static macroscopic simulation considers the effect of congestion by calculating the travel times, a dynamic mesoscopic simulation is more accurate in this calculation. For making the ToD module more accurate, it is recommended to investigate the effect of using the dynamic mesoscopic simulation in the ToD module. Besides that a mesoscopic simulation runs way longer than a macroscopic simulation (around 6 hours for 6 replications versus 15 minutes), there is expected that it takes longer to reach convergence.
At last, it is advised to further investigate the distribution percentages of routes that are fixed in the static assignment, the percentage that has a predefined route but can switch en-route and the percentage that is free to choose a route at any moment. In this research, the routes for 64% of the traffic is based on the static routes, 16% initially follows the static route but can switch and 20% is free to change route at any moment. When a different distribution is chosen, the used routes could change.

9.5.2 Recommendations for further research road pricing in general

First, including the destination and transport mode choice in further research is unavoidable. The destination choice could change since the closer destinations become more attractive. Furthermore, other transport modes become more attractive, or one can decide to not travel at all and work from home for example. In reality, it is likely that the demand for car traffic reduces, having positive effects on the liveability and congestion.
Next, it is advised to investigate the combination of form 2 included with a location component. There is found that form 2 is most effective in improving liveability and a location charge is effective in banning traffic from an area. Combining both forms, could therefore lead to even more increases of liveability. The most realistic way of implementing this new form, is to control with cameras which vehicles enter the areas with the location charge. A fixed price is levied for entering the area and does not depend on the route that is taken. Again, it is advised to exempt the residents and the businesses which are located inside the area. As possible additional measure, there can be thought about levying lower charges on the main roads. In this way, traffic is stimulated to use these roads. The disadvantage of this system is that travellers are punished to leave the main roads when incidents happened. This could be solved by assuring that travellers can retrieve (part of) their paid charge when they can prove that an incident happened upstream.
Furthermore, investigating the exact values of the charges is required. It is not by definition the case that the higher the charge, the higher the reduction of congestion. When the peak shoulders become really congested, the overall problems with congestion are not solved. Besides, residents will not accept a road pricing scheme which has unreasonably high charges. Therefore, a wise consideration between the height of the charge and the objective a government wants to achieve is required. To improve the acceptability among residents, it is necessary to explicitly explain what happens with the revenues gained from the road pricing scheme. By for example explaining that the revenues will be used for improving the road network, the acceptation improves.
Moreover, the emission of greenhouse gasses is nowadays a hot topic. Especially nearby vulnerable nature reserves, strict norms are currently used for the emission of nitrogen. Investigating the effect of road pricing on the emissions, is therefore relevant. For the practise of such a research, it is needed to use a microscopic simulation model since a mesoscopic model is not detailed enough. Therefore, it is important to think carefully about how to execute this. A possible solution is to use a mesoscopic model as basis and to pick some locations that are simulated in a microscopic model (hybrid model). When the government has the main objective to reduce the emission of greenhouse gasses, an interesting form of road pricing is to base the charge on the degree of emission of the car. In this way, people are stimulated to buy the more

environmentally friendly cars. Besides, the people that still own a harmful car are discouraged to use the car.

At last, no distinction is made between passenger cars and freight traffic in this research. However starting from 2023, a road pricing form for freight traffic will be implemented in the Netherlands (van der Aa, 2019). For the region of Eindhoven, the charge for trucks will be implemented on all highways, the N279 and the N2. Trucks are going to pay a charge of 15 cent per kilometre on average, without peak charge. There is recommended to consider this charge in further research, since it is something that could influence the traffic flows in the region. However, there is not expected that this would have a big effect, since the travel time is way more important in the world of transporting goods. The potential savings of money by taking a shorter route mostly will not outweigh the increase of travel times.

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Appendix A - ToD modules

As said in Chapter 2.5, five different ToD modules are analysed in this research. In the following paragraphs, these forms are explained more extensive.

A.1 Kristoffersson & Engelson

Kirstoffersson & Engelson (2009) for example, introduced a microscopic ToD method using a discrete choice model with the concept of penalties for arriving late, for determining the peak spread for Stockholm. In total, there are 14 time periods considered (12 between 06:30 and 09:30, one before 06:30 and one after 09:30). In this approach, the discrete choice model consists of the 14-time intervals, and the choice for switching to public transport. The utility of each time interval is calculated using a Multinomial logit model (the model is based on a SP and RP survey in Börjesson (2008)). In this model, the parameters schedule deviation late and early, monetary cost of travelling, mean car travel duration, standard deviation of car travel duration and the standard error are included. Using this model, the utility for each possible option is calculated, leading to a distribution among the departure intervals. A strength of this method is that the high level of detail in terms of the time intervals which can be chosen. On the other hand, the integrated ToD and modal split approach of the model makes it difficult to implement in an existing traffic model since an integrated departure time and transport mode choice model does not suit in most standard traffic models. Besides, the parameters are estimated for the Stockholm case study area, which has another geographical and sociodemographic character. At last, only the morning peak is analysed causing that something must be invented for the evening peak.

A.2 HADES

Another ToD method is based on Heterogeneous Arrival and Departure times based on Equilibrium Scheduling theory (HADES). This method is somewhat different compared to the other methods discussed, since this method searches for an equilibrium in multiple iterations. Of course, some of the other methods also require multiple iterations, but they do not proceed with the aim of finding a user equilibrium. When a perfect user equilibrium is achieved, no one can reduce its generalised costs by making another decision (in this context, by taking another departure time).
Although the method is somewhat different in HADES, the underlying theory again is based on a discrete choice model. The time intervals are not predefined, but the method is originally designed for small time intervals (so a microscopic model). The initial choice for a specific departure time, is based on the travel duration and a penalty when arriving before or after the preferred arrival time window. Using the method, the preferred arrival times and behavioural characteristics are needed as input and will not change after any iteration. Subsequently, the calculation of the departure times is an iterative process between a new distribution of departure times followed by a new traffic assignment. Following from the new traffic assignment, new travel durations are gained which are used as input to define new departure times.
Compared to the method discussed previously, the HADES theory is based on finding a user equilibrium. The advantage of this theory is the simplicity and understandability of the method. Besides, the time intervals can be chosen as detailed as needed. On the other hand, According to Kristoffersson & Engelson (2009), there are some disadvantages of the HADES approach. They stated: '*Future peak spreading models should be based on discrete choice methods since the EST (equilibrium scheduling theory) implementation faced problems with inconsistencies between travel time gradients at the demand and supply side, and since some of the heterogeneity in the travelling population was difficult to capture within the EST framework'.* In other words, there cannot be made a difference between different population groups (e.g. a flex-worker is more flexible of changing its departure time than a teacher). Furthermore, there are inconsistencies between travel time gradients at the demand and supply side, meaning that hardly any equilibrium can be found.

A.3 Hilderink model

A model that overcomes the problems with the difference in geographical and sociodemographic characters, is composed by Hilderink for the Netherlands (Hilderink, 2003). Except for the location where the model is composed for, it is quite similar to the model of Kristoffersson & Engelson. The period from 06:00 till 10:00 is divided in 7 intervals (per 30 minutes and one from 07:30-08:30) and the distribution between the time intervals is calculated by utility functions which include the travel time, travel distance and a penalty for arriving early or late. The parameters are estimated based on revealed preference surveys conducted in the Netherlands from 1996 till 2000. As an advantage over the previous model, the parameters are estimated for the Dutch study area. However, the disadvantage of only a model for the morning peak remains. Besides, the dataset used is quite outdated and a parameter for travel costs is missing. Therefore, this method is less reliable and easy applicable, since an additional parameter can disturb the equilibrium of the model.

A.4 LMS 7.0

Another model that is specially developed for the Netherlands, is the ToD module of the LMS 7.0. The LMS is a nationwide traffic model owned by Rijkswaterstaat, including the main road network and the bigger parts of the underlying road network. LMS 7.0 is not the latest version of the LMS, but this method is considered since the approach is quite different compared to the latest version.
In LMS 7.0, a macroscopic model is used to forecast the distribution of trips between the morning peak, evening peak and rest of the day. Again, the basis is a discrete choice model without the concept of a preferred arrival and/or departure time. In this method, one decides to either depart in the morning peak, evening peak or rest of the day based on the travel time and the travel cost of that corresponding period. For the estimation of the parameters, a survey held in 1995 is used to determine the values of the parameters. Since the valuation of travel time and travel costs is not the same for each trip purpose, different values for the parameters are estimated for different trip motives. However, there are differences in the attractiveness of the three periods since the chance on a home-work trip is much higher in the morning peak compared to the evening peak. Therefore, the base distribution between morning peak, evening peak and rest of the day is taken as input in the model.
One of the advantages of this model, is the fact that it is built for the Dutch case area. Besides, it is used for many times in a renowned model and the model is easy understandable. On the other hand, the parameter values are based on a survey of 25 years ago. Furthermore, it is a macroscopic model whereas a microscopic model is required for investigating the effects for the peak-shoulders.

A.5 Groeimodel (GM)

Since the model used in LMS 7.0 is that outdated, a revision has been made of that model. Besides a different dataset on which the parameter values are based, also the approach of the model has been changed. Whereas the ToD module in LMS 7.0 is a stand-alone model, the new version is an integrated destination, transport mode and departure time model. The ToD in the GM also is a macroscopic model (five periods; morning peak, morning peak shoulders, evening peak, evening peak shoulders and rest of the day), without the concept of a preferred arrival and/or departure time and with a discrete choice model as basis. The choice for a certain departure time, is calculated for each trip motive by lots of parameters as travel costs, travel distance and personal characteristics as income level, education level for instance. The values of these parameters are estimated based on the MON2007-2009 (MON= mobility research in the Netherlands).
Compared to the model used in LMS 7.0, the advantage is the more recent data set the parameters are based on and the more different time periods. On the other hand, the method in the GM is much more complicated, since it is integrated with the destination and transport mode choice.

Appendix B- Prove of Time of Day module

In Chapter 3.4 the ToD method used in LMS 7.0 is explained. Although the source of this model is not found in any document concerning LMS 7.0, this method is based on a theory. In this chapter, the prove is given that the method in LMS 7.0 uses the concept of a discrete choice model, and be more specific, a logit model. The formula used in LMS 7.0, is presented in B.1 (example is for the morning peak, but evening peak is similar):

$$P_{N+1}^{MP} = \frac{f_N^{MP} * e^{V_{N+1}^{MP}}}{f_N^{MP} * e^{V_{N+1}^{MP}} + f_N^{EP} * e^{V_{N+1}^{EP}} + f_N^{RoD}} \qquad (B.1)$$

Where:

P_{N+1}^{MP}= Probability for choosing alternative MP (morning peak) in iteration $N+1$
f_N^{MP}= Fraction of alternative MP in iteration N
V_{N+1}^{MP}= Utility for choosing alternative MP in iteration $N+1$
f_N^{EP}= Fraction of alternative EP (evening peak) in iteration N
V_{N+1}^{EP}= Utility for choosing alternative EP in iteration $N+1$
f_N^{RoD}= Fraction of alternative RoD (rest of day) in iteration N

For this prove, there is assumed that there are two possible choice options, to reduce the complexity of this prove; departing during rush hour or departing outside rush hour. The formula for the chance on departing during peak hours is as follows:

$$P_{N+1}^{Peak} = \frac{f_N^{Peak} * e^{v_{N+1}^{Peak}}}{f_N^{Peak} * e^{v_{N+1}^{Peak}} + f_N^{Off-peak}} \qquad (B.2)$$

Where:

P_{N+1}^{Peak}= Probability for choosing alternative 'Peak' in iteration $N+1$
f_N^{Peak}= Fraction of alternative 'Peak' in iteration N
v_{N+1}^{Peak}= Utility of choosing alternative 'Peak' in iteration $N+1$
$f_N^{Off-peak}$= Fraction of alternative 'Off-peak' in iteration N

For a general discrete choice model, probability of choosing an alternative is calculated by the following formula:

$$P_i = \frac{e^{\mu v_i}}{\sum_{j=1}^{N} e^{\mu v_j}} \qquad (B.3)$$

In this formula, P_i is the probability of choosing for alternative i, v_i is the utility of alternative i, v_j is the utility of all alternatives and μ is the perception error. When a μ of 1 is chosen, it means that the option with the maximum (systematic) utility is always chosen. When the μ goes to zero, the perception error goes to infinite indicating that the information is not useful (all alternatives have an equal utility). When μ is unknown, it is reasonable to assume a μ of 1.

Followed from Wittink (2011), there is known that formula B.3 can be rewritten as:

$$P(i)_n = \frac{e^{(\mu V_{in})}}{e^{(\mu V_{in})} + e^{(\mu V_{jn})}} = \frac{1}{1 + e^{\mu(x_{in} - x_{jn})}} \qquad (B.4)$$

Where μ is assumed to be one. Using this formula, formula B.2 can be rewritten as:

$$P_N^{Peak} = \frac{1}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)}} \qquad (B.5)$$

Furthermore, there is known that:

$$P_{N+1}^{Peak} = \frac{1}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right) + \Delta V}} \qquad (B.6)$$

Where:

ΔV= The difference in utility between iteration N and $N + 1$

And in formula:

$$\Delta V = ((\beta_{Time} * \left(TT_N^{peak} - TT_{N+1}^{peak}\right) + \beta_{cost} * \left(C_N^{peak} - C_{N+1}^{peak}\right)) - ((\beta_{Time} * \left(TT_N^{off-peak} - TT_{N+1}^{off-peak}\right) + \beta_{cost} * \left(C_N^{off-peak} - C_{N+1}^{off-peak}\right)) \qquad (B.7)$$

Dividing formula B.5 by formula B.6 gives:

$$\frac{P_N^{MP}}{P_{N+1}^{MP}} = \frac{\frac{1}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)}}}{\frac{1}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right) + \Delta V}}} = \frac{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)} * e^{\Delta V}}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)}} \qquad (B.8)$$

And rewriting gives:

$$P_{N+1}^{MP} = P_N^{MP} * \frac{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)}}{1 + e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right) + \Delta V}} \qquad (B.9)$$

Furthermore, formula B.5 can be rewritten as:

$$e^{\mu\left(v_N^{Peak} - v_N^{Off-peak}\right)} = \frac{1}{P_N^{Peak}} - 1 = \frac{1 - P_N^{Peak}}{P_N^{Peak}} = \frac{P_N^{Off-peak}}{P_N^{Peak}} \qquad (B.10)$$

Implementing formula B.10 in formula B.9, gives:

$$P_{N+1}^{Peak} = P_N^{Peak} * \frac{\left(1 + \frac{P_N^{Off-peak}}{P_N^{Peak}}\right)}{\left(1 + \frac{P_N^{Off-peak}}{P_N^{Peak}} * e^{\Delta V}\right)} \qquad (B.11)$$

Now for proving the correctness of formula B.11, an example is executed of a fictive situation in two iterations. The conditions that are used for testing are presented in Table B-1.

Table B-1 Conditions test case

	% peak	% off-peak	TT peak	TT off-peak	Costs peak	Costs off-peak
Base year	0.7	0.3	25	20	0	0
Future year	X_1	X_2	27	21	2	0
β_{Time}	-0.0358					
β_{Costs}	-0.143					

Using formula B.2 and the data of Table B-1, X_1 is calculated as follows:

$$P_{N+1}^{Peak} = \frac{0.7 * e^{-0.0358*(6-5)-0.143*(2-0)}}{0.7 * e^{-0.0358*(6-5)-0.143*(2-0)} + 0.3} = 0.6284$$

Using the same data from Table B-1 and formula B.11, X_1 is calculated as follows:

$$P_{N+1}^{Peak} = 0.7 * \frac{\left(1 + \frac{0.3}{0.7}\right)}{\left(1 + \frac{0.3}{0.7} * e^{(-0.0358*(25-27)-0.143*(0-2))-(-0.0358*(20-21)-0.143*(0-0))}\right)} = 0.6284$$

Both answers are exactly the same, what proves that the idea of the ToD module in the LMS 7.0 is based on a logit model.

Appendix C - Time of Day module LMS 7.0

In this Appendix, first an example of the calculations in the ToD module are provided. Next, the valuation of the time and costs parameters in the ToD module are presented.

C.1 Example ToD module

In the following text box, an example of a calculation in the ToD module of one single OD-pair is presented.

Consider a home-work trip with origin O and destination D
The level-of-service variables from O to D in the base year are:

MP:	Travel time = 8 min.	Travel cost = 0
EP:	Travel time = 6 min.	Travel cost = 0
RoD	Travel time = 3 min	Travel cost = 0

And the distribution between day period in the base year: 64% in MP, 5% in EP and 31% in RoD

The level-of-service variables from O to D in the future year:

MP:	Travel time = 12 min	Travel cost = fl. 3.00
EP:	Travel time = 8 min	Travel cost = fl. 2.00
RoD:	Travel time = 4 min	Travel cost = fl. 1.00

The difference between level-of-service between peak and non-peak are:

Base year:	MP: 5 min. and fl. 0.00
	EP: 3 min. and fl. 0.00
Future year:	MP: 8 min. and fl. 2.00
	EP: 4 min. and fl. 1.00

The formulas for re-calculating the share per day period are:

MP:

$$H^{MP,m} = H_{base}^{MP,m} * (\exp(\gamma^{MP,m} * (TDif^{MP,m} + \beta^{am,m} * CDif^{MP,m})) \qquad (C.1)$$

EP:

$$H^{EP,m} = H_{base}^{EP,m} * (\exp(\gamma^{EP,m} * TDif^{EP,m} + \beta^{EP,m} * CDif^{EP,m})) \qquad (C.2)$$

RoD:

$$H^{RoD,m} = H_{base}^{RoD,m} \qquad (C.3)$$

Where:

m =is the trip purpose
$H^{per,m}$= New percentage of trips in period *per* for motive *m*
$H_{base}^{per,m}$=Percentage of trips in period *per* for motive *m* for the base year
$TDif^{per,m}$= Difference in travel time in rest of the day and the travel time in period *per*, for motive *m*
$CDif^{per,m}$= Difference in travel cost in the rest of the day and the travel cost in period *per*, for motive *m*
γ, β= model parameters which represent the valuation of either travel time or travel cost, per motive *m*

Applying formulas C.1 till C.3 gives:

$$H^{MP,m} = 0.64 * exp^{-0.0358*(8-5)-0.143*(2-0)} = 0.43185$$
$$H^{EP,m} = 0.05 * exp^{-0.0358*(4-3)-0.143*(1-0)} = 0.04181$$
$$H^{RoD,m} = 0.31$$

Re-scaling of the new period choice is:

$$H^{MP,m} = \frac{0.43185}{0.43185 + 0.041818 + 0.31} * 100\% = 55.1\%$$

$$H^{EP,m} = \frac{0.04181}{0.43185 + 0.041818 + 0.31} * 100\% = 5.3\%$$

$$H^{RoD,m} = \frac{0.31}{0.43185 + 0.041818 + 0.31} * 100\% = 39.6\%$$

So, the output of this ToD-module is a new distribution between the morning peak, evening peak and rest of the day.

C.2 Valuation travel time and travel costs per trip purpose

In Table C-1, the valuations of the travel time and travel costs per trip purpose are presented. These numbers followed from the documentation of the LMS 7.0 (Hague Consulting Group, 2000). In these table, three footnotes need explanation:

1. In the LMS 7.0, the trip motives home-other and other-home are used whereas Aimsun uses the trip motive ‘other’. Therefore, the average of the home-other and other-home motives are taken for the implementation in Aimsun.
2. There is assumed that the travel costs do not influence the departure time in these trip motives, since these travel costs will be paid by the employer.
3. Average of the trip motives home-business, business-home, not-home-business and business-not-home. This is done since in Aimsun the trip purpose ‘Business’ is used.

Table C-1 Valuation of travel time and travel cost

Trip motive	Beta travel time	Beta travel cost
Other	-0.0327	-0.1365[1]
School-Home	-0.0327	-0.124
Work-Home	-0.0349	-0.155
Shopping-Home	-0.0327	-0.124
Home-School	-0.0327	-0.149
Home-Work	-0.0358	-0.143
Home-Shopping	-0.0327	-0.149
Home-Business	-0.045	0[2]
Business	-0.0455[3]	0[2]
Business-Home	-0.0440	0[2]

Appendix D- Base scenario in Aimsun

In this appendix, the process of composing the OD-matrices in Aimsun is presented. Secondly, the technical settings in the static macroscopic and dynamic mesoscopic simulation of the base scenario in Aimsun are presented. At last, the calculations of the required number of replications of the dynamic mesoscopic assignment are presented.

D.1 Composing matrices

In the following paragraphs, there is explained how the OD-matrices per different trip purpose are composed.

Internal traffic

For conducting OD-matrices for the internal traffic, the standard trip generation and distribution process in Aimsun is followed. The output of these steps are synthetic matrices per trip purpose per time period. In Figure D-1, a visualisation of the trip generation is provided. The information provided in this chapter is based on the manual made by Royal HaskoningDHV (Royal HaskoningDHV, 2019).

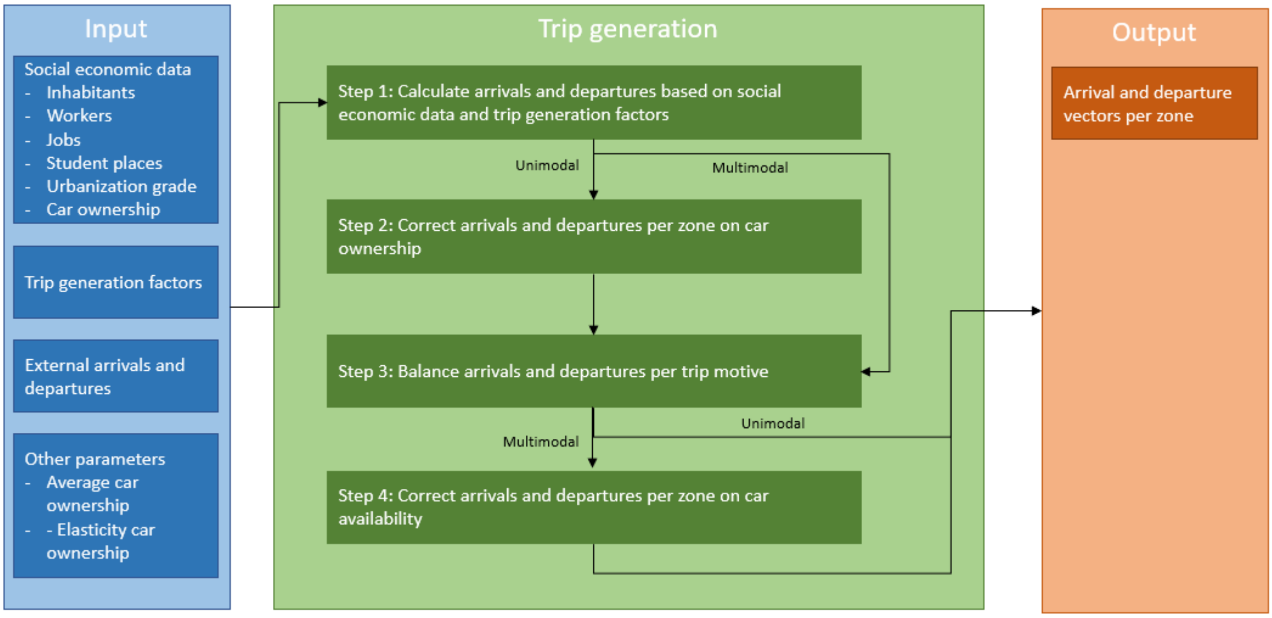

Figure D-1 Visualisation trip generation (Royal HaskoningDHV, 2019)

The input data consists of social economic data (number of jobs retail, number of jobs services, number of jobs other, number of residents, number of scholar places and number of workers), trip generation factors, external arrivals/departures and other parameters (average car ownership and elasticity car ownership). Subsequently, the trip generation is executed in four different steps:

1. Calculate the number of arrivals and departures based on the social economic data and the trip generation factors
2. Correct the number of arrivals and departures per zone based on average car ownership
3. Balance the arrivals and departures per trip motive
4. Correct the number of arrivals and departures based on car availability

Step 1

For each zone in the study area, for each trip motive and time period, the number of trips generated and produced are calculated by multiplying the trip generation factors by the social-economic data. There is a set of trip generation factors (based on OViN data) available that includes the average number of trips per travel motive, urbanization grade and time period. For example, in the morning peak, the following generation and attraction factors are used for an 'urban' area for trip purpose Home-Work:

$$\# \, trips_{gen} = Factor_{gen} * \#_{workers} \quad (D.1)$$

$$\# \, trips_{att} = Factor_{att} * \#_{jobs\ retail} + Factor_{att} * \#_{jobs\ services} + Factor_{att} * \#_{jobs\ other} \quad (D.2)$$

Step 2

In the second step, the number of trips produced and attracted per zone is corrected by the car ownership rate in that zone. In a zone where the average car ownership is higher than the average car ownership of the Netherlands, the number of trips produced increases. In formula form this is:

$$factor = 1 + elasticity_{car} * \left(\frac{Car\ ownership_{zone}}{Car\ ownership_{avg}} - 1 \right) \quad (D.3)$$

In this formula, the parameter $elasticity_{car}$ and $Car\ ownership_{avg}$ are based on data of the NRM.

Step 3

After the trip generation, the number of arrivals and departures must be the same for each trip motive. Therefore, the calculated arrivals and departures are multiplied with a balancing factor. In Aimsun, there are three balancing methods available:

1. Balancing on arrival side; arrivals remain the same and departures will be adjusted
2. Balancing on departure side; departures remain the same and arrivals will be adjusted
3. Balancing by averaging the arrival and departure side; both the arrivals and departures will be adjusted

For each zone, it is possible to indicate which balancing method must be used.

Step 4

This step is only conducted in a multimodal model. Since the model used in this research is only unimodal, this step is not executed.

Trip distribution

As an output of the trip generation, vectors are created with either the arriving or departing trips for each zone. These factors are used to build the OD-matrix per trip purpose, in which the total number of arrivals is similar to the total number of departures. In Aimsun, this process is combined with the modal split. But since only car is considered as possible transport mode, all trips are assigned to car as transport mode.

Correct internal traffic

So far, the matrices of the internal traffic per trip purpose are not calibrated. This is an essential step, since the trips estimated in a model are never exactly like the traffic count. This is also not wanted since traffic counts could also be wrong, but in general there is aimed to match the modelled values as much as possible to the traffic counts. As already said, there are already calibrated matrices per day period available which do not make a distinction between trip purposes. However, these matrices are used to build calibrated matrices per trip purpose using the following formula:

$$ODmatrix_{Kal}^{Motive} = \frac{ODmatrix_{Syn}^{Motive}}{ODmatrix_{Syn}^{Total}} * ODmatrix_{Kal}^{Total} \qquad (D.4)$$

Where:

$ODmatrix_{Kal}^{Motive}$= The calibrated matrix per trip motive
$ODmatrix_{Syn}^{Motive}$= The synthetic matrix per trip motive
$ODmatrix_{Syn}^{Total}$= The total synthetic matrix
$ODmatrix_{Kal}^{Total}$= The total calibrated matrix

In this way, the trips of the total calibrated matrix are distributed over the distribution in trip purposes. The distribution in trip purposes is OD-pair specific. The outputs of this step are calibrated matrices per trip purpose.

D.2 Distribution trip purposes through traffic

As said in Chapter 5.2, the distribution among trip purposes of the through traffic is not possible on the usual method, since nothing is known about the origin or destination centroid. Therefore, the distribution is made manually based on the distribution found of the internal trips. In Table D-1, the distribution among trips purposes of the internal trips are presented per day period. These values are used as base distribution but are adjusted based on expert judgement to the values presented in Table D-2 (e.g. it is not likely that through traffic has the trip purpose 'home-school', since home-school traffic is usually short-distance traffic whereas through traffic is long-distance traffic).

Table D-1 Distribution among trip purposes internal trips

	Morning peak	Evening peak	Rest of day
Other	19%	32%	44%
School-Work	0%	0%	0%
Work-Home	1%	42%	13%
Shopping-Home	1%	10%	9%
Home-School	1%	0%	0%
Home-Work	69%	2%	12%
Home-Shopping	3%	8%	12%
Home-Business	2%	1%	1%
Business	6%	3%	6%
Business-Home	0%	3%	1%
Total	100%	100%	100%

Table D-2 Final distributions among trip purposes through traffic

	Morning peak	Evening peak	Rest of day
Other	16%	33%	50%
School-Work	0%	0%	0%
Work-Home	1%	54%	18%
Shopping-Home	0%	1%	1%
Home-School	0%	0%	0%
Home-Work	74%	3%	17%
Home-Shopping	0%	1%	2%
Home-Business	3%	1%	2%
Business	6%	4%	8%
Business-Home	0%	3%	2%
Total	100%	100%	100%

The matrices with the through traffic are multiplied by the values presented in Table D-2 and are added to the corresponding matrices with the internal traffic.

D.3 Static macroscopic simulation

For conducting the ToD-module, the OD-matrices are composed as described in Chapter 5.2. In the iterative process of the ToD-module, static assignments are used to calculate the travel times after a new distribution is found between the morning peak, evening peak and the rest of day. In the paragraphs below, the important settings of this simulation are explained.

Road section

Each road section is different. Hence, the following settings must be implemented for each road section (there are many more, but only the important ones are discussed here):

- **Maximum speed:** This is the real maximum speed of the road section, in kilometres per hour
- **Capacity:** This is the capacity of the road section, expressed in PCU's per hour.
- **Volume delay function (VDF):** The volume delay function is used to model the generalised costs of a road section. In the base scenario, the generalised costs consist of the travel time and the travel distance. The ratio between the valuation of both parameters is $TravelTime = 0.25 * TravelDistance$. In theory, the ratio could be different for each trip purpose, but this is currently not used.

Node/turn

Just as for the road sections, each turn is different in design. Therefore, among others, the following settings must be set:

- **Turn penalty function (TPF):** Similar to the volume delay function described before.
- **Junction delay function (JDF):** The junction delay function models the generalised costs on a turn caused by conflicting turns. The costs depend on the volume of the conflicting turn and on the volume of the turn itself.

Vehicle type

Besides the settings on network level, there are also differences per vehicle type. The most important settings per vehicle type are:

- **Maximum speed:** For each vehicle time, the maximum speed needs to be determined. The maximum speed for cars on the Dutch highway is 130 kilometres per hour. However, not everyone drives this speed when it is possible. Some cars are not used to drive 130 km/h, some people do not dare to drive 130 km/h and others do not drive 130 km/h to save fuel. Therefore, the maximum speed is not a fixed value, but is a distribution between 100 km/h and 130 km/h, with a mean of 115 km/h and a deviation of 10 km/h. For trucks, the maximum speed is between 75 km/h and 95 km/h, with a mean of 90 km/h and a deviation of 10 km/h.
- **PCU:** The passenger car unit needs to be set for each vehicle type. The PCU for a car is one and for trucks it is set at 1.75.

Experiment

As final step, the traffic is assigned to the network using an experiment. The most important settings on experiment level are:

- **Type of experiment:** As first, there is chosen which type of simulation is used. The MSA method is used with the stopping criteria of either 25 iterations or a relative gap below 0.01% of successive iterations. MSA is chosen since the results of the simulation converge relatively fast in this method.
- **Traffic demand:** There must be chosen which OD-matrices are used as input for the simulation. In this traffic demand, the OD-matrix of cars is merged together with the OD-matrix of trucks for the corresponding time period.

D.4 Number of replications dynamic mesoscopic simulation

The results of a replication are quite reliable, but each replication of a mesoscopic scenario deals with some randomness. This is caused by the fact that there is a difference in how the 'best route' is experienced. Due to this randomness, the result of each replication is somewhat different. For minimizing the effects of randomness on the results, multiple replications are needed, and the average of these replications is calculated. For determining the number of replications that are needed, the base scenario evening period is simulated five times with different seeds. For each replication, the total vehicle loss hours of the complete network are used as parameter for the calculation of the number of replications since this is a way of scoring the performance of the network.

Table D-3 Total vehicle loss hours of the total network

	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Average	Variance
Vehicle loss hours (h)	29895.2	30451.4	28993.3	31241.8	30810.4	30278.4	759823.2

For calculating the required number of iterations, the data of Table D-5 is used. In Law (2014), the following formula is used for calculating the number of replications:

$$n^* \geq S_n^2 \left(\frac{t_{i-1,\frac{\alpha}{2}}}{\gamma' * X_n^{avg}} \right)^2 \qquad (D.5)$$

Where:

n^*= minimal number of iterations
S_n^2= Variance of the replication results
α= confidence level
$t_{i-1,1-\frac{\alpha}{2}}$= t-value
γ'= actual relative error, calculated by $\frac{\gamma}{1+\gamma}$. γ is the relative error.
X_n^{avg}= average of the replication results

In this case, there is chosen for a confidence level of 95% ($\alpha = 0.05$) and a relative error of 0.025. The corresponding T-value for a confidence level of 95% and 4 degrees of freedom, is 2.776. Subsequently, the number of replications is determined as:

$$n^* = 759823 * \left(\frac{2.776}{0.02439 * 30278} \right)^2 = 10.73$$

Using the vehicle loss hours of the complete network, the minimum number of replications is 11. However, since the running time of one replication is there is chosen to only conduct 6 replications to limit the required computational time. The consequence of this assumption is, that randomness could have a small influence on the results of this research.

D.5 Dynamic mesoscopic simulation

In the following paragraphs, the most important parameters for the mesoscopic simulation are explained.

Node/turn

Compared to the macroscopic simulation, the turn penalty function and the junction delay function are not used. Instead, the following settings are needed:

- **Traffic light settings (optional).** For intersections that have traffic lights in reality, settings must be made about green times for each direction-group. This is done by using COCON for calculating the cycle-time, green-times and red-times.
- **Initial cost function:** A function must be selected for the initial calculation of the shortest routes.
- **Dynamic cost function:** After calculating the initial route, the shortest route can be changed due to congestion for instance. Therefore, the new shortest route is calculated by a function. This function could be different from the function for the initial route, but in this research both functions are similar.

Road section

Additional to the capacity and the maximum speed, the following settings are required:

- **Jam density (per lane):** The density during complete congestion in vehicles per kilometre. The standard for highways is between 140 and 160 vehicles per kilometre. This parameter is used to create the correct length of the traffic jam.
- **Reaction time factor:** For each vehicle type, the reaction time is given. However, due to local differences, the reaction time for each road section could be somewhat different. The reaction time factor is used to compensate these local differences.

Vehicle type

- **Speed acceptance:** The degree of acceptance of the maximum speed. The minimum is 0.9, the maximum 1, the mean 1 and the deviation is 0.05. A value 1 indicates a perfect acceptance of the speed limit.
- **Clearance:** The distance between a vehicle and its preceding vehicle when stopped. The mean and deviation are 2.20 and 0.20 meters, with a minimum of 1.80 meters and a maximum of 2.60 meters.
- **Maximum give way time:** The maximum time someone accepts to give-way at a standstill. When this time is exceeded, one becomes more aggressive. The minimum and maximum are 15 and 25 seconds respectively, with a mean of 20 seconds and a deviation of 2 seconds.
- **Reaction time:** The time it takes for a driver to react on speed changes of the preceding vehicle. For cars the reaction time is set at 1.2 and for trucks at 1.8 seconds.
- **Reaction time for front vehicle at traffic light:** The time it takes for the front vehicle at a traffic light to react on the change to green of a traffic light. For both cars and trucks, the value is set at 2.2 seconds.

Experiment

To assign the traffic to the network, a dynamic mesoscopic scenario is simulated. In the following paragraphs, the most important settings of the experiment are explained:

- **Traffic demand:** Same as for the static macroscopic simulation, all OD-matrices are merged in one traffic demand. For both trucks and cars, the 15-minute matrices are combined in one traffic demand.
- **Path assignment:** Following from a static assignment, a path assignment is used as input for the dynamic simulation. In the path file, for each OD-pair, the most-taken routes are stored. The reason for using this file as input, is to prevent big fluctuations in the dynamic assignment results. Without a (partly) fixed path for trips, each 15-minute the shortest route is recalculated. What would happen, is that route A is most attractive in interval x, whereas route B is most attractive in interval $x + 1$ due to the congestion on route A in interval x. For interval $x + 2$, again route A would be the most attractive. This effect is not wanted and therefore a percentage of the total trips have a fixed predefined route following from a static assignment.
- **Master control plan:** A control plan of the settings of traffic lights of all intersections within the network with traffic lights. The master control plan is copied from an earlier project in Eindhoven and are composed by using COCON.
- **Look-ahead distance variability:** The variability in the distance one can look ahead. The standard setting is 80%, meaning that with a lookahead distance of 1000 meter, the real lookahead distance is between 600 and 1400 meter. This parameter is used to assure that lane-changes does not happen always on the same time.
- **Global arrivals:** For the dynamic simulation, OD-matrices are made for every 15-minute interval. In the global arrivals parameter, the spread of departing within this 15-minute interval is regulated. An exponential distribution is most realistic, but the unpredictability of this distribution makes comparing several scenarios unreliable. Therefore, the normal distribution is used for the distribution in departures.
- **Number of intervals:** For determining the route someone takes, there is calculated which route has the lowest total generalised costs. The number of intervals indicates how often the generalised costs per route are recalculated. Here, the number of intervals is set at 2, meaning that each 7,5 minute a recalculation is executed for the generalised costs per route.
- **Route choice model parameters:** For determining which routes will be taken, several parameters are used. First, there is set that 64 per cent of the total traffic, follows the routes calculated in the path-file from the static simulation. Furthermore, 16 per cent initially follows the routes from the path-file but can change route due to real-time traffic conditions. At last, 20 per cent of the total traffic is free to change route any moment, also before departing.
- **Initial K-SP Trees:** Number of shortest routes that are calculated at the beginning of the simulation. The default is set three routes per OD-pair.

Appendix E- Structure diagrams Aimsun

In this appendix, the structure diagrams for each road pricing form are presented.

E.1 Form 1

In the following paragraphs, the structure diagrams including explanation for form 1 are presented. There is started with an overall view, followed by a separate static and dynamic part.

Overall diagram

In Figure E-1, the structure of the process in Aimsun is presented. In Table E-1, the steps of Figure E-1 are explained.

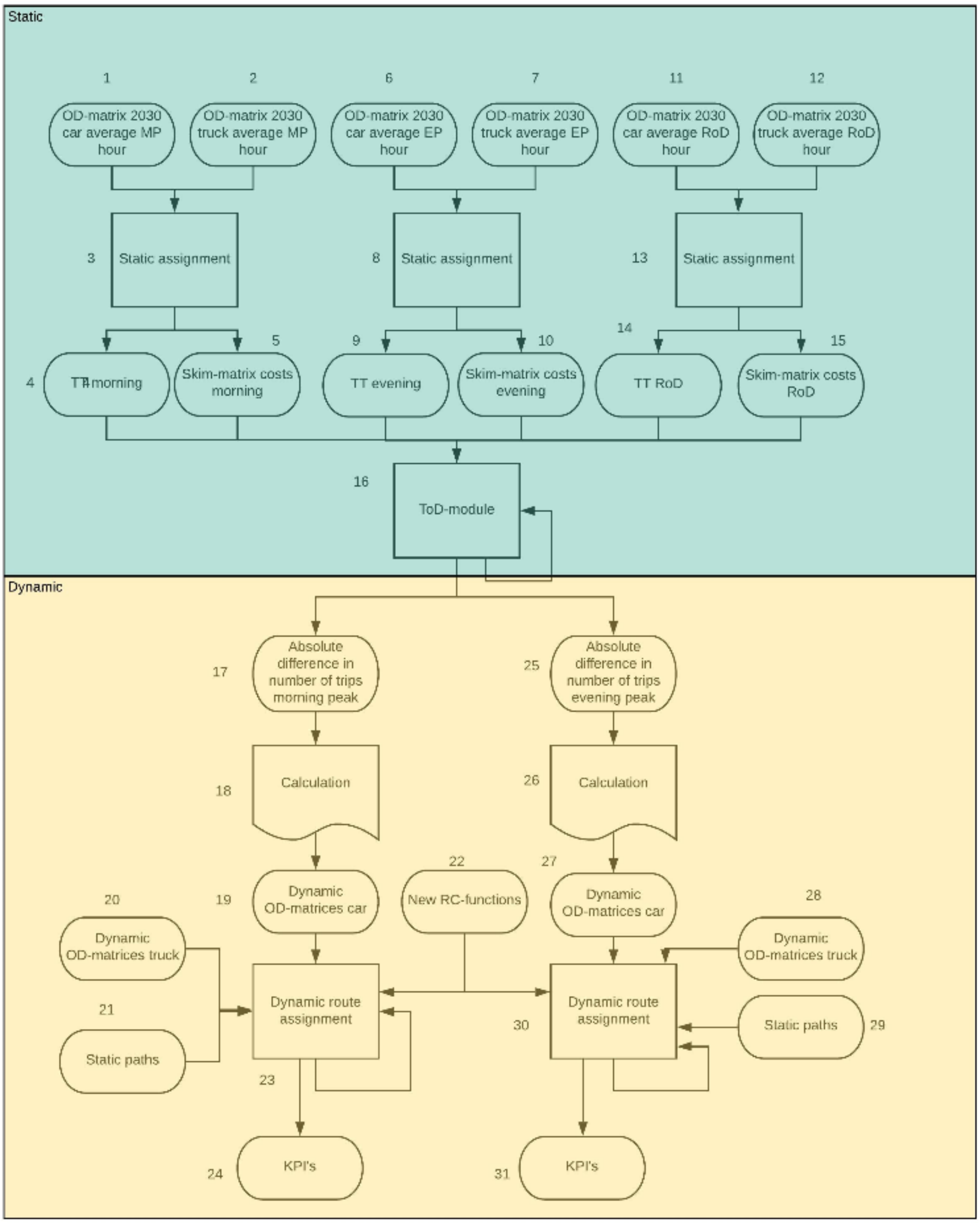

Figure E-1 Overview road pricing form 1

Table E-1 Explanation structure overall diagram Form 1

Number	Name	Explanation
1	OD-matrix car average MP hour	OD-matrix of cars of an average morning peak hour. SEG data is the basis for this matrix. The composition of this matrix is explained in Chapter 5.2
2	OD-matrix truck average MP hour	OD-matrix of trucks for an average morning peak hour. This matrix is delivered as input.
3	Static assignment	Using the OD-matrices for cars and trucks as input, the static assignment is conducted following the default settings, see Appendix E.
4	TT morning	The output of this static assignment is a skim-matrix with the travel times for each O-D pair for an average morning peak hour.
5	Skim-matrix costs morning	Matrix generated from the static assignment, in which the costs per OD-pair are presented
6	OD-matrix car average EP hour	Same principle as step 1
7	OD-matrix truck average EP hour	Same principle as step 2
8	Static assignment	Same principle as step 3
9	TT evening	Same principle as step 4
10	Skim-matrix costs evening	Same principle as step 5
11	OD-matrix car average RoD hour	Same principle as step 1
12	OD-matrix truck average RoD hour	Same principle as step 2
13	Static assignment	Same principle as step 3
14	TT RoD	Same principle as step 4
15	Skim-matrix costs RoD	
16	ToD-module	In this step, the ToD-module is executed. This is done in an iterative process
17	Absolute difference in number of trips morning peak	Output of the ToD-module, is a difference in absolute number of trips made during an average morning peak hour
18	Calculation	In this step, the new 15-minute OD-matrices will be calculated
19	Dynamic OD-matrices car	The output of the calculation of the previous step, are dynamic OD-matrices car per 15-minute interval
20	Dynamic OD-matrices truck	Dynamic OD-matrices for truck per 15-minute interval

21	Static paths	As an output of the static assignment (step 3), the static paths are used as input for the dynamic assignment. These paths contain the information about which percentage of traffic takes which route from A to B
22	New RC-functions (without costs)	To determine which percentage of the traffic takes which route, new dynamic cost functions are used. This function is described in Chapter 6.4
23	Dynamic route assignment	Using the input of the previous steps, a dynamic route assignment is conducted
24	KPIs	To grade the performance of the road pricing form, the KPIs described in Chapter 4 are used
25	Absolute difference in number of trips evening peak	Same principle as step 17
26	Calculation	Same principle as step 18
27	Dynamic OD-matrices car	Same principle as step 19
28	Dynamic OD-matrices truck	Same principle as step 20
29	Static paths	Same principle as step 21
30	Dynamic route assignment	Same principle as step 23
31	KPIs	Same principle as step 31

Static part

In Figure E-2, the steps of the static part of road pricing form are presented. In Table E-2, all these steps are explained.

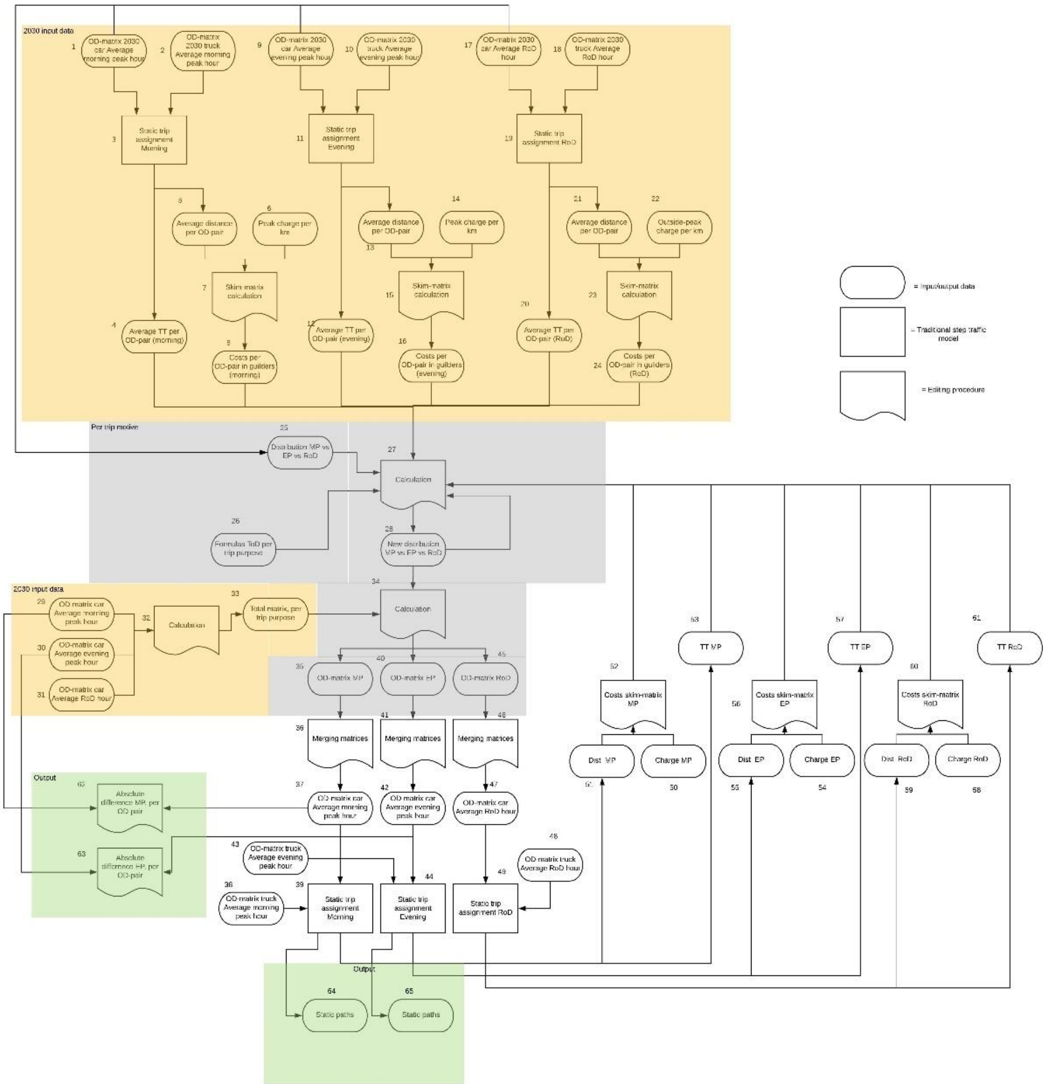

Figure E-2 Overview static part road pricing form 1

Table E-2 Explanation static part form 1

Number	Name	Explanation
1	OD-matrix 2030 car Average morning peak	Per hour
2	OD-matrix 2030 truck average morning peak	Per hour
3	Static trip assignment morning	Static trip assignment using the default settings
4	Average TT per OD-pair (morning)	Output of the static assignment is the travel time per OD-pair
5	Average distance per OD-pair	Average distance between each OD-pair
6	Peak charge per km	Charge per kilometre during the morning peak
7	Skim-matrix calculation	Calculation of the costs-skim matrix by multiplying the peak charge by the distance per OD-pair
8	Costs per OD-pair in guilders (morning)	Cost matrix for the morning peak
9	OD-matrix 2030 car average evening peak	Per hour
10	OD-matrix 2030 car average evening peak	Per hour
11	Static trip assignment evening	Same principle as step 3
12	Average TT per OD-pair (evening)	Same principle as step 4
13	Average distance per OD-pair	Same principle as step 5
14	Peak charge per km	Same principle as step 6
15	Skim matrix calculation	Same principle as step 7
16	Costs per OD-pair in guilders (evening)	Same principle as step 8
17	OD-matrix car average Rest-of-Day hour (RoD)	Per hour
18	OD-matrix truck average RoD hour	Per hour
19	Static trip assignment RoD	Same principle as step 3
20	Average TT per OD-pair (RoD)	Same principle as step 4
21	Average distance per OD-pair	Same principle as step 5
22	Outside peak charge per km	Charge per kilometre for the off-peak hour
23	Skim matrix calculation	Same principle as step 7
24	Costs per OD-pair in guilders (RoD)	Same principle as step 8
25	Distribution Morning peak (MP) vs. Evening peak (EP) vs. Rest-of-Day (RoD)	A distribution between the MP/EP/RoD will be retrieved per trip purpose. This distribution is used as base scenario
26	Formulas ToD per trip purpose	For each trip purpose, a valuation of the travel time and travel costs is known (see Appendix B)
27	Calculation	Script which calculates the new distribution between MP/EP/RoD based on the base

		distribution, formulas and average travel times
28	New distribution MP/EP/RoD	Output of the script is the new distribution MP/EP/RoD. In the following iteration, these are used as new ‘base input’
29	OD-matrix 2030 car Average morning peak hour	-
30	OD-matrix 2030 car average evening peak hour	-
31	OD-matrix 2030 car RoD hour	-
32	Calculation	Script that merges the average morning peak, evening peak and rest of day hours
33	Total matrix, per trip purpose	Output of the previous step is a matrix including an average morning peak, evening peak and rest of day hour
34	Calculation	Script in which OD-matrices with absolute numbers per day period are calculated, per trip purpose
35	OD-matrix MP	OD-matrix of an average morning peak hour, per trip purpose
36	Merging matrices	Merging all matrices with the different trip purposes to one matrix for an average morning peak hour
37	OD-matrix car average morning peak hour	New OD-matrix car of an average morning peak hour
38	OD-matrix truck average morning peak hour	-
39	Static trip assignment morning	Executing the static trip assignment including the changed VDF and TPF (see Chapter 6.1)
40	OD-matrix EP	Same principle as step 35
41	Merging matrices	Same principle as step 36
42	OD-matrix car average evening peak hour	New OD-matrix car of an average evening peak hour
43	OD-matrix truck average evening peak hour	-
44	Static trip assignment evening	Same principle as step 39
45	OD-matrix RoD	-
46	Merging matrices	Same principle as step 36
47	OD-matrix car average RoD hour	New OD-matrix car of an average RoD hour
48	OD-matrix truck average RoD hour	-
49	Static trip assignment RoD	Same principle as step 39
50	Charge MP	Charge per kilometre for the morning peak
51	Dist MP	Matrix with the distances between each OD-pair

52	Costs skim-matrix MP	Multiplying the charge with the distances per OD-pair to obtain the costs skim matrix
53	TT MP	The output of step 39is the average travel time in the morning peak. This data, is used in the new iteration in step 27
54	Charge EP	Charge per kilometre for the evening peak
55	Dist EP	Matrix with the distances between each OD-pair
56	Costs skim-matrix EP	Same principle as step 52
57	TT EP	Same principle as step 53
58	Charge RoD	Charge for a rest of day hour per kilometre
59	Dist RoD	Matrix with the distance between each OD-pair
60	Costs skim-matrix RoD	Same principle as step 52
61	TT RoD	Same principle as step 39
62	Absolute difference MP, per OD-pair	The output of this iterative process is the absolute difference in number of trips in the morning peak. This difference is calculated by comparing the total number of the base scenario by the total number of the new scenario
63	Absolute difference EP, per OD-pair	Same principle as step 62
64	Static paths	Output of the static trip assignment is the static paths data, for the morning peak
65	Static paths	See step 44

Dynamic part

In Figure E-3, the steps in the dynamic part are presented and are explained in Table E-3.

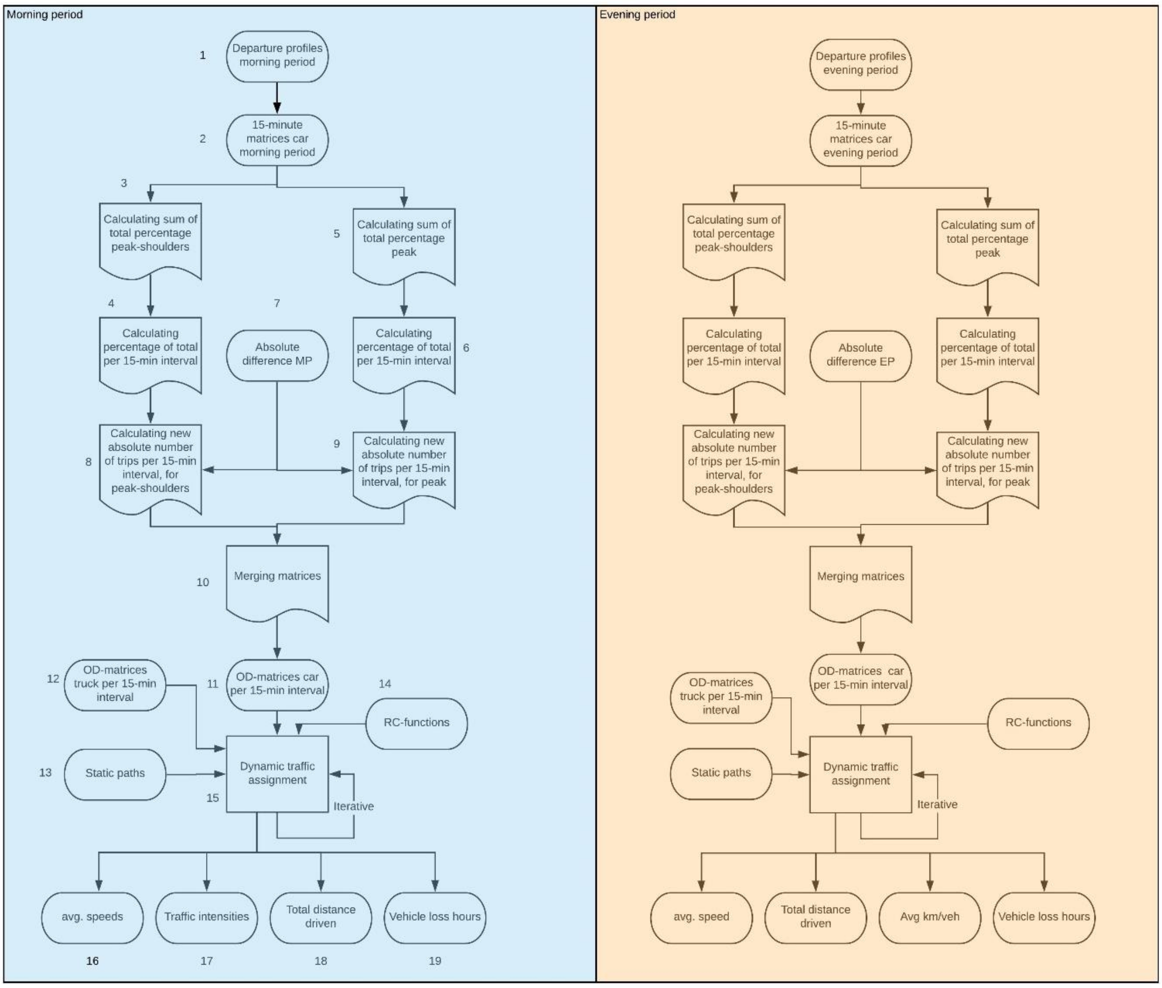

Figure E-3 Overview dynamic part road pricing form 1

Table E-3 Explanation dynamic part form 1

Number	Name	Explanation
1	Departure profiles morning period	Departure profiles as presented in Figure 5-3
2	15-minute matrices car evening period	Dynamic matrices for the car composed in the base scenario morning period
3	Calculating sum of total percentages peak-shoulders	The percentages of traffic that is assigned in each 15-minute interval in the peak-shoulders, is summed.
4	Calculating percentage of total per 15-min interval	For each 15-minute interval, there is calculated which percentage of the total traffic (of the peak-shoulders) departures within that interval

5	Calculating sum of total percentage peak	Same principle as step 3
6	Calculating percentage of total per 15-min interval	Same principle as step 4
7	Absolute difference MP	As an output of the static part, the absolute difference in number of trips in the morning peak is generated.
8	Calculating new absolute number of trips per 15-min interval, for peak-shoulders	The new absolute number of trips per 15-minute interval is calculated, for the peak shoulders
9	Calculating new absolute number of trips per 15-min interval, for peak	The new absolute number of trips per 15-minute interval is calculated, for the peak hours
10	Merging matrices	In this step, all 15-minute matrices are merged to one dynamic traffic demand
11	OD-matrices per 15-min interval	The output of the previous step is the dynamic traffic demand
12	OD-matrices truck per 15-min interval	Besides the matrices of the car, also the 15-minute interval are used as input for the dynamic traffic assignment
13	Static paths	As an output of the static assignment, the static paths are used as input for the dynamic assignment. These paths contain the information about which percentage of traffic takes which route from A to B
14	RC-functions	The new defined route-choice functions will be used
15	Dynamic traffic assignment	Using the input as described in the steps 11 up to and including 14, the dynamic traffic assignment is executed using the default settings. The dynamic assignment is executed 6 times after which the average is calculated
16	Avg. speeds	KPI to score the performance on trajectories
17	Traffic intensities	KPI to score the amount of rat running
18	Total distance driven	KPI to score the amount of rat running
19	Vehicle loss hours	KPI to grade the degree of congestion of an area

E.2 Form 2

In the following chapters, the structure diagrams of form 2 are presented. First, the overall diagram is showed, followed by a separate for the static and dynamic part. Since all steps are extensively described for form 1, only the differences between form 2 and 1 are described in this chapter

Overall diagram

In Figure E-4, the overall diagram of form 2 is presented. Compared to form 1, The only difference is that in step 22 the route choice function is used without the monetary value parameter.

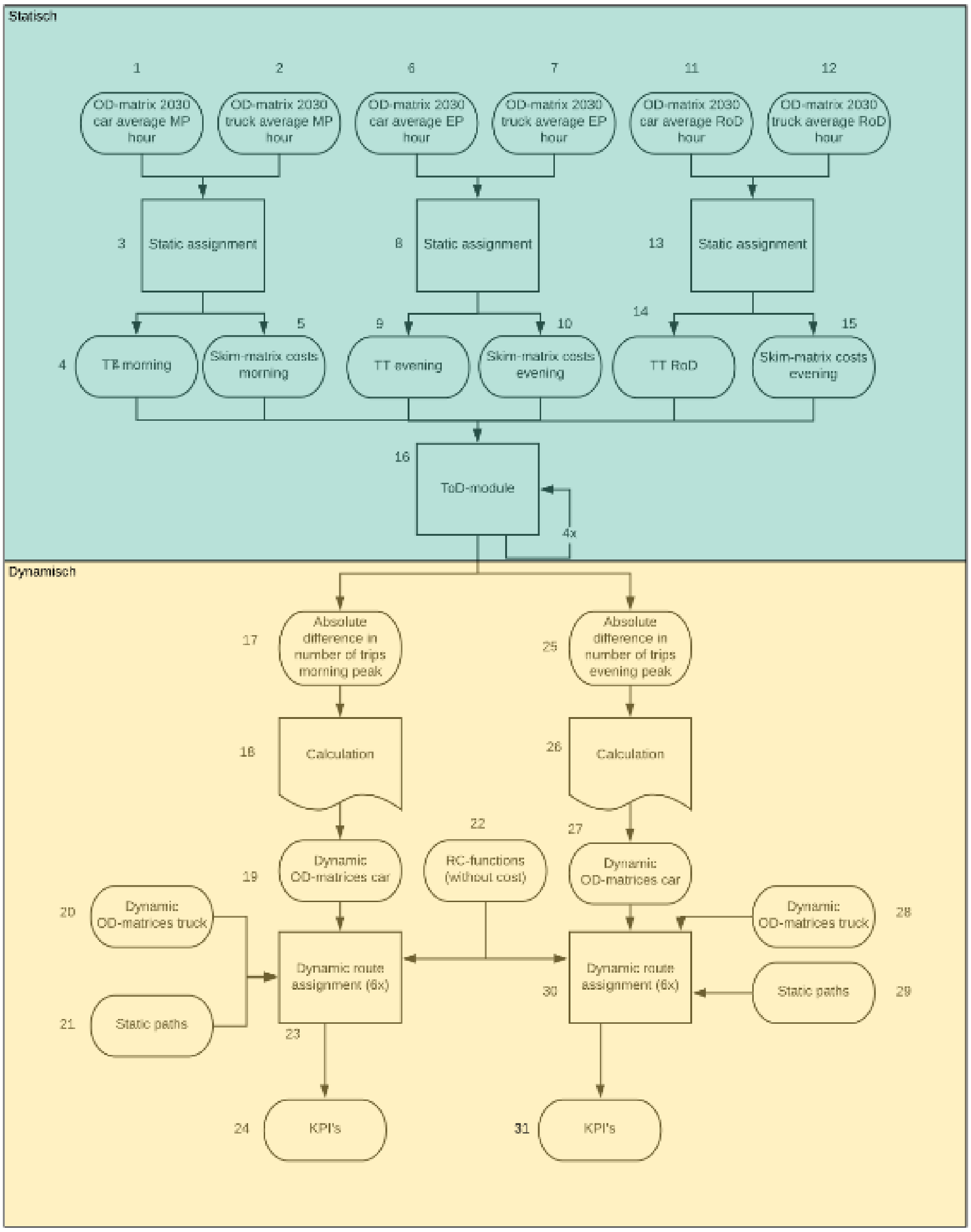

Figure E-4 Overall diagram form 2

Static part

In Figure E-5, the static part of form 2 is presented. Compared to form 1, the difference is that the travel costs are only added in the first iteration of the ToD module. This is done since the travel costs do not depend on the route that is taken.

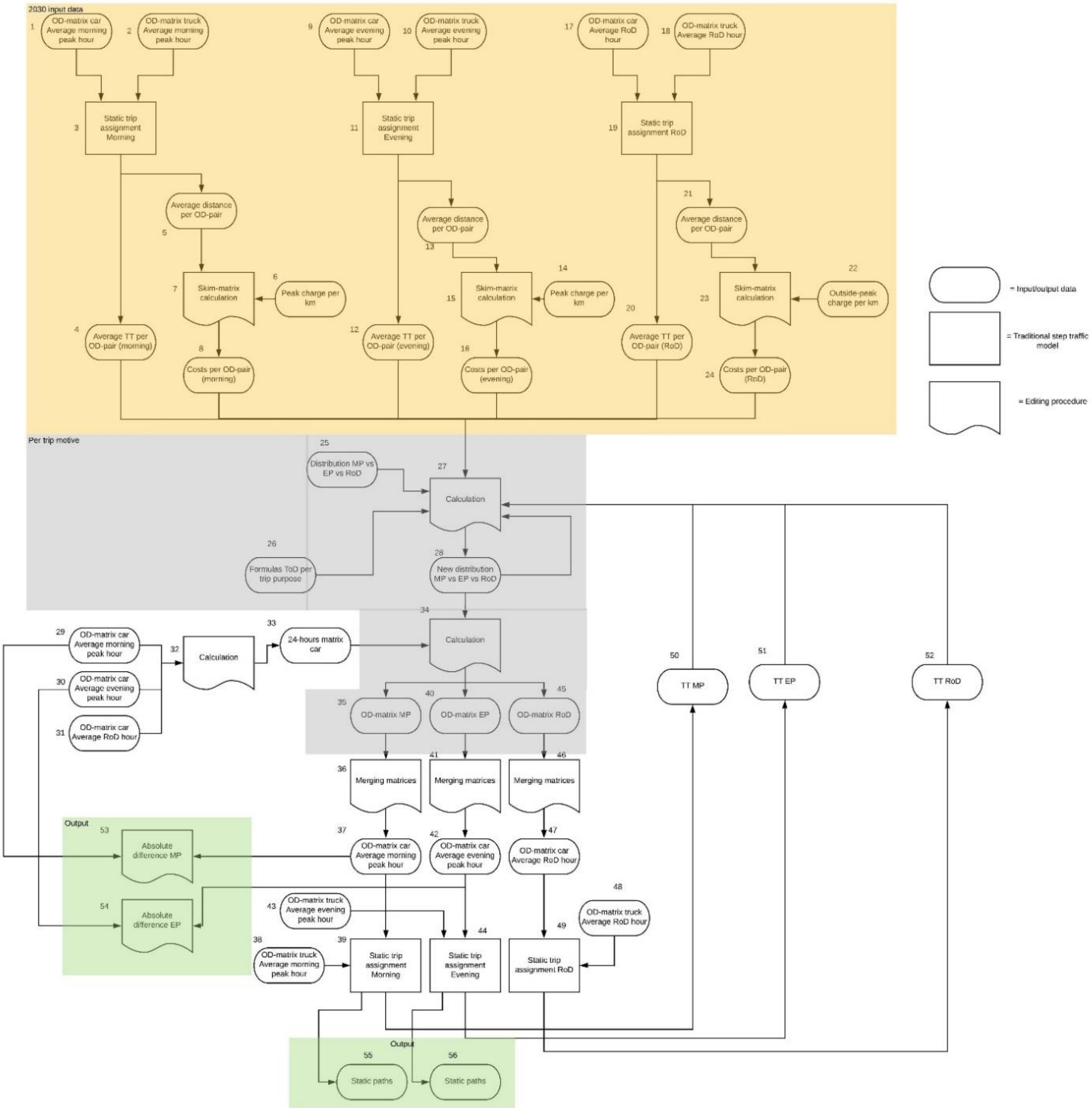

Figure E-5 Static part form 2

Dynamic part

In Figure E-6, the dynamic part of form 2 is presented. Compared to form 2, the difference is that in step 14 the route choice function without monetary costs is used.

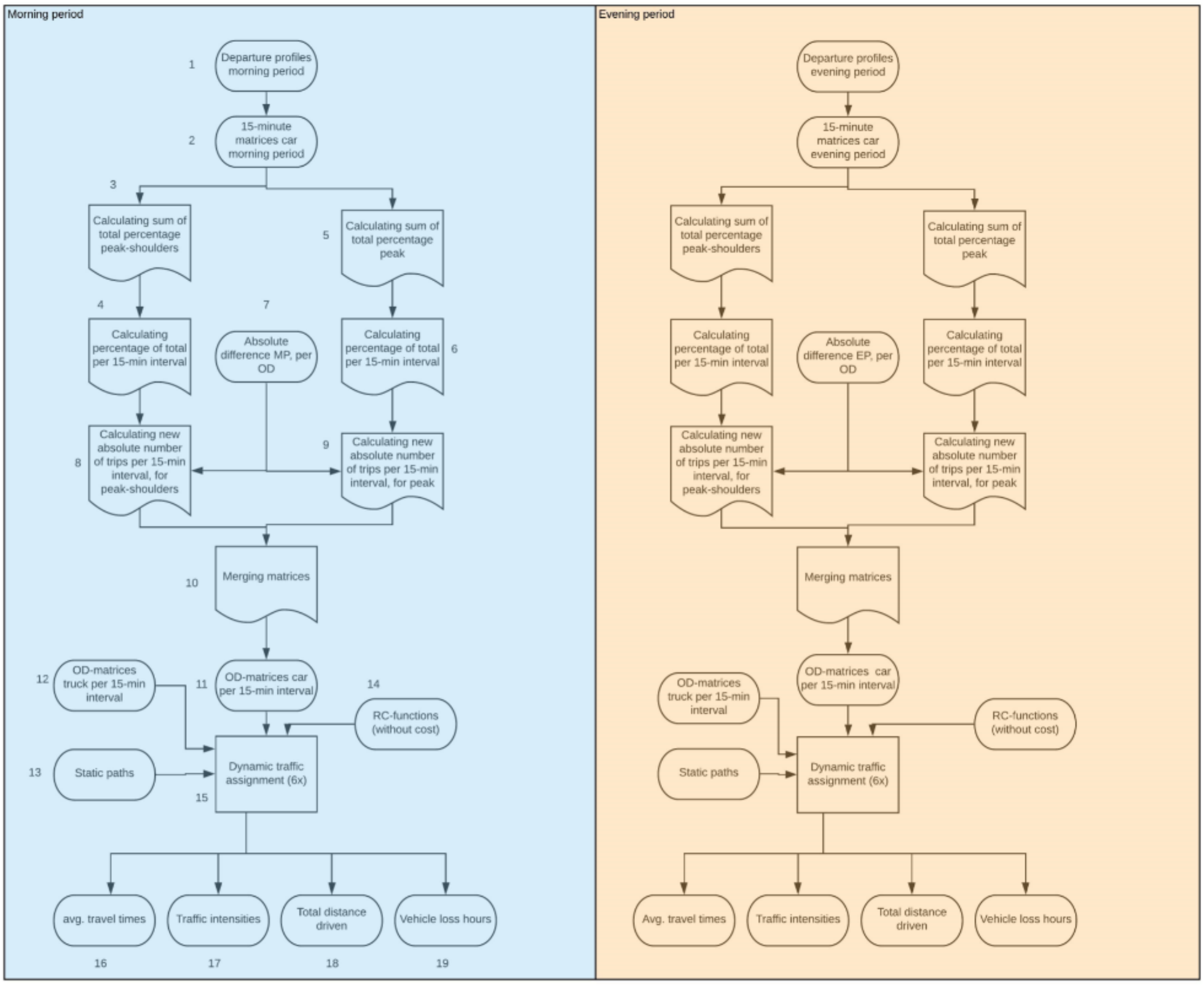

Figure E-6 Dynamic part form 2

E.3 Form 3

In this chapter, the structure diagrams of form 3 are presented. There is started with an overall diagram, followed by the static and dynamic part separately. Just as is done for form 2, only the differences with form 1 are elaborated.

Overall diagram

In Figure E-7, the overall diagram of form 3 is presented. Compared to form 1, the difference is in step 22. In form 3, the location component is included whereas this is not done in form 1.

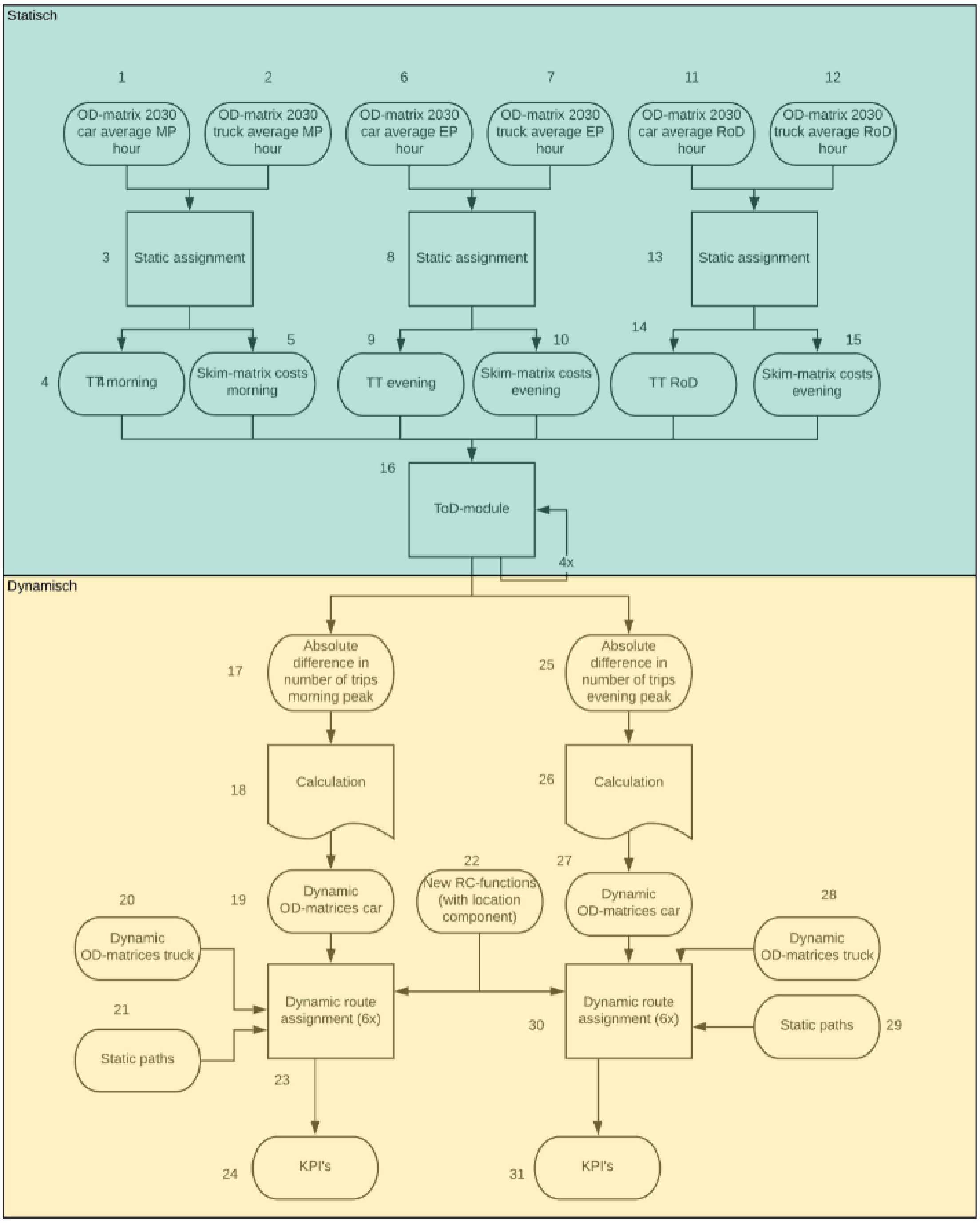

Figure E-7 Overall diagram form 3

Static part

In Figure E-8, the structure of the static part in Aimsun is presented. The only difference compared to form 1, is that in step 38 the location component is included in the static route choice function.

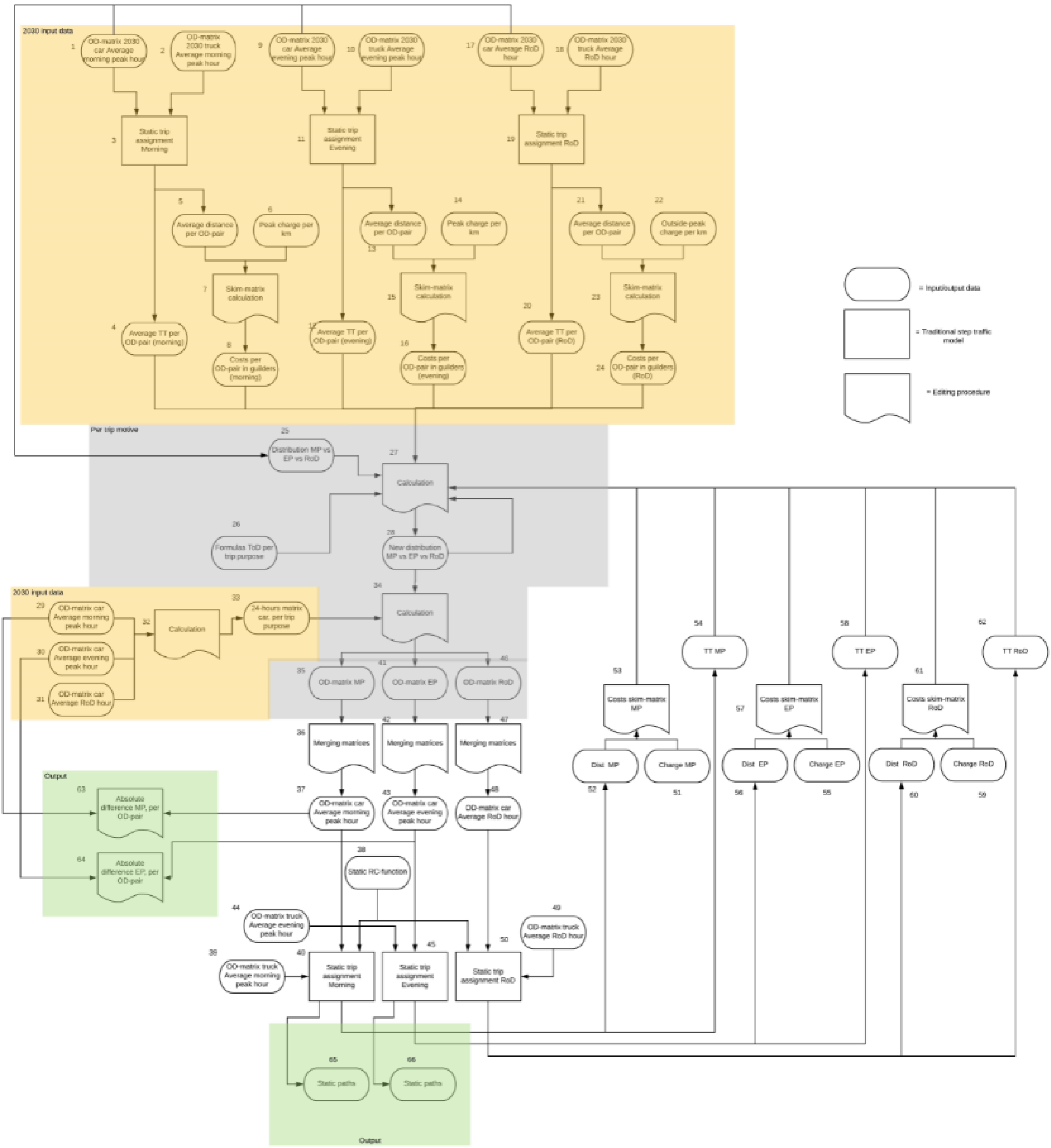

Figure E-8 Static part form 3

Dynamic part

In Figure E-9, the structure of the dynamic part in Aimsun of form 3 is presented. Compared to form 1, step 14 is included in which the location component is included in the dynamic route choice function.

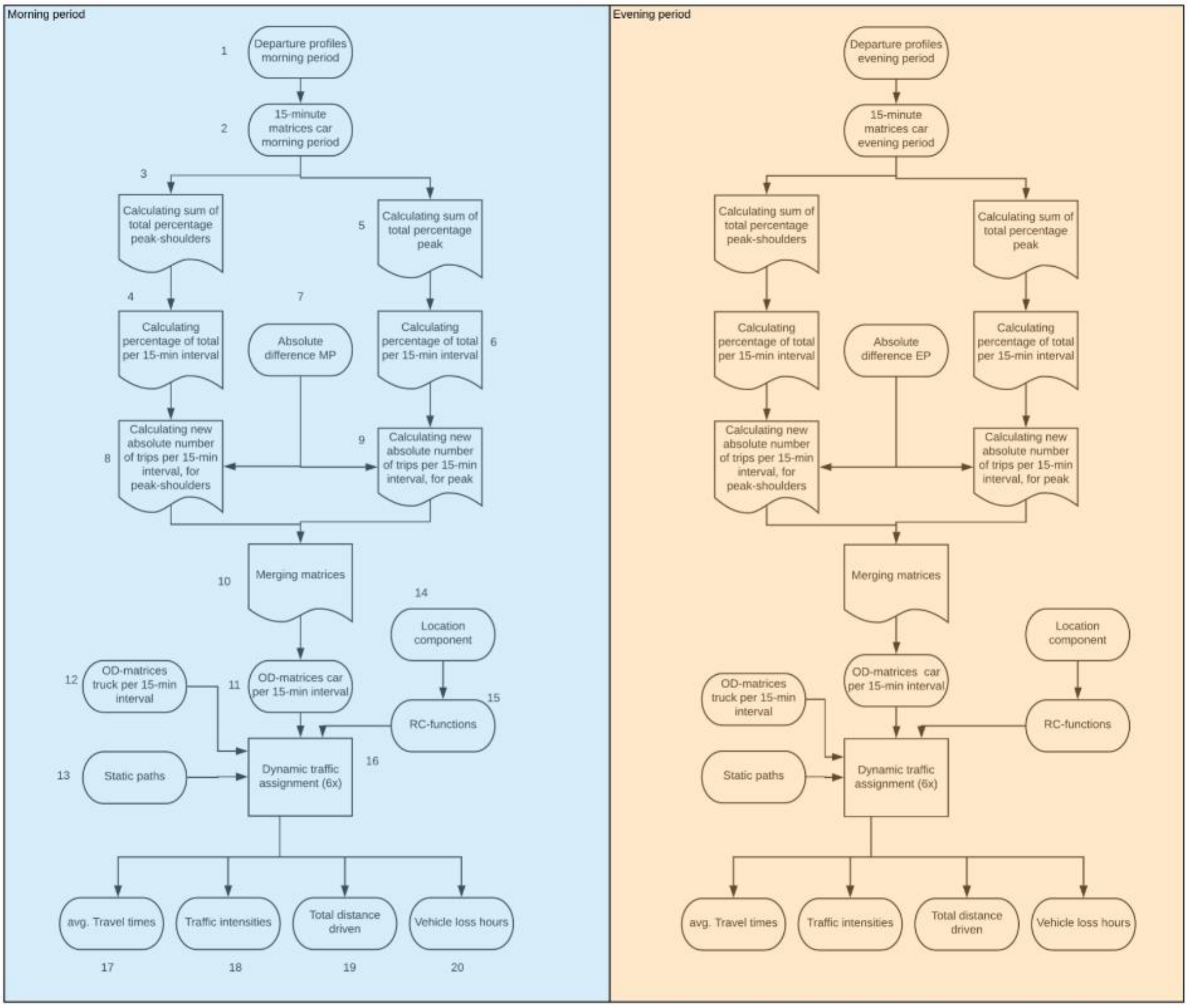

Figure E-9 Dynamic part form 3

Appendix F- Road pricing in Aimsun

In this appendix, detailed information is given for the number of iterations of the ToD module. Besides, a calculation example is given for the transition from macroscopic to mesoscopic in the road pricing forms.

F.1 Number of iterations of ToD module

The process of determining the new distributions between the morning peak, evening peak and the rest of the day is an iterative process. In the first iteration, some people will adjust its departure time from peak hours to rest of the day, to save money. In the second iteration, some people will go back to the peak periods since the travel time decreased compared to the base scenario. In theory, this process repeats until a predefined threshold has been reached. However, since the computational time of one iteration is approximately four hours, there is a limit on how many iterations can be conducted.
For testing whether the results of the ToD model converge, ten iterations of the ToD module are simulated for road pricing form 1. In Table F-1, the absolute number of trips per period per iteration are presented. The base scenario is the scenario with the OD-matrices of 2030 without road pricing. In the first iteration, the costs per driven kilometre are implemented. As one can see, this leads to a decrease of traffic in the peak periods and an increase of traffic in the rest of the day.

Table F-1 Number of trips per period per iteration

	Morning peak	Evening peak	Rest of day
Base scenario	151242	182115	115927
Iteration 1	147638	177617	124029
Iteration 2	147746	177804	123735
Iteration 3	147712	177817	123756
Iteration 4	147738	177780	123758
Iteration 5	147734	177808	123743
Iteration 6	147738	177788	123758
Iteration 7	147735	177808	123742
Iteration 8	147718	177797	123770
Iteration 9	147733	177808	123743
Iteration 10	147739	177788	123758

For providing a better overview of the differences per iteration, Table F-2 presents the absolute differences of two successive iterations. In other words, In the row 'Iteration 1' the differences in total demand between the base scenario (without road pricing) and iteration 1 (with road pricing) are presented. Following from the two tables, there can be concluded that the differences of two successive iterations are minor after iteration 3.

Table F-2 Absolute differences of successive iterations road pricing form 1

	Morning peak	Evening peak	Rest of day
Iteration 1	-3604	-4498	8102
Iteration 2	108	186	-294
Iteration 3	-35	13	21
Iteration 4	27	-37	2
Iteration 5	-5	28	-16
Iteration 6	5	-20	16
Iteration 7	-4	20	-16
Iteration 8	-17	-11	28
Iteration 9	16	11	-27
Iteration 10	6	-21	15

Following the data in Table F-2, it does not seem to have any added value to execute more than three iterations. For minimising the effect of any unforeseen results in other road pricing forms, there is chosen to execute four iterations of the ToD module for the road pricing forms.

F.2 Macroscopic to mesoscopic

In this appendix, a calculation example is given of how traffic is redistributed over the 15-minute intervals following from the outcomes of the ToD module. For example, following from the ToD module there are 50 trips less after implementing any form of road pricing. These trips are proportionally removed from the hours 07:00-09:00. See Table F-3 for an example.

Table F-3 Calculation example removing traffic morning peak hours

	Number of trips	Percentage of trips	Δ trips	New # trips
07:00-07:15	24.5	0.122	-6.1	18.4
07:15-07:30	26.9	0.134	-6.7	20.2
07:30-07:45	28	0.140	-7.0	21.0
07:45-08:00	27.8	0.139	-6.9	20.9
08:00-08:15	26.4	0.132	-6.6	19.8
08:15-08:30	24.4	0.122	-6.1	18.3
08:30-08:45	22.1	0.110	-5.5	16.6
08:45-09:00	20	0.100	-5.0	15.0
Total	200	1	-50	150
Δ#trips	-50			

For instance, in the quarter 07:00-07:15 depart 24.5 trips in the scenario without road pricing, what is 12,2% of the total trips in this morning peak. Following this percentage, there is found that 6,1 (0,122*50=6,1) less trips depart within this quarter due to the implementation of road pricing. The new number of trips departing in this quarter, becomes 18.4.
Subsequently, the similar approach is used to redistribute 50 trips over the peak shoulders. See Table F-4 for the calculation example. The principle is the same as described above, except for the fact that traffic is added instead of removed.

Table F-4 Calculation example adding traffic to peak shoulders

	Number of trips	Percentage of trips	Δ trips	New # trips
06:00-06:15	6.4	0.060	3.0	9.4
06:15-06:30	8.6	0.081	4.0	12.6
06:30-06:45	11.5	0.108	5.4	16.9
06:45-07:00	15.2	0.143	7.1	22.3
09:00-09:15	19.9	0.187	9.3	29.2
09:15-09:30	17	0.160	8.0	25.0
09:30-09:45	14.6	0.137	6.9	21.5
09:45-10:00	13.3	0.125	6.2	19.5
Total	106.5	1	50	156.5
Δ#trips	50			