
COMMUTING BY MOTORCYCLE: IMPACT ANALYSIS

Final report commissioned by:

Febiac vzw

Woluwedal 46, box 6

1200 BRUSSELS

21 September 2011



TRANSPORT & MOBILITY LEUVEN

DIESTSESTEENWEG 57

3010 KESSEL-LO (LEUVEN)

BELGIUM

+32 (16) 31.77.30

<http://www.tmlleuven.be>

Report number:

10.69

Author:

I. Yperman (TML)

Contents

CONTENTS	3
TABLES.....	4
ILLUSTRATIONS.....	5
1 INTRODUCTION.....	6
2 EFFECT ON TRAFFIC FLOW AND CONGESTION	7
2.1 LEUVEN-BRUSSELS CASE STUDY	7
2.1.1 <i>Reference scenario</i>	8
2.1.2 <i>Modal shift scenario</i>	19
2.1.3 <i>Effect of modal shift on traffic flow</i>	27
2.2 OVERALL EFFECT ON THE ROAD NETWORK	29
2.2.1 <i>Case study: modal shift scenario including knock-on effect</i>	30
2.2.2 <i>Lost vehicle hours and time benefits on the entire network of primary roads</i>	32
2.3 OVERALL EFFECT ON THE SECONDARY ROAD NETWORK	32
3 EFFECT ON EMISSIONS.....	34
3.1 EMISSIONS FROM MOTORCYCLES AND CARS	34
3.1.1 <i>Emission factors</i>	34
3.1.2 <i>External emission costs</i>	37
3.2 LEUVEN-BRUSSELS CASE STUDY: EMISSION COSTS.....	39
4 CONCLUSIONS	43
4.1 EFFECT ON TRAFFIC FLOW AND CONGESTION	43
4.1.1 <i>Leuven-Brussels case study</i>	43
4.1.2 <i>Overall effect on the primary road network</i>	43
4.1.3 <i>Overall effect on the secondary road network</i>	44
4.2 IMPACT ON EMISSIONS.....	44
REFERENCES	45
APPENDIX A: DESCRIPTION OF THE LINK TRANSMISSION MODEL	47

Tables

Tabel 1: Value in 2010 in terms of €/kg (CO2 in €/ton), euro at 2009 value (source: De Nocker et al. (2010))

38

Illustrations

Figure 1: The area of the case study between Leuven and Brussels	7
Figure 2: Sites in the study area where remote data is collected	8
Figure 3: Traffic intensities and speeds in Sterrebeek travelling towards Brussels on Tuesday 18 May 2010.	9
Figure 4: R0 Zaventem observation points in an intensity-speed diagram	11
Figure 5: R0 Zaventem observation points in a density-intensity diagram	11
Figure 6: traffic intensities on the main carriageway in Sterrebeek in the direction of Brussels (measured and simulated)	12
Figure 7: traffic speeds on the main carriageway in Sterrebeek in the direction of Brussels (measured and simulated)	13
Figure 8: Queue propagation in the morning rush hour in the reference scenario	17
Figure 9: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario	18
Figure 10: PCE value of the motorcycle in relation to traffic density	20
Figure 11: Queue propagation in the morning rush hour in the modal shift scenario	25
Figure 12: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the modal shift scenario	26
Figure 13: Travel time on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario and in the modal shift scenario	28
Figure 14: Travel time on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario and in the scenarios with modal shift	29
Figure 15: Travel time on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the modal shift scenario including knock-on effects and in the other scenarios reviewed	31
Figure 16: Emission factors for motorcycles and cars on motorways as a function of average speed	36
Figure 17: Emission factors of the different pollutants for motorcycles and cars	37
Figure 18: External emission costs for motorcycles and cars on motorways as a function of average speed	38
Figure 19: External emission costs of the different pollutants for motorcycles and cars	39
Figure 20: External emission costs for all vehicle categories on motorways as a function of average speed	40
Figure 21: Total emission costs by Vehicle category for the Leuven-Brussels journey during the morning rush hour	41
Figure 22: Total emission costs per pollutant for the Leuven-Brussels journey in the morning rush hour	42

1 Introduction

Reducing traffic congestion and improving air quality in relation to road traffic represent important challenges for our mobility.

In this study, we investigate whether commuting by motorcycle can make a contribution in this context. We examine whether achieving a modal shift from cars to motorcycles has an effect on traffic flow and congestion. Furthermore, we look at the impact such a modal shift would have on vehicle emissions and air quality.

The report is structured as follows: Chapter 2 considers the effect on traffic flow and congestion of a modal shift of commuters from cars to motorcycles. The effect on emissions is examined in Chapter 3. Finally, in Chapter 4 we formulate the main conclusions.

2 Impact on traffic flow and congestion

In this Chapter we study the effect on traffic flow of a modal shift in commuter traffic from cars to motorcycles. Because motorcycles take up less physical space on the road, a smoother flow of traffic can be expected when more commuters leave their cars at home and travel to work by motorcycle.

The impact on traffic flow is examined using by a case study in which the traffic on the motorway route between Leuven and Brussels is accurately simulated (see Section 2.1), first in a reference scenario and then in a scenario in which there is a modal shift from cars to motorcycles. In Section 2.2 we look at the effect of a modal shift on the overall road network in Belgium. Finally, Section 2.3 considers the overall impact on the secondary road network.

2.1 *Leuven-Brussels case study*

As a case study we consider the traffic flow on the motorway route between Leuven and Brussels during a typical morning rush hour. Figure 1 is a map of the area covered by the case study: the E40 motorway between Leuven and Brussels, from the intersection in the east between the E314 and the E40 (in Leuven), to the intersection in the west of the E40 and the R0 Brussels orbital motorway (in Sint-Stevens-Woluwe/Woluwe Saint Etienne).

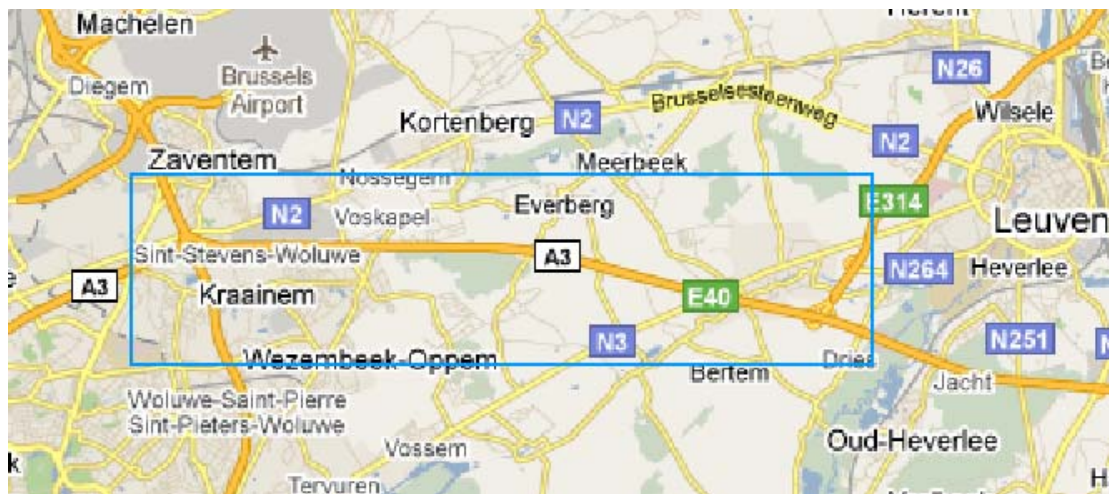


Figure 1: The area of the case study between Leuven and Brussels

As a first step we construct the reference scenario, in which we analyse the traffic flow under existing conditions (Section 2.1.1). Next we consider a scenario in which there is a modal shift from cars to motorcycles (Section 2.1.2). By comparing both scenarios we can determine the effect of the modal shift on traffic flow (Section 2.1.3).

2.1.1 Reference scenario

The reference scenario shows the traffic flow under existing conditions. Using a traffic model, realistic simulations are made of the traffic flows in the area of the study.

2.1.1.1 Traffic model

The traffic model that we use is the Link Transmission Model (LTM) that was developed at KULeuven (Yperman (2007)). LTM simulates traffic flows in networks in a realistic manner. It is a dynamic model that shows the evolution of the traffic situation in arbitrary time intervals (e.g. 5 minutes). The process of the build-up and dispersal of queues is modelled in detail. This state-of-the-art model lends itself perfectly to the simulation of queues and the propagation of queues in large road networks. A detailed description of the model and how it works is included as Appendix A.

Data is entered into the traffic model in respect of traffic demand and a traffic network. After this has been entered, the model calculates how the traffic flows propagate in the traffic network. As output we get a graphic representation of traffic intensities, speeds and densities on the different parts of the network over the course of time. The origin and proliferation of queues is visualised in a film. Travel times over the course of the time period under review are the model's output.

2.1.1.2 Traffic demand

Traffic demand has to be defined and input into the model. For the case study under consideration the traffic demand can be derived from traffic censuses made available by the Flemish Traffic Centre.

We can use traffic censuses at 7 locations in the study area, where data is continuously collected remotely by means of sensors located in the road network. These data collection sites are located at the entrances and exits at the Leuven complex (E314), Haasrode (E40), Bertem (E40), Sterrebeek (E40), Kraainem (E40), Wezembeek-Oppeem (R0) and Zaventem (R0).

Figure 2 shows an overview of these 7 sites at which remote data is collected:



Figure 2: Sites in the study area where remote data is collected

6 sensors have been installed at each location: at the entrance, exit, main carriageway between the entrance and exit, and each of these in both directions.

The remote data at these locations was made available by the Flemish Traffic Centre for the entire month of May 2011, at time intervals of 5 minutes. Bertem was the only site at which no data was available for the period of May 2011. Data for this location, is therefore taken from the month of May 2010.

The morning rush hour of Thursday 12 May 2011 was selected in order to come up with a 'typical morning rush hour'. The total traffic volume in the morning rush hour was equal to the median of the traffic volumes in the morning rush hour of all working days in May 2011. The morning rush hour of 12 May 2011 is assumed to be representative of a typical morning rush hour. In Bertem and Sterrebeek the data of Tuesday 18 May 2010 were used to represent a typical morning rush hour. Traffic volumes in the morning rush hour in Sterrebeek on this day are virtually identical to those of Thursday 12 May 2011.

Figure 3 shows an example of the measured intensities and speeds in Sterrebeek on the main carriageway towards Brussels on Tuesday 18 May 2010. The blue curve shows the traffic intensity (Car equivalents/5min) over the course of the day, the red curve shows the speed of the traffic flow (km/h).

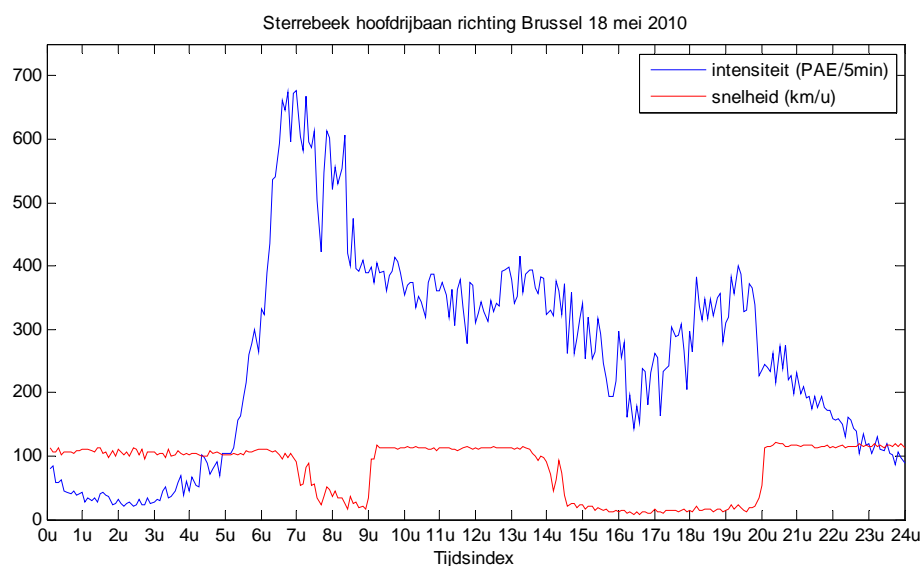


Figure 3: Traffic intensities and speeds in Sterrebeek travelling towards Brussels on Tuesday 18 May 2010.

There is a strong increase in traffic intensity between 5 a.m. and 7 a.m. A queue forms at around 6.45 that is characterised by the slower speed of the traffic flow. The queue continues until approximately 9 a.m. From here on we will consider the period from 6.30 a.m. to 9.30 a.m. as the morning rush hour period.

Note that an incident occurred on 18 May 2010 at around 2 p.m. Low intensities and very slow speeds are observed until approximately 8 p.m. On a ‘normal’ day at Sterrebeek there is no structural queue after midday in the direction of Brussels.

Based on the traffic censuses of 12 May 2011 and 18 May 2010, source-destination matrices were prepared at the different locations for each time interval of 5 minutes between 6.30 a.m. and 9.30 a.m. These matrices show for each time interval the number of trips made between the different sources and destinations. The traffic demand was entered in the traffic model in the form of source-destination matrices. These matrices were prepared by applying one of the Source-Destination estimating methodologies developed at KULeuven (Frederix et al. (2010)).

The traffic censuses also contain information about the composition of the traffic flows. On average, for the morning rush hour in the area of the study, we noted that:

- 83.4% of vehicles were shorter than 4.9m (cars and motorcycles)
- 7.5% of vehicles were between 4.9m and 6.9m in length (vans)
- 9.1% of vehicles were longer than 6.9m (trucks and buses)

The first category can be sub-divided into cars and motorcycles in proportion to the vehicle kilometres travelled on the Belgian motorway network of both vehicle categories. For this we rely on the traffic censuses carried out by the Federal Planning Bureau (Federaal Planbureau (2009)). This then results in the following traffic mix:

- 0.9% motorcycles
- 82.5% cars (< 4.9m)
- 7.5% vans (4.9m to 6.9m)
- 9.1% trucks and buses (> 6.9m)

2.1.1.3 Traffic network

Apart from the traffic demand, a traffic network also has to be constructed and entered. For this, the study area was divided into road sections of approximately 1 km in length. A maximum speed, capacity (or maximum intensity) and a maximum density are defined for each road section. Where possible, we derive these quantities from the traffic censuses.

We illustrate this with the road section that corresponds with the main carriageway on the outer ring R0 at Zaventem.

In Figure 4 all observations (traffic censuses) from the month of May 2011 on the outer ring R0 in Zaventem are plotted as a scatter diagram. Each point is an observation (intensity and average speed) in a time interval of 5 minutes.

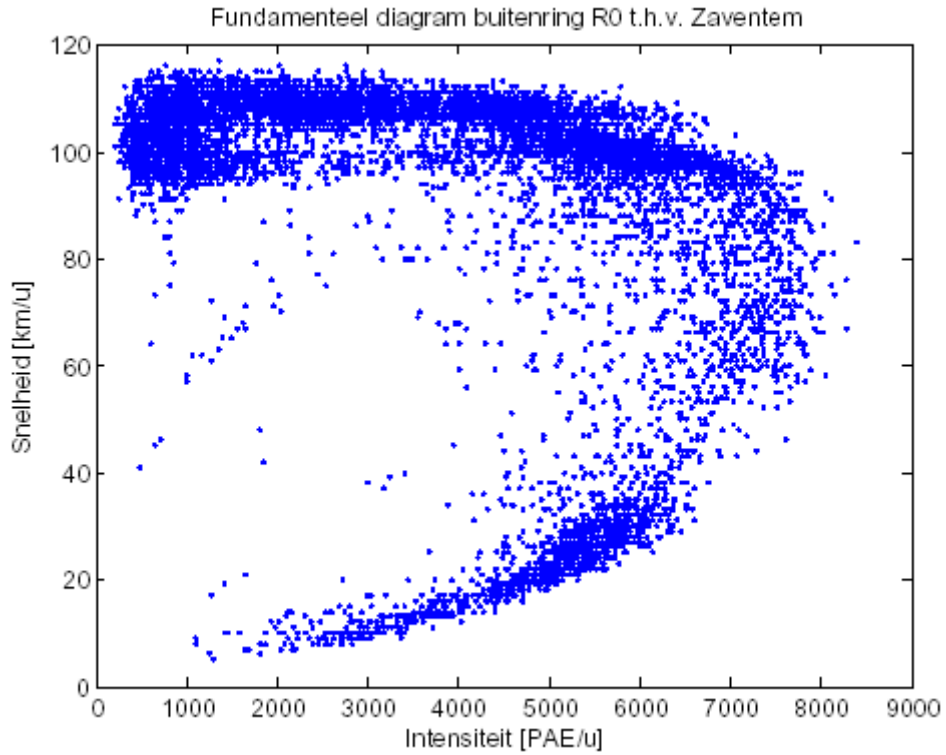


Figure 4: R0 Zaventem observation points in an intensity-speed diagram

The traffic density is calculated as the quotient of the intensity and the average speed. Figure 5 places the observation points in a density-intensity diagram.

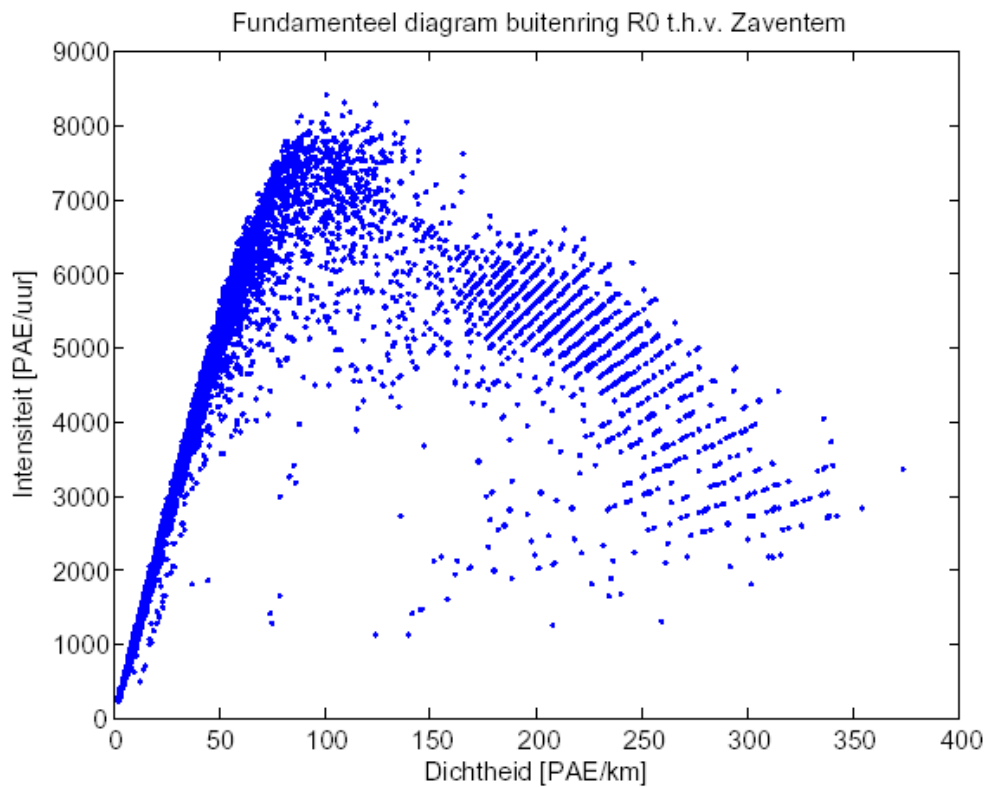


Figure 5: R0 Zaventem observation points in a density-intensity diagram

From these observations we can deduce the following values that are allocated to the road section in question on the R0 outer ring in Zaventem:

- maximum speed = 120 km/h
- capacity = maximum intensity = 8000 vehicles/hour
- maximum density = 400 vehicles/km

The maximum speed, capacity and maximum density of the other links in the traffic network are determined in an analogous manner.

2.1.1.4 Results

After inputting the traffic demand and the traffic network, the traffic model can start to be calculated. For each road section the traffic model calculates traffic intensities, densities and speeds for each time interval of 5 minutes. This is how the traffic flows were simulated in the area of the study on 12 May 2011 between 6.30 a.m. and 9.30 a.m.

Following the simulation, the resulting intensities and speeds are checked to see whether they correspond to the data collected remotely. The simulation results correspond well with the remote data at all locations and time intervals. Figure 6 and Figure 7 illustrate the simulated and measured intensities and speeds in Sterrebeek.

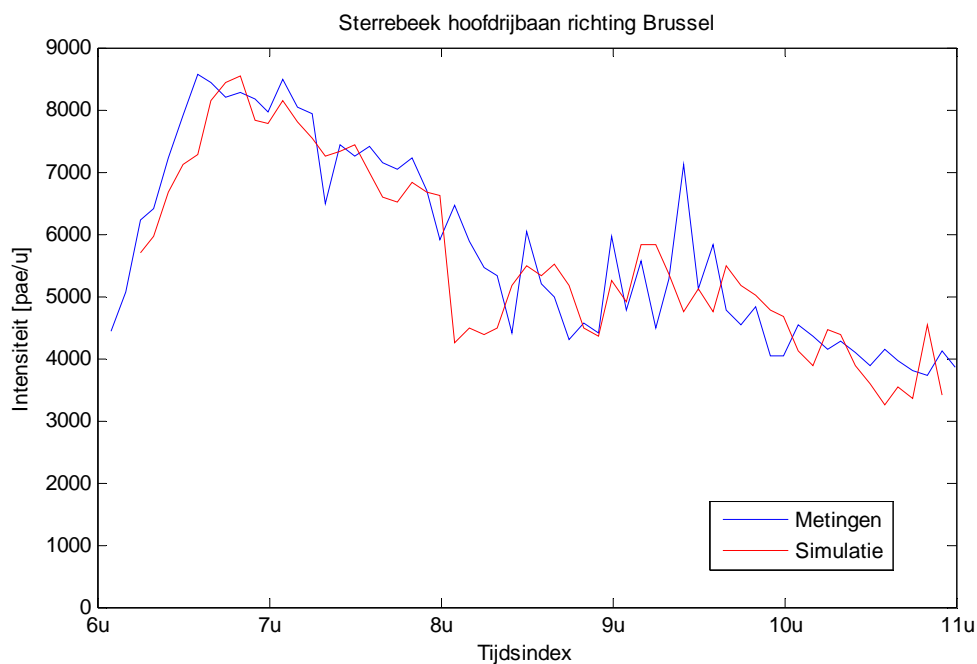


Figure 6: Traffic intensities on the main carriageway in Sterrebeek in the direction of Brussels (measured and simulated)

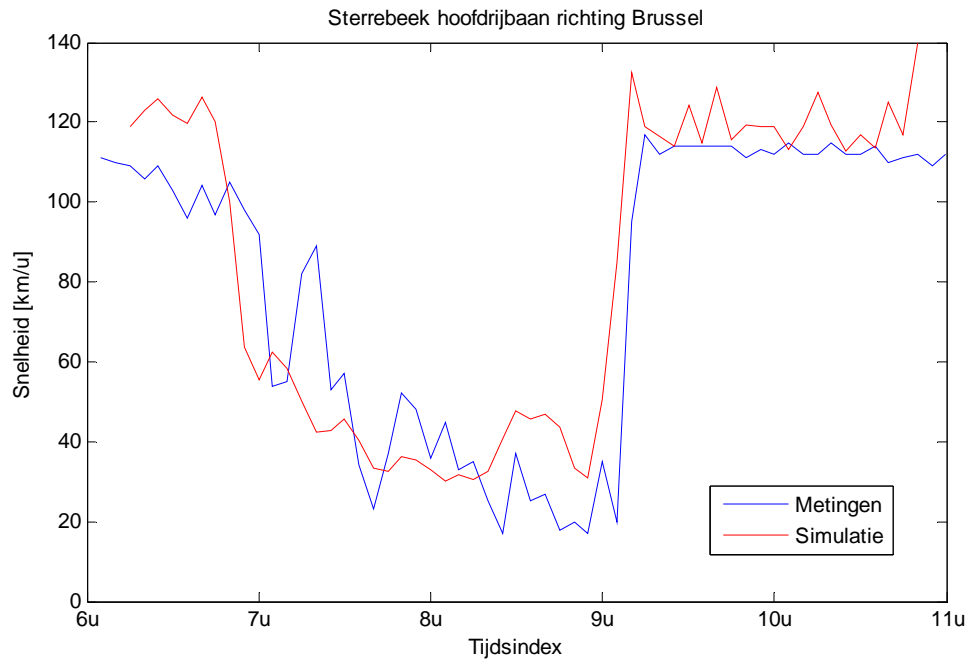
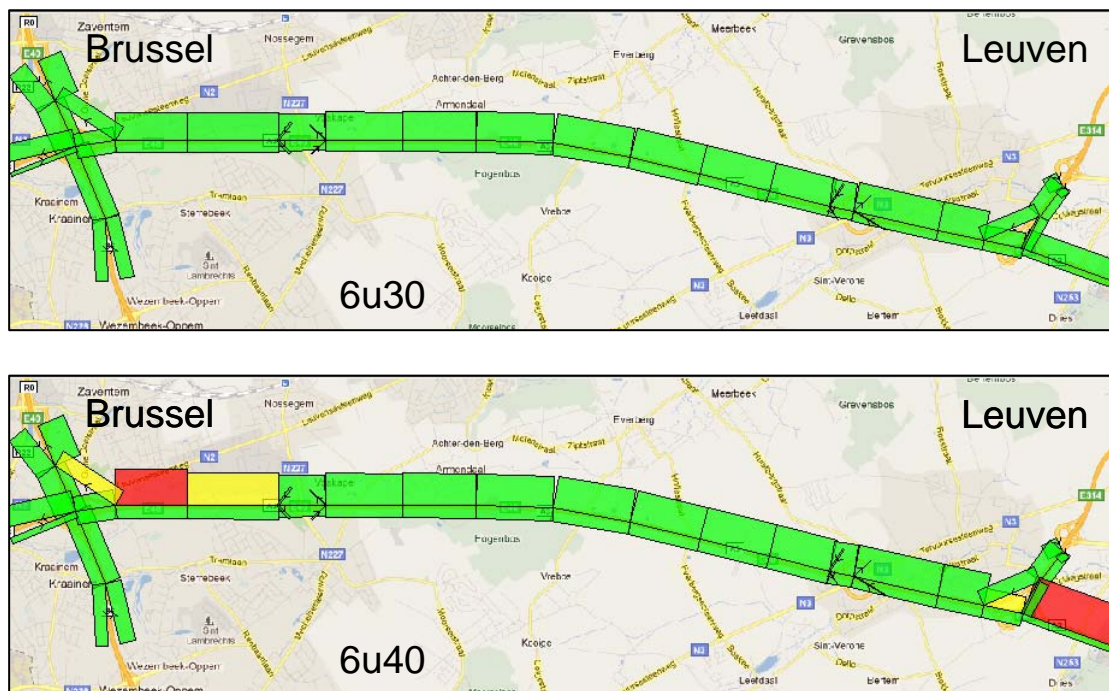
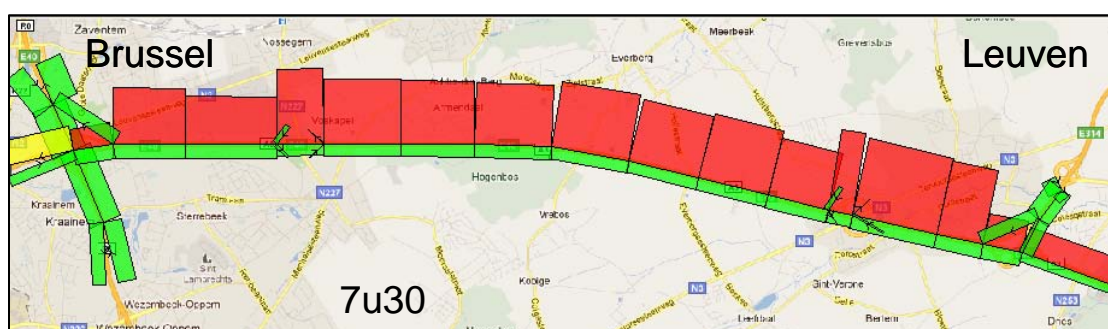
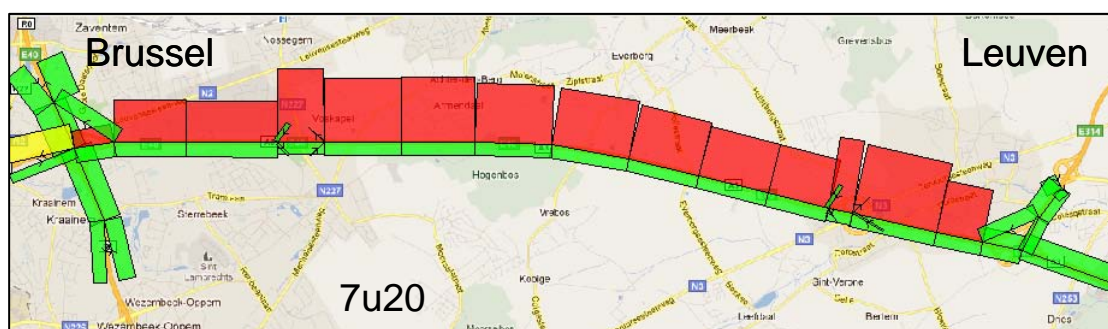
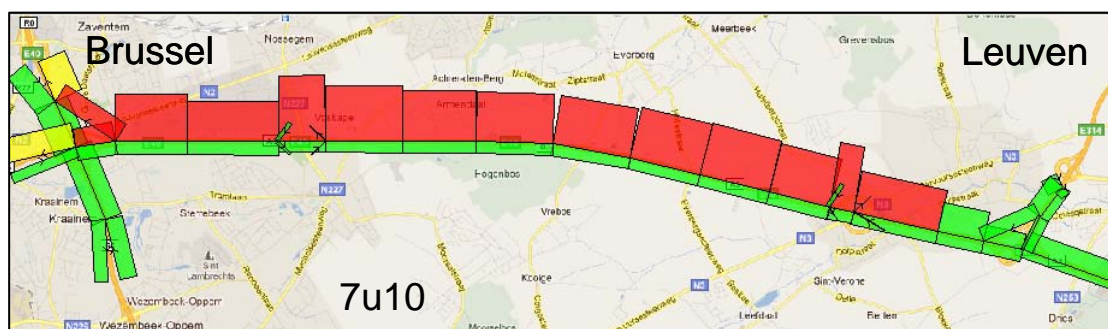
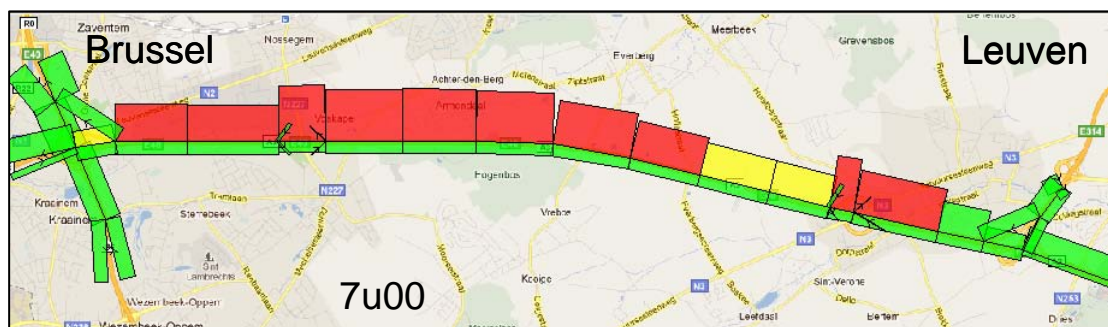
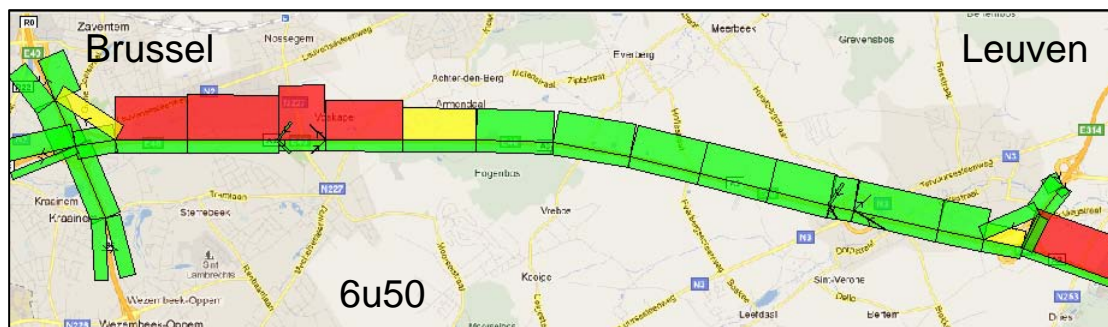


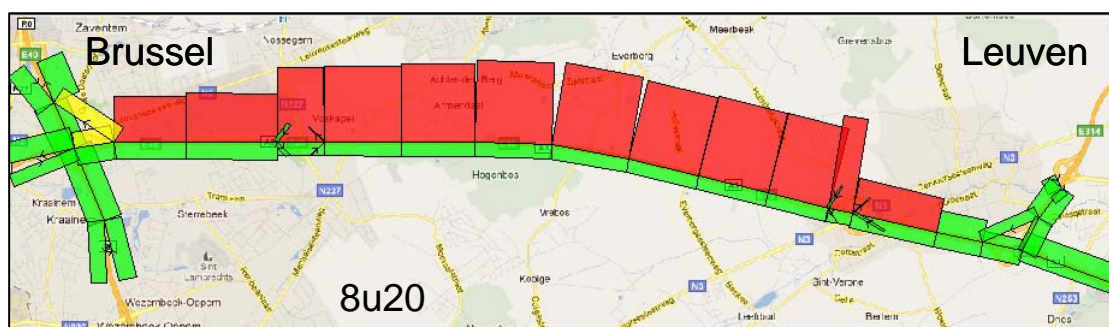
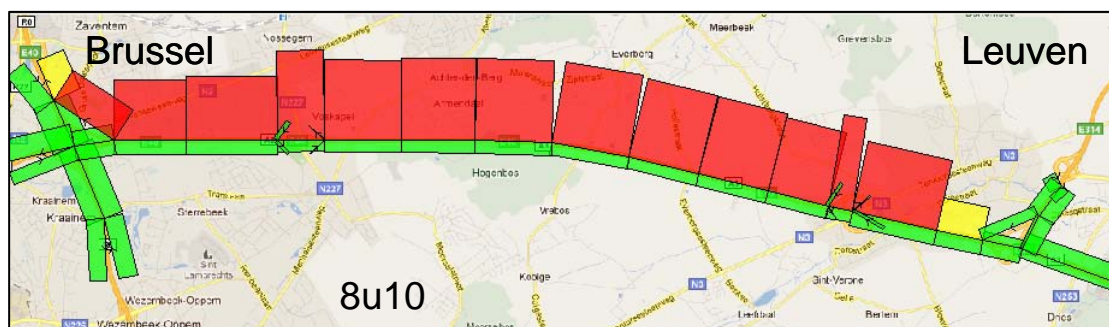
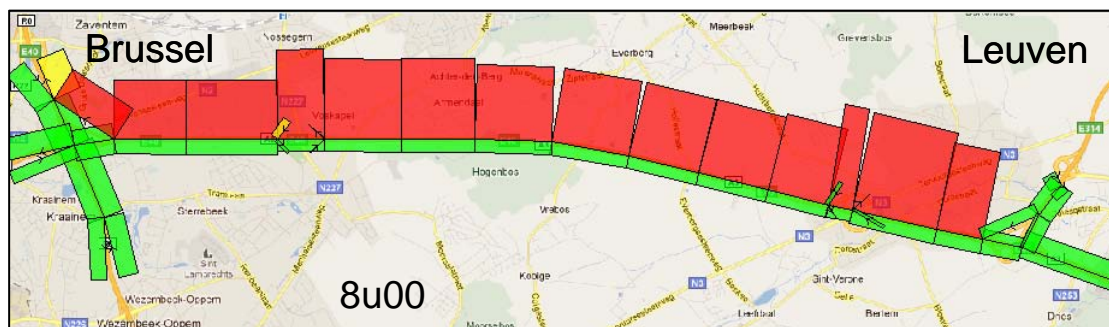
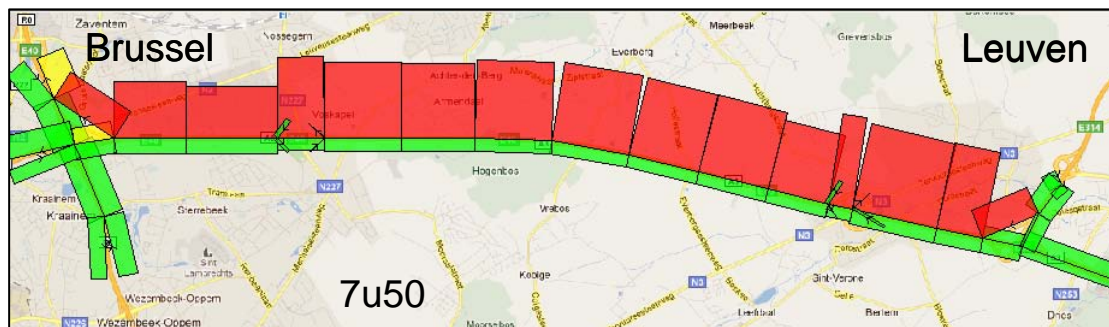
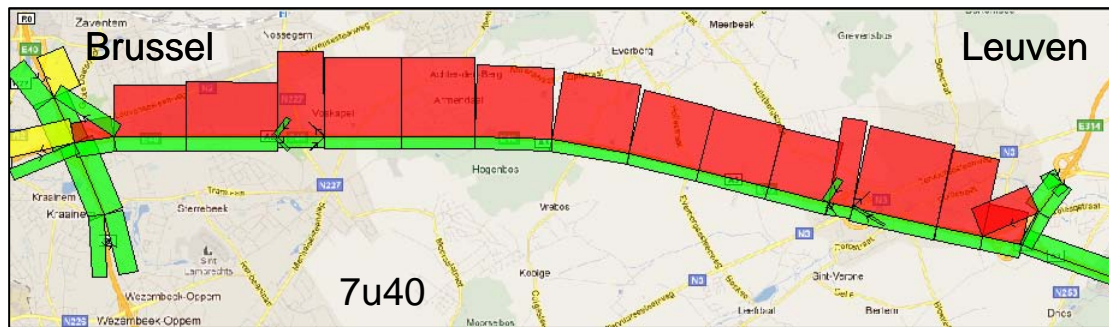
Figure 7: Traffic speeds on the main carriageway in Sterrebeek in the direction of Brussels (measured and simulated)

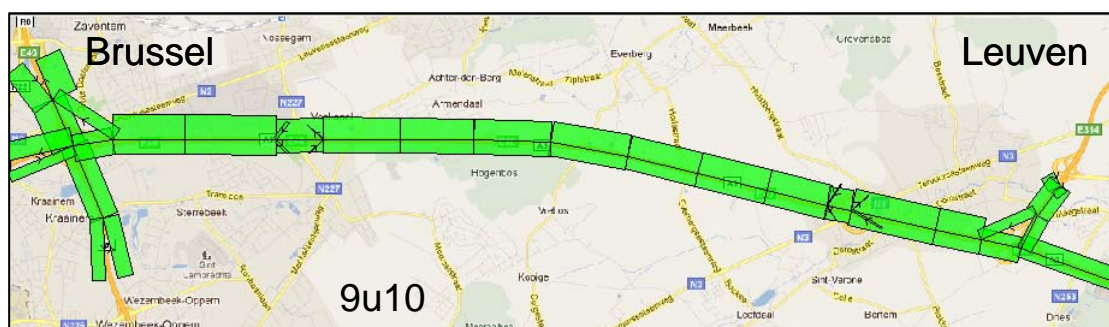
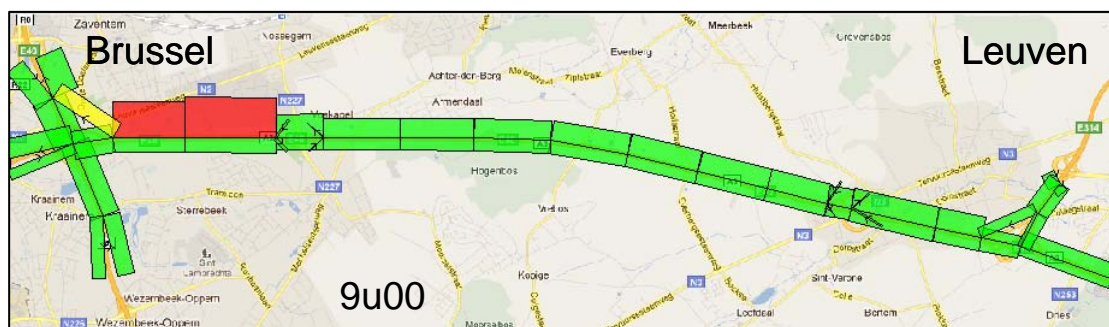
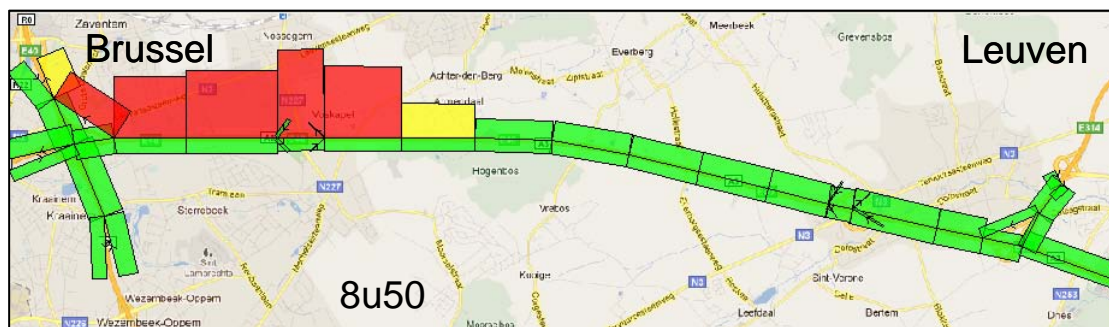
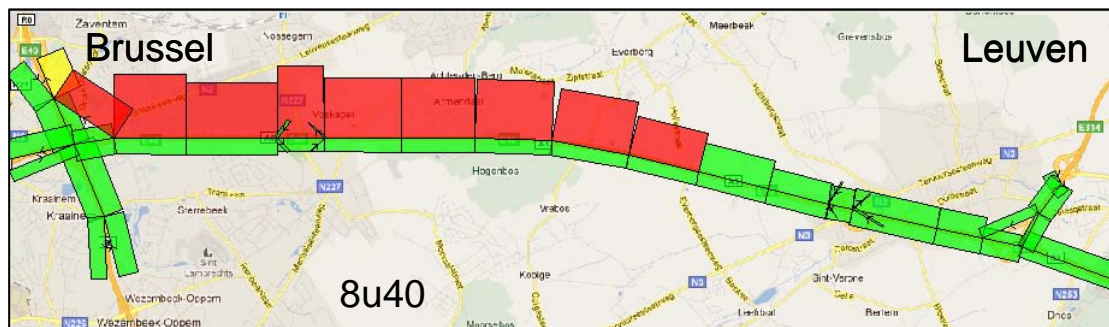
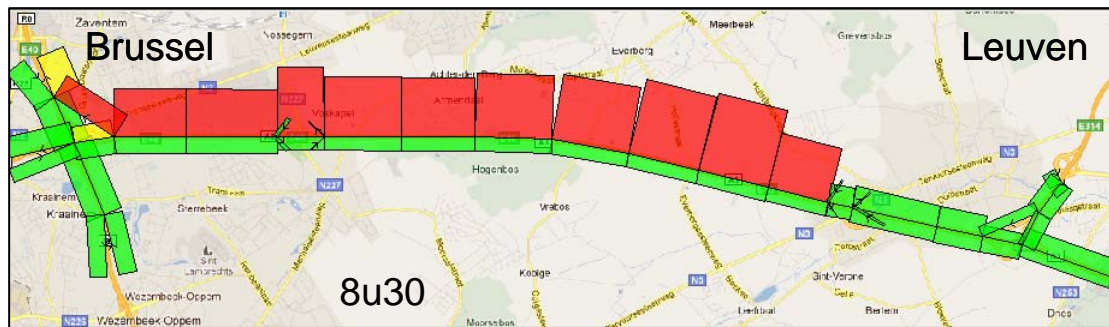
Queue propagation

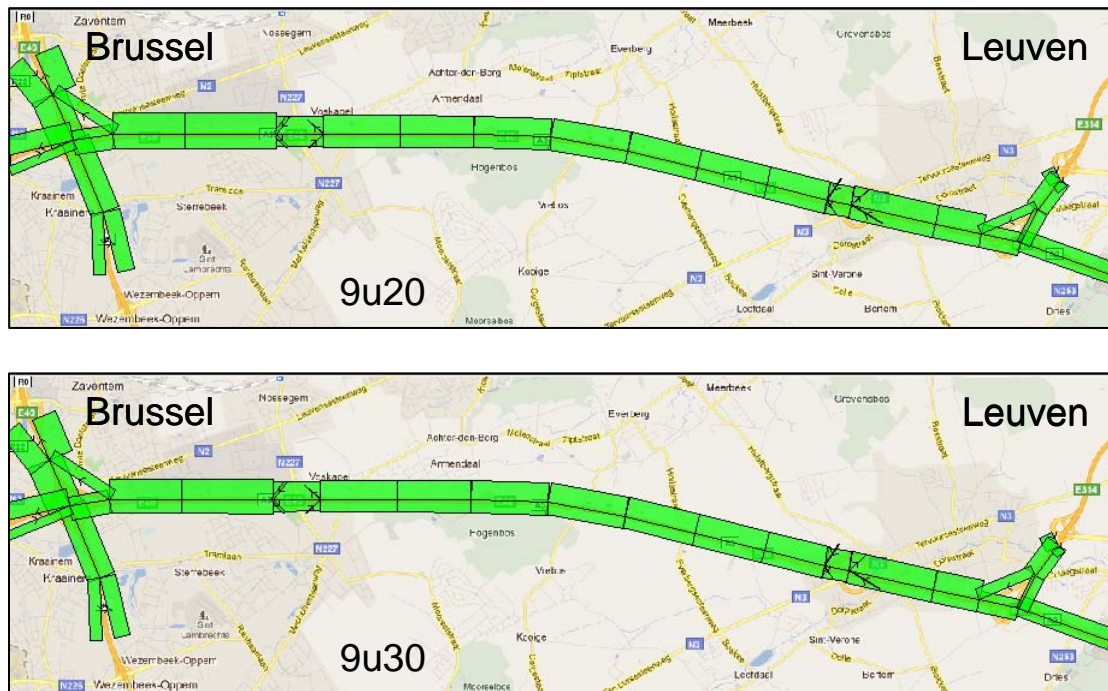
Figure 8 illustrates the queue propagation during the morning rush hour. A snapshot is shown every 10 minutes. The bars on the various links represent the traffic densities. Thicker and darker bars represent higher densities.











A queue begins to form at 6.40 a.m. near the intersection of the E40 and the R0. The main carriageway on the R0 outer ring around Zaventem does not have sufficient capacity to accommodate both streams i) from the easterly E40 and ii) from the southerly R0. This road section on the R0 outer ring acts as a bottleneck. Behind this bottleneck a queue forms on the E40 in the direction of Leuven. From 6.40 a.m. this queue in the direction of Leuven gets continuously longer and traffic density increases steadily. At 7.30 a.m. the queue stretches all the way back to Haasrode. At 7.40 a.m. the queue reaches Leuven. From 8 a.m. the queue in the direction of Brussels starts to disperse. The queue had disappeared by 9.10 a.m.

Travel times

The queues also result in higher travel times. Figure 9 shows the travel time on the E40 from the E40-E314 intersection (Leuven) to the E40-R0 intersection (Sint-Stevens-Woluwe/Woluwe Saint Etienne) over the course of time. The travel time starts to increase from 6.40 a.m. At 7.50 a.m. a journey on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne takes 14 minutes longer than at 6.40. After 7.50 the travel time gradually starts to decrease, to return to the same level at 9.00 a.m. as it was at 6.40.

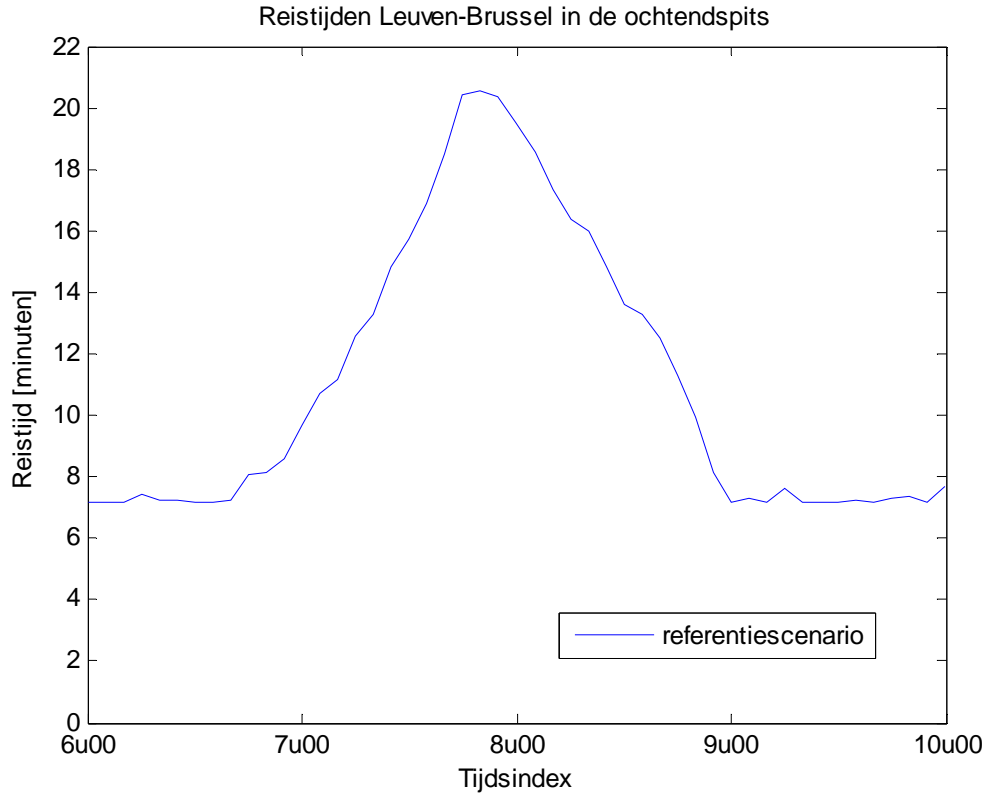


Figure 9: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario

Lost vehicle hours

We work out the total number of lost vehicle hours for the reference scenario. These show how much time is lost by all vehicles combined. This gives a good indication of traffic congestion.

In the first instance we determine the time lost over the course of the peak period, on the E40 from the E40-E314 intersection (Leuven) to the E40-R0 intersection (Sint-Stevens-Woluwe/Woluwe Saint Etienne). Time lost is the difference between the observed actual travel time and the travel time in an uncongested network with free-flowing traffic.

Next we determine the total lost vehicle hours by multiplying the time lost by the volume of traffic that is subject to the loss of time. Lost vehicle hours is the total time lost by all vehicles combined and is calculated as follows:

$$VVU = \int_{t=6u30}^{t=9u30} qVdt$$

where VVU = lost vehicle hours in the morning rush hour (Vehicle hours)

q = traffic volume (Vehicles/time unit)

V = lost time (hours)

There was a total of **1925** lost vehicle hours in the reference scenario.

2.1.2 Modal shift scenario

In this scenario we consider a modal shift from cars to motorcycles. We assume that 10% of the cars are replaced. First we look at how to adjust the simulation parameters in order to be able to model a modal shift of this sort (Section 2.1.2.1). We then perform a simulation with these new parameters and look at the results (Section 2.1.2.2).

2.1.2.1 *Adjusting simulation parameters*

Car equivalent (PCE) of the motorcycle

The space occupied by motorcycles on the road can be compared with the space taken up by the cars, and can then be expressed in terms of passenger car equivalents (PCE). The PCE value of a motorcycle represents how many cars would have the same effect on the flow of traffic and the capacity of the road.

When there is little traffic on the road, it can be expected that motorcycles will take up as much space on the road as cars. A motorcycle then has a PCE value of 1. However, when the road becomes busier, and the speed of the traffic flow falls, motorcycles take up less space. Some motorcycles keep less distance from the vehicle in front or ride between two lanes. The passenger car equivalent of the motorcycle is consequently reduced. When traffic comes to a complete standstill, it can be assumed that all motorcycles drive between two lanes. In this case, the motorcycle has a PCE value of 0.

The PCE value of a motorcycle is therefore dependent on the speed and the traffic situation on the road. Furthermore, the PCE value is also dependent on the type of road (motorway, regional road, crossroads, etc...) and on the number of motorcycles in the traffic flow.

Different values can be found in the literature for the PCE of a motorcycle.

In 1963, Holroyd suggested a value of 0.6 PCE, based on empirical material that was researched at the UK Transport and Road Research Laboratory (Holroyd (1963)). This value was not differentiated by road type or traffic flow regime. Furthermore, the vehicle and traffic flow characteristics from 1963 are no longer relevant to the current situation.

In 2007, Lee recognised that the PCE value is dependent on the share of motorcycles and the speed of the traffic flow. He developed a model to determine the PCE of motorcycles in different circumstances. Lee proposes values of 0.4 PCE to 0.75 PCE depending on the traffic situation (Lee (2007)).

Various researchers suggested values of 0 PCE to 0.33 PCE in an urban environment close to traffic lights (Ellis (2005), UK Department for Transport (2004), Powell (2000), Holroyd (1963)). These values cannot be applied to motorways.

Minh finds a PCE value of 0.28 (Minh (2005)) and Powell finds values between 0 PCE and 0.65 PCE (Powell (2000)), but these are based on tests in Indonesia, Malaysia and Thailand where

there is a very high proportion of motorcycles and they cannot be used in Europe without adjustment.

Wigan reviewed the existing literature and decided that the most suitable value for motorways amounted to 0.5 PCE.

For the case study under consideration, this value of 0.5 PCE was used in order to characterise the traffic situation with the maximum intensity (capacity). At this maximum intensity (q_M) there is a traffic density k_M . In free-flowing traffic with low traffic density ($k \approx 0$) the value approaches 1 PCE. In this case the distance between vehicles is more or less identical, regardless whether they are cars or motorcycles. Intermediate traffic regimes ($0 < k_M < k_{MAX}$) are characterised by an intermediate value ($1 > PCE > 0.5$). In heavily congested traffic with a high traffic density ($k \approx k_{MAX}$) the value approaches 0 PCE. In this situation, motorcycles drive in between the lanes and overtake cars without hindering them. Intermediate traffic regimes ($k_M < k < k_{MAX}$) are characterised by an intermediate value ($0.5 > PCE > 0$).

Taking account of the above information, we postulate the following relationship between the PCE and traffic density:

$$PCE_{\text{motorcycle}} = (1 - 0.5 \frac{k}{k_M}) \quad \text{for } k \leq k_M$$

$$PCE_{\text{motorcycle}} = 0.5(1 - \frac{k - k_M}{k_{MAX} - k_M}) \quad \text{for } k \geq k_M$$

where:

k = traffic density (PCE/km)

k_M = traffic density at regime capacity (PCE/km)

k_{MAX} = maximum traffic density (PCE/km)

This relationship is represented graphically in Figure 10:

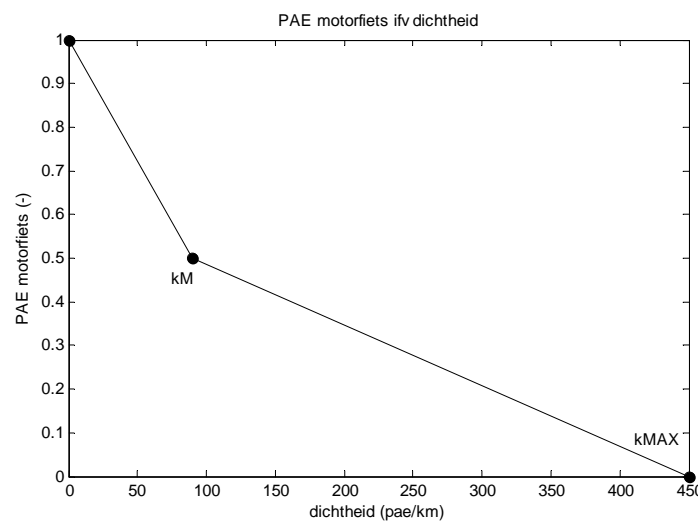


Figure 10: PCE value of the motorcycle in relation to traffic density

Simulation parameters

In order to simulate the modal shift scenario, the traffic flows from the points of origin have been adapted, as has the capacity of the bottleneck links. This was done as follows:

$$Q = Q^* (1 - f \cdot p_{pw} \cdot pae_{pw} + f \cdot p_{pw} \frac{BG_{pw}}{BG_{moto}} pae_{moto}^c)$$

$$C = C^* - (pae_{moto}^k - pae_{moto}^c) \cdot f \cdot p_{pw} \cdot Q^*$$

where:

Q = adjusted traffic demand from point of origin (PCE/u)

Q^* = original traffic demand from point of origin (PCE/u)

f = fractions of cars that are replaced (-)

p_{pw} = original percentage of cars in the traffic flow (-)

PCE_{pw} = PCE value for cars (-)

BG_{pw} = occupancy rate for cars (-)

BG_{moto} = occupancy rate for motorcycles (-)

PCE_{moto}^c = PCE value for motorcycle in congestion ($k_M < k$) (-)

C = adjusted capacity of bottleneck link (PCE/u)

C^* = original capacity of bottleneck link (PCE/u)

PCE_{moto}^k = PCE value of motorcycle at capacity ($k = k_M$) (-)

The modal shift can be modelled using these formulae. It is assumed that a certain fraction f (in this case 10%) of the car traffic exchanges their car for a motorcycle. This also allows the different occupancy rate of cars compared to motorcycles to be taken into account. There are usually more people in a car than on a motorcycle. For commuter traffic in Flanders, there is an occupancy rate of 1.1 persons per car (OVG Vlaanderen (2010)). For motorcycles we take an occupancy rate of 1 person per motorcycle. This means that 10 cars will be replaced by 11 motorcycles. The number of vans and trucks remains unchanged. The following simulation parameters were used:

$$f = 10\%$$

$$p_{pw} = 83.4\%$$

$$PCE_{pw} = 1$$

$$BG_{pw} = 1.1$$

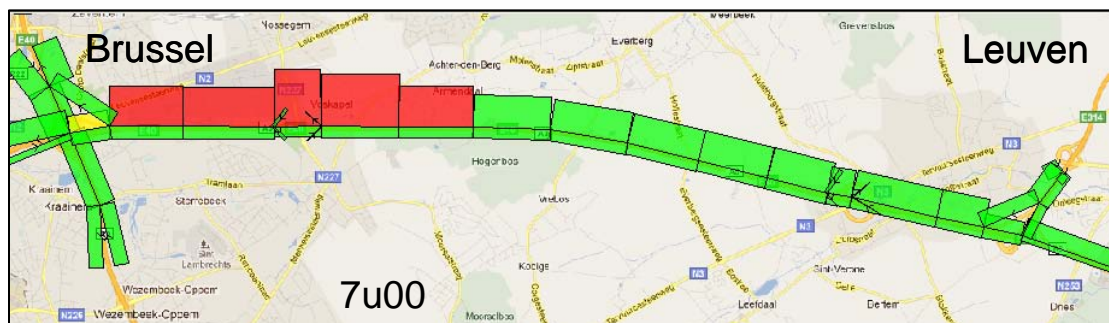
$$BG_{moto} = 1$$

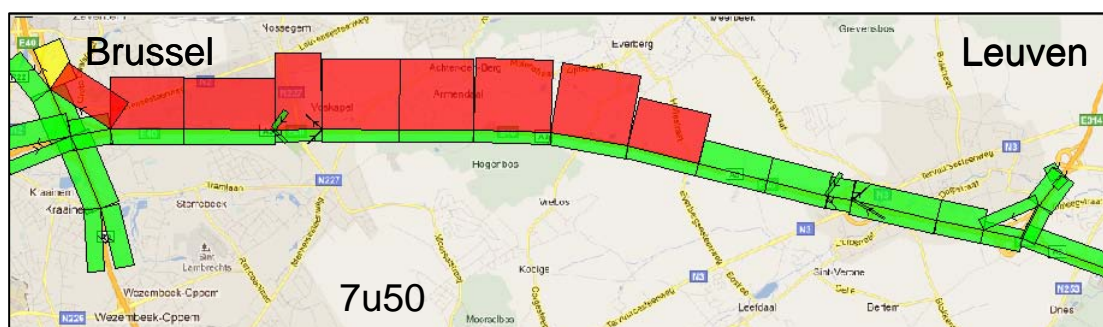
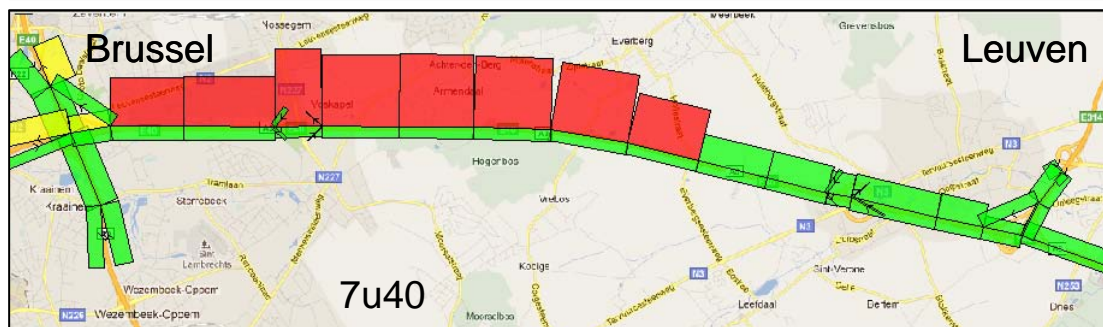
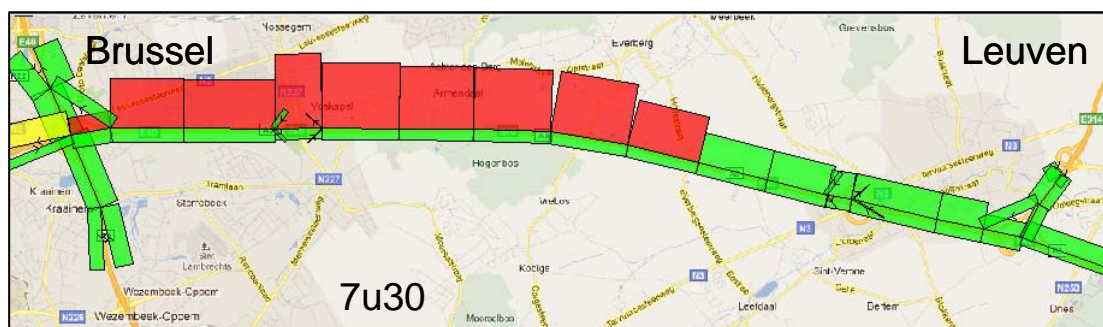
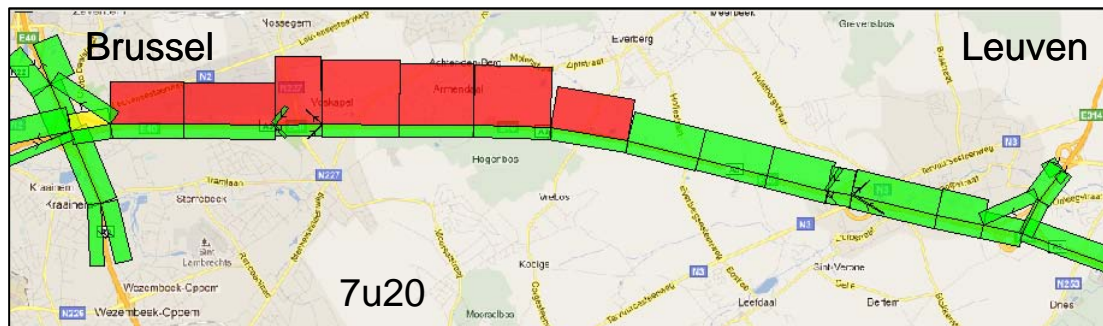
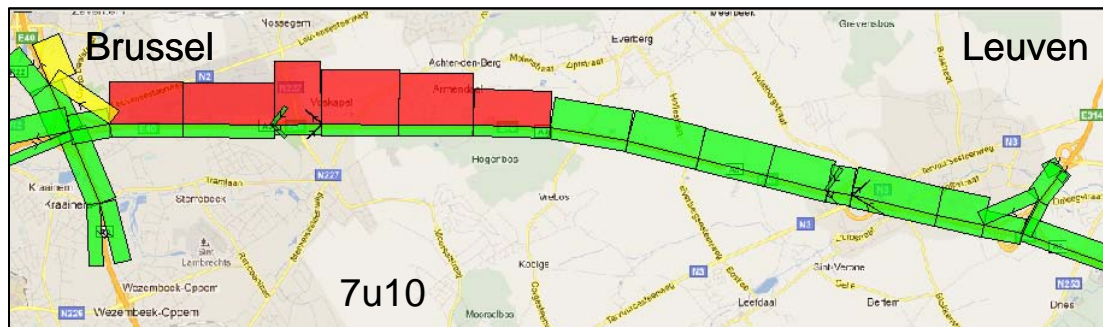
$$PCE_{moto}^k = 0.5$$

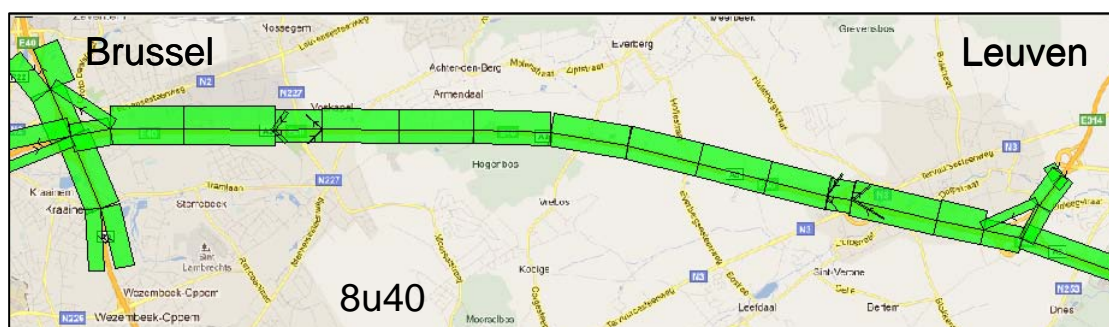
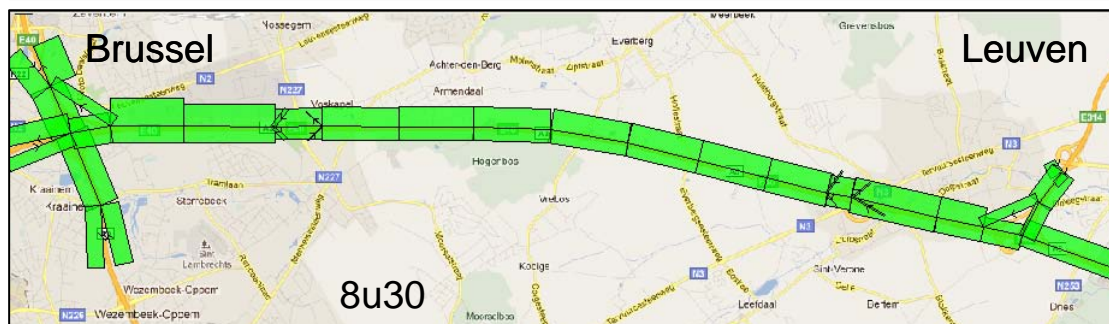
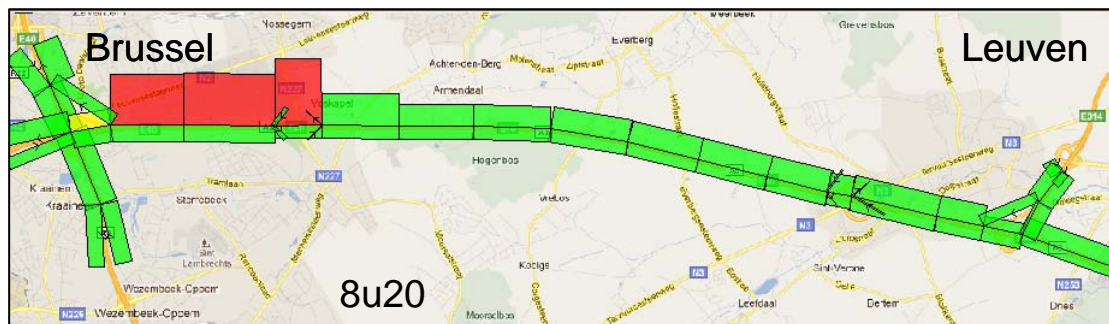
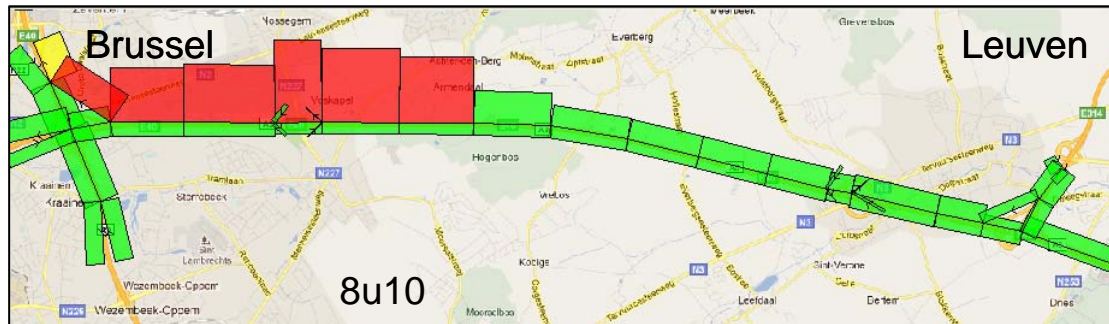
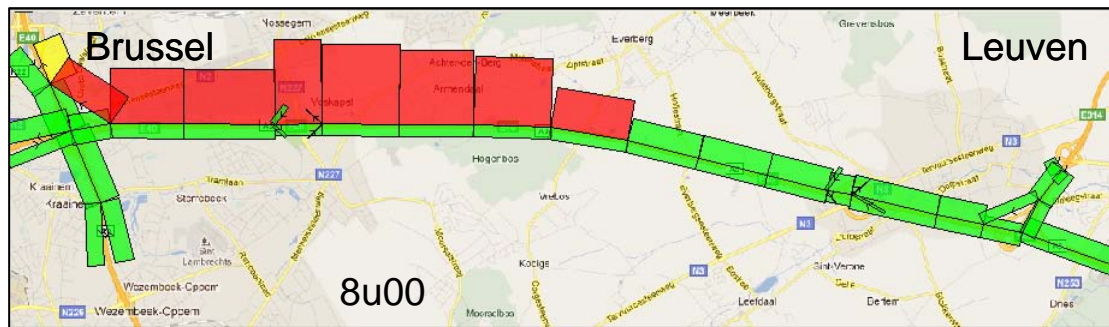
2.1.2.2 Results

After the simulation parameters have been adjusted, we can use the traffic model to calculate a modal shift scenario. This yields the following results:

Figure 11 illustrates the queue propagation in the morning rush hour. A snapshot is shown every 10 minutes. The bars on the various links represent the traffic densities. Thicker and darker bars represent higher densities.







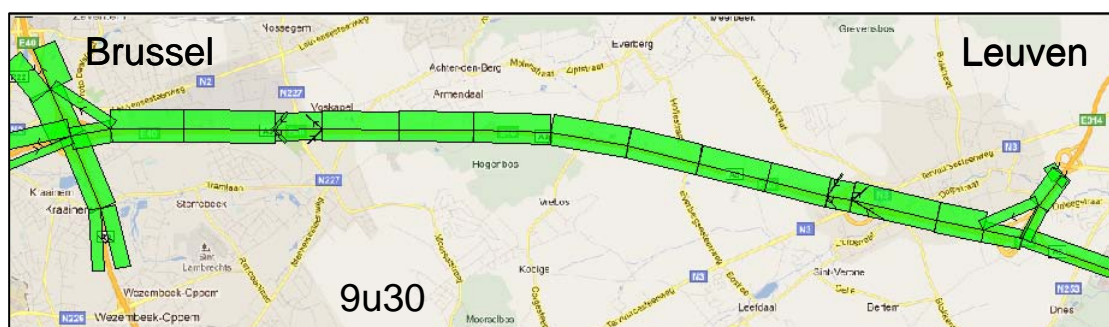
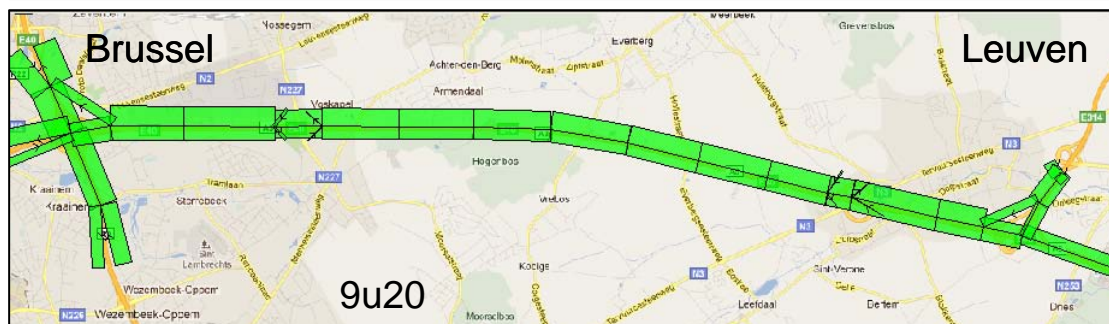
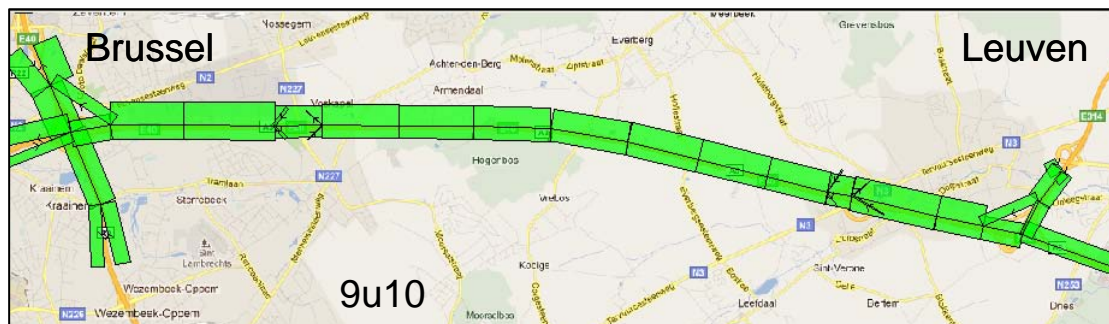
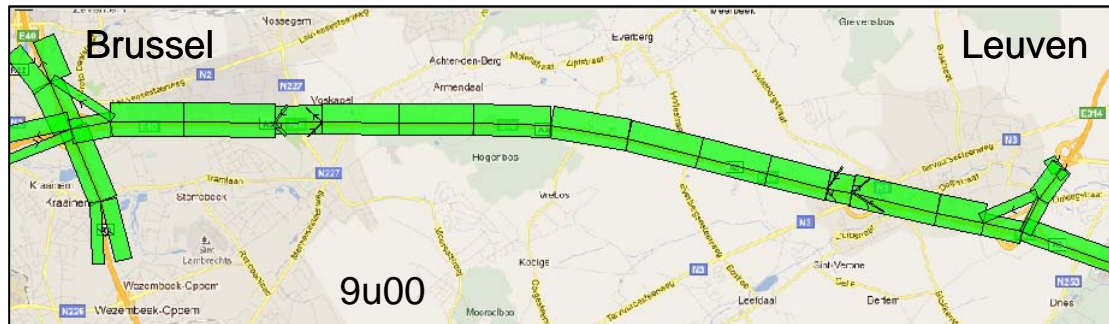
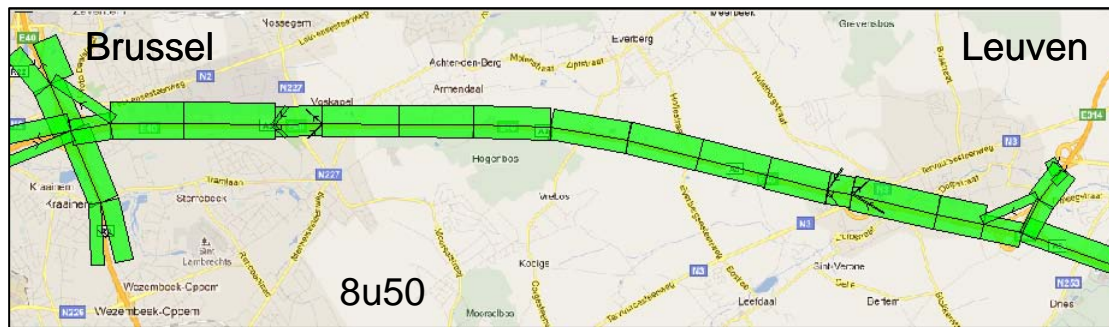


Figure 11: Queue propagation in the morning rush hour in the modal shift scenario

At 6.40 a.m. a queue starts to form at the intersection of the E40 and the R0. The main carriageway on the R0 outer ring in the area around Zaventem has insufficient capacity to accommodate both streams i) from the easterly E40 and ii) from the southerly R0. This road section on the R0 outer ring acts as a bottleneck. Behind this bottleneck a queue forms on the E40 in the direction of Leuven. From 6.40 a.m. this queue in the direction of Leuven continues to lengthen and traffic density increases steadily. The queue reaches its maximum extent at 7.50 when it stretches back to around half-way between Sterrebeek and Bertem. From 8 a.m. the queue in the direction of Brussels starts to ease. The queue had disappeared by 8.30 a.m.

Travel times

The queues also result in higher travel times. Figure 12 shows the travel time on the E40 from the E40-E314 intersection (Leuven) to the E40-R0 intersection (Sint-Stevens-Woluwe/Woluwe Saint Etienne) over the course of time. Travel times start to increase from 6.40 a.m. At 7.50 a.m. a journey on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne takes 6 minutes longer than at 6.40. After 7.50 the travel time gradually starts to decrease, returning to the same level at 8.30 a.m. as it was at 6.40.

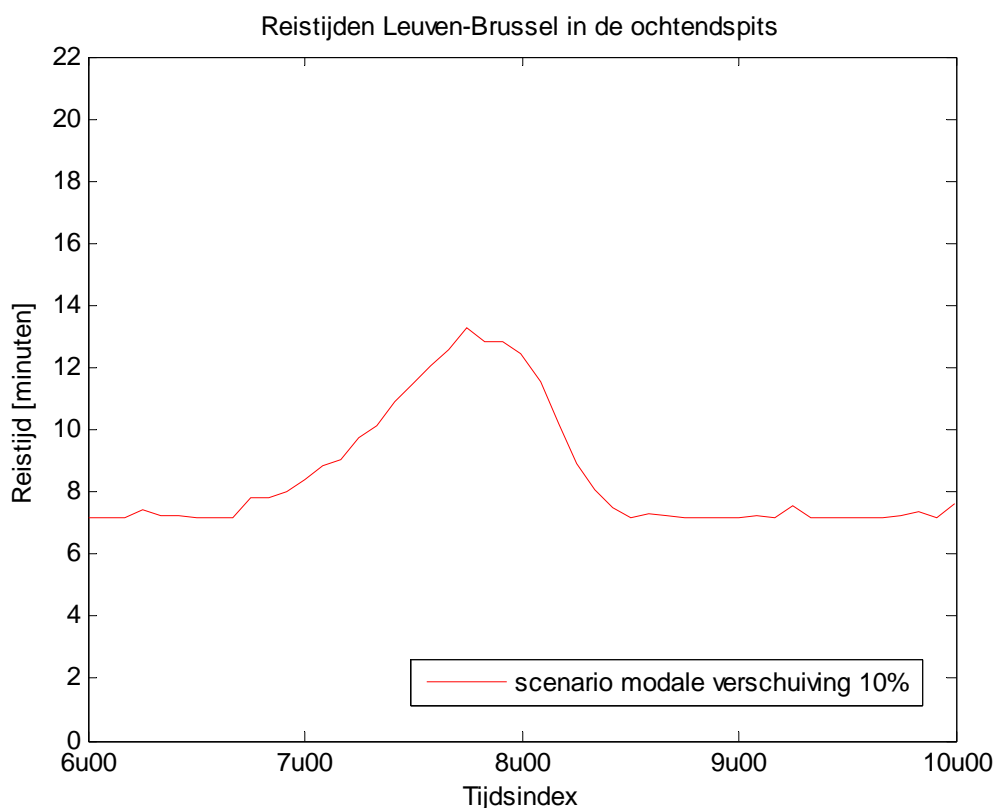


Figure 12: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the modal shift scenario

Note that these are the travel times of an ‘average’ vehicle in the traffic flow. It is assumed that motorcycles travel at the same speed as cars.

Lost vehicle hours

Lost vehicle hours, which shows how much time is lost by all vehicles combined, is calculated in the same way as was indicated in Section 2.1.1.4.

In the modal shift scenario there was a total of **706** lost vehicle hours.

2.1.3 Impact of modal shift on traffic flow

By comparing the modal shift scenario with the reference scenario we can work out the effect of the modal shift on the traffic flow.

2.1.3.1 Queue propagation

In both scenarios, a queue begins to form on the E40 in the area of its intersection with the R0 at the same time (6.40 a.m.) and for the same reason. The queue goes back in the direction of Leuven. The queue increases at a faster rate in the reference scenario and also becomes somewhat longer. The queue reaches its peak at 7.40/7.50. In the reference scenario the queue stretches all the way back to Leuven (see Figure 8), while in the modal shift scenario the queue stretches no further than halfway between Sterrebeek and Bertem (see Figure 11). From 8.00 a.m. the queue begins to ease in the direction towards Brussels. In the reference scenario the queue has disappeared by 9.10, while in the modal shift scenario it has already gone by 8.30.

We can conclude that the queue becomes shorter and disperses more quickly as a result of the modal shift.

2.1.3.2 Travel times

These findings are confirmed when we compare the travel times in both scenarios. Figure 13 shows the travel times on the E40 from the entrance at the E40-E314 intersection (Leuven) to the exit at the E40-R0 intersection (Sint-Stevens-Woluwe/Woluwe Saint Etienne) over the course of time.

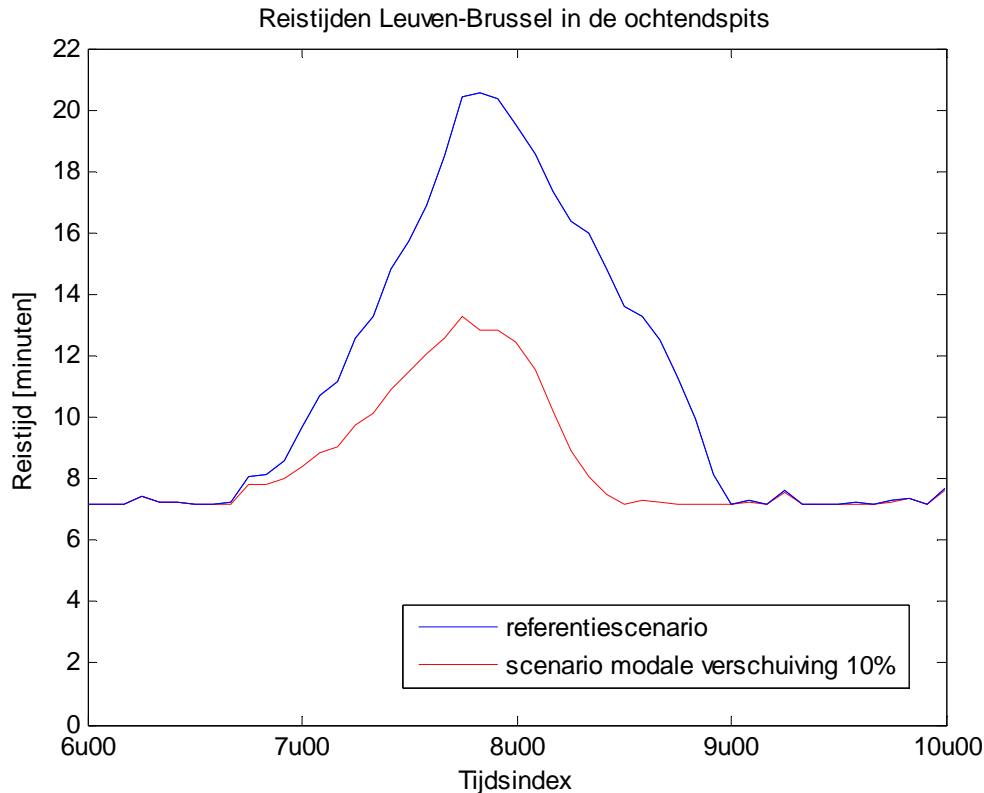


Figure 13: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario and in the modal shift scenario

Travel time starts to increase from 6.40 a.m. The travel time increases at a faster rate in the reference scenario. At 7.50 a.m. the travel time lost in this scenario is almost double that in comparison with the modal shift scenario, where the queue is somewhat shorter. The queue is not only shorter, it also disappears more quickly in the modal shift scenario. At 8.30 a.m. the travel time has returned to its original level. In the reference scenario this does not occur until 9.10 a.m.

2.1.3.3 Lost vehicle hours

The modal shift results in a fall in the number of lost vehicle hours (i.e. the time lost by all vehicles combined) from **1925 to 706 hours**. This represents a reduction of **63%**. Note that this does not take account of any possible knock-on effects.

2.1.3.4 Scenario without congestion

In addition to the scenario where 10% of the cars are replaced by motorcycles, we also considered the modal shift that would be required to eliminate queues completely. To this end we systematically adjust the simulation parameter f (fraction of cars that are replaced) and look at the resulting traffic flow after running it through the traffic model. It turns out that a modal shift of **25%** of cars would be required in order to eliminate congestion completely. Figure 14 shows the corresponding travel times in comparison with the other scenarios.

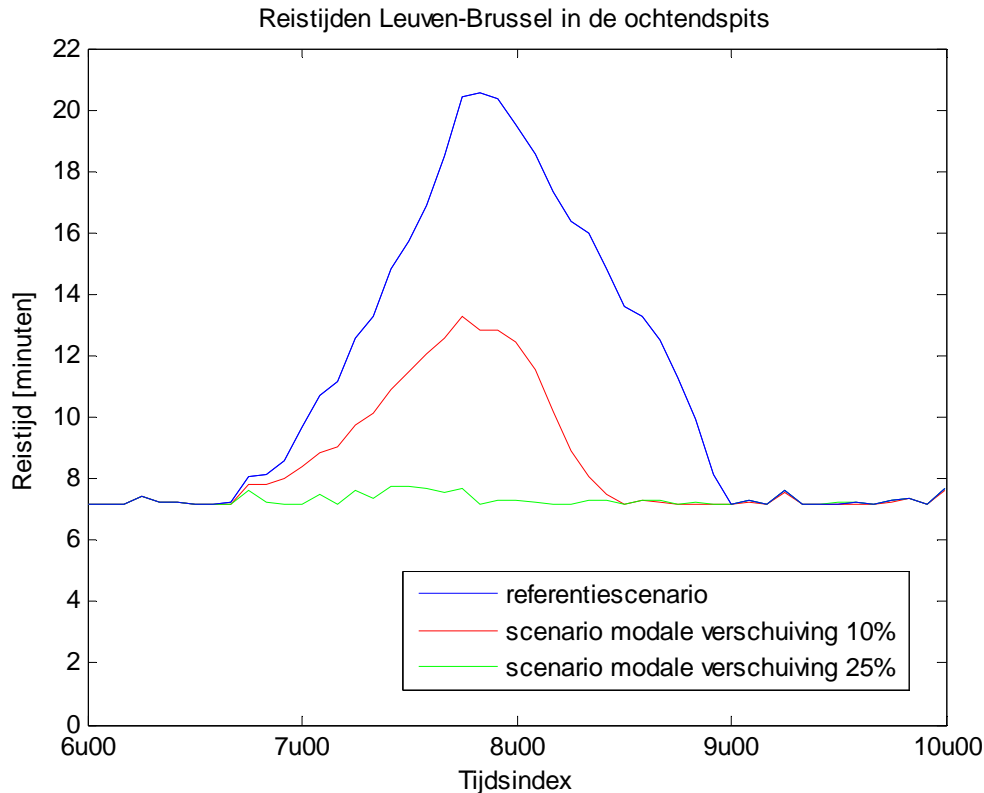


Figure 14: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the reference scenario and in the modal shift scenarios

2.2 Overall effect on the road network

In this Section we consider the impact on lost vehicle hours when a modal shift is achieved throughout the Belgian road network. We try to determine the effect when 10% of cars are replaced by motorcycles on the entire road network during the rush hour period. To this end we extrapolate the effects of the modal shift that emerged in the case study to the entire road network.

However, it is clear that the effects of a modal shift are dependent on the local traffic situation. The queues that develop at each bottleneck have different characteristics, which are dependent on local circumstances, such as the local traffic demand and the capacity of the local bottleneck and upstream road sections. The relationship between the modal shift and the change in traffic flow, the reduction in travel times and the reduction in lost vehicle hours will consequently differ for each location.

The result of an overall calculation for the entire road network based on extrapolating the results of the case study can therefore only serve as an indication of the order of magnitude of the impact of a global modal shift. In order to obtain more precise results, a traffic simulation would have to be carried out across the entire Belgian road network. This is outside the scope of this study.

Below we examine first the impact in the Leuven-Brussels case study on travel times and lost vehicle hours of a modal shift of 10% from cars to motorcycles, in which we take the knock-on effect into account (Section 2.2.1). Next the results are extrapolated to the entire road network (Section 2.2.2). The total time benefits are also calculated.

2.2.1 Case study: modal shift scenario including knock-on effect

A reduction of 63% in total lost vehicle hours was observed in the Leuven-Brussels case study. This took no account of possible knock-on effects. When a particular transport option becomes more attractive, this option can be expected to attract more traffic. Thus, an improvement in the situation resulting in shorter travel times on the primary road network will attract extra traffic. This extra traffic will partly be made up of journeys that previously would not have been made, and partly of journeys that previously would have been made in a different manner, e.g. using the secondary road network or another mode of transport (public transport, bicycle, etc...).

Using ‘elasticity’ we can see how much extra traffic is attracted when the traffic situation improves, i.e. when the transport cost falls. In the literature on commuter traffic (‘essential trips in peak periods’) **price elasticity** (with respect to the generalised transport cost) of **-0.2** has been suggested (Mayeres (1999)). This maintains that for commuter traffic, traffic demand will increase by 0.2% when the total price of a journey falls by 1%, or conversely, that traffic demand will fall by 0.2% when the total price of a journey rises by 1%.

For the Leuven-Brussels case study under consideration, we now determine the extent of the knock-on effect and its impact on lost vehicle hours.

We base this on a ‘typical’ journey, assuming that a journey from Leuven to Brussels on the E40 from the entrance at the E40-E314 intersection (Leuven) to the exit at the E40-R0 intersection (Sint-Stevens-Woluwe/Woluwe Saint Etienne) covering a distance of 14 km can be considered as a ‘typical’ journey. The cost of this journey is made up of a vehicle cost (purchase, maintenance, fuel, road taxes, insurance, etc...) and a time cost.

The vehicle cost is reflected in the official mileage allowance for business trips undertaken using one’s own car. This vehicle cost current amounts to €0.33/km (Agentschap voor binnenlands bestuur – Local government agency (2011)). In other words, the vehicle cost for a journey of 14 km amounts to €4.70.

In order to determine the time cost, a monetary value has to be placed on travel time. For commuter traffic we assume a time value of €21.60/hour per traveller (source: De Ceuster (2010)). To put it another way, a commuter would pay €21.60 to save an hour of travel time during the peak period. We multiply this number by the occupancy rate of 1.1 travellers per vehicle, giving us a time value of €23.76/hour per vehicle for commuter traffic.

In the reference scenario the time cost of the 14 km journey varies between €2.80 (for journeys that take place before 6.40 a.m. or after 9.00 a.m.) and €8.30 (for a journey at 7.50 a.m.). In the modal shift scenario this time cost varies between €2.80 and € 5.50.

For a journey at 7.50 a.m. (at the peak of congestion) the total cost of a journey (vehicle cost + time cost) is 21% lower in the modal shift scenario compared to the reference scenario (total journey costs amount to €10.20 and €13.00 respectively). Consequently, traffic volume will increase by around 4%. For journeys before 6.40 a.m. and after 9.00 a.m. the transport cost will remain the same and no extra traffic will be attracted. Between 6.40 and 9.00 an average of around **2% of extra traffic** will be attracted.

When we calculate a scenario with respect to the traffic model that takes account of this extra traffic demand, it delivers the following results:

Travel times

Figure 15 compares the travel times in this modal shift scenario including the knock-on effects with the travel times in the other scenarios considered. With respect to the modal shift scenario without knock-on effects, travel times increase at a faster rate (because of longer queues) and persist for a longer time before returning to their original level (i.e. before the queue has disappeared).

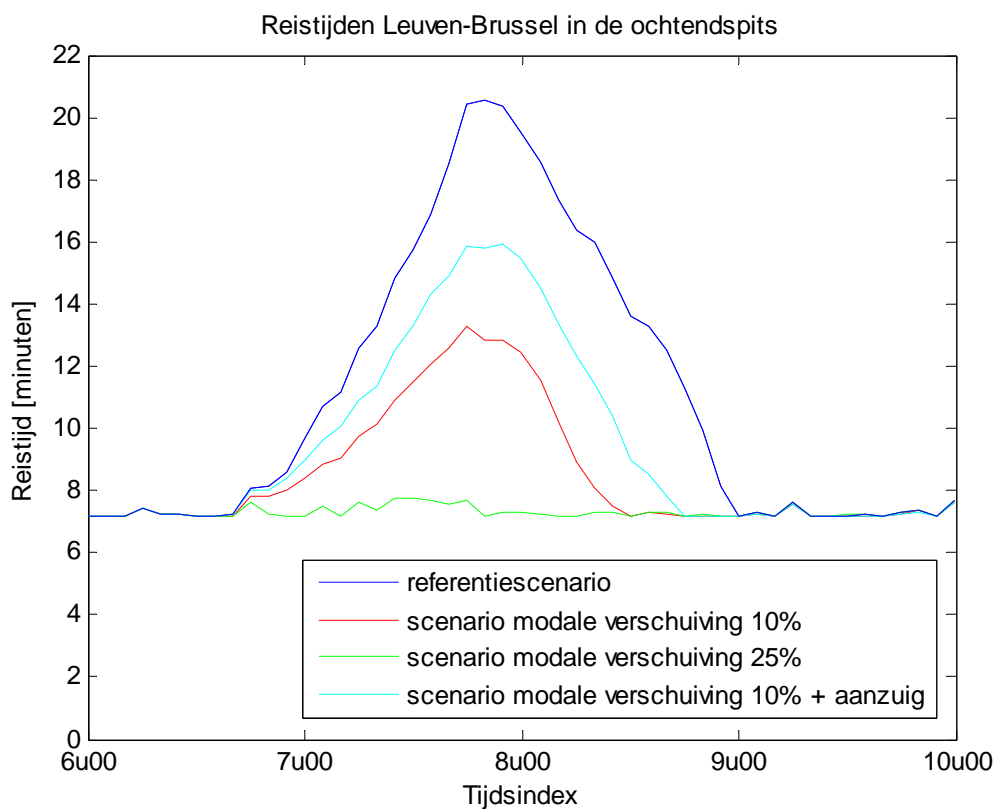


Figure 15: Travel times on the E40 between Leuven and Sint-Stevens-Woluwe/Woluwe Saint Etienne in the morning rush hour in the modal shift scenario including knock-on effects, as well as in the other scenarios considered

Lost vehicle hours

As a consequence of the knock-on effects, the total of lost vehicle hours increases from **706 hours** (in the modal shift scenario without knock-on effects) to **1158 hours**. Compared to the

reference scenario, the modal shift scenario including knock-on effects shows a reduction in lost vehicle hours of **40%**.

In the modal shift scenario without knock-on effects the reduction in lost vehicle hours amounted to **63%**. This is despite the fact that the knock-on only results in (on average) 2% of extra traffic. Note that the results in this case study are highly sensitive to small fluctuations in traffic demand.

2.2.2 Lost vehicle hours and time benefits on the entire primary road network

We now determine the reduction in lost vehicle hours and the resulting time benefits, when a modal shift of 10% takes place from cars to motorcycles across the entire network of primary roads in Belgium. As described above, we extrapolate the result of the case study to the whole of the primary road network. Taking account of the knock-on effects, we assume that there would be 40% fewer lost vehicle hours as a consequence of a modal shift from cars of 10%. Note once more that this figure (40%) only has an indicative value.

In the study 'Analysis of congestion in Belgium' (Maerivoet S. & I. Yperman (2008)) it was found that a total of around 37,000 hours were lost every day on the primary road network in Belgium by all vehicles combined. When we apply a reduction of 40% as a consequence of the modal shift, a saving could be made of approximately **15,000 lost vehicle hours**. Multiplying this by the time value of €23.76/hour per vehicle, gives us a total time benefit of around **€350,000** per day as a consequence of the modal shift from cars to motorcycles.

2.3 Overall effect on the secondary road network

The impact of a modal shift on the secondary road network is difficult to determine without additional research and further case studies and traffic simulations. The secondary road network is characterised by a number of factors that make it different from the main road network. For example, there is a different composition of traffic on the secondary network. There is also a different relationship between the passenger car equivalent of a motorcycle and traffic density. Moreover, the proportion of commuter traffic on the secondary road network is smaller than on the primary road network. We do not have precise figures available. While it is assumed that passenger transport on the primary road network in the morning rush hour consists of 100% commuter traffic, it is also assumed (for the purposes of this exercise) that commuters account for 30% of passenger traffic on the secondary road network (calculated on the basis of the average percentage of commuter traffic during the morning rush hour in Flanders (55%)(OVG Vlaanderen (2010)) and on the basis of the known traffic volumes on the primary and secondary networks (primary road network 34.86×10^9 vehicle km/year; secondary road network 61.15×10^9 vehicle km/year)(Maerivoet S. & I. Yperman (2008))).

Given the different character of the primary and secondary road networks, there will in general be a different relationship between the modal shift on one hand and the change in traffic flow, reduction in travel times and reduction in lost vehicle hours. Based on the Leuven-Brussels case study we cannot make any quantitative statements about the secondary road network.

We can however make the following observations:

- In the literature, lower values are generally proposed for the PCE of motorcycles on the secondary road network than those applicable to the primary road network (see Section 2.1.2.1).
- First, with the primary road network becoming more attractive, it will attract a number of journeys that previously would have used the secondary road network. This phenomenon could have a favourable impact on curtailing traffic creep. Furthermore, the secondary road network will also become more attractive (because of shorter travel times) so that a knock-on effect can occur here also.
- If a modal shift is only achieved for commuter traffic, the overall shift in relative terms will be 3 times smaller on the assumption that only 30% of traffic consists of commuters compared to the situation on the primary road network where commuters are assumed to account for 100% of passenger traffic.
- By contrast, the daily number of lost vehicle hours on the secondary road network is more than 5 times higher than the daily number of lost vehicle hours on the primary road network (Maerivoet S. & I. Yperman (2008)).

Based on the above considerations, at first sight a time benefit can be expected of the same order of magnitude as that on the primary road network. Additional research is needed to substantiate this assertion and to obtain more concrete numbers.

3 Impact on emissions

In this Chapter we examine the effect on emissions of a modal shift from cars to motorcycles. First, an effect can be expected as a result of the difference in emissions between motorcycles and cars. Section 3.1 goes into this in more detail. Moreover, the changed character of the traffic flow can also be expected to have an effect. The total impact on emissions (i.e. the sum of these two effects) will be looked at in Section 3.2 using the Leuven-Brussels case study.

3.1 *Emissions from motorcycles and cars*

3.1.1 Emission factors

An emission factor expresses the emission of a particular pollutant per vehicle kilometre driven (unit: g/km). In this study we consider the emission factors of 7 pollutants (CO_2 , NO_x , NO_2 , $\text{PM}_{2.5}$ —exhaust emissions, EC, $\text{PM}_{2.5}$ —non-exhaust emissions, VOC) for 4 classes of vehicle:

- A motorcycle ≤ 250 cc, emissions class Euro 3
- An ‘average’ car
- An ‘average’ van
- An ‘average’ truck

The pollutants listed above are together responsible for (as good as) the complete external cost of emissions in the transport sector (see Section 3.1.2). Other pollutants are not significant and are not considered in this study. Note that NO_2 is a component of NO_x . $\text{PM}_{2.5}$ are fine particulates with a diameter smaller than 2.5 micrometres. A distinction is made between $\text{PM}_{2.5}$ —exhaust emissions that are emitted directly from the vehicle exhaust, and $\text{PM}_{2.5}$ —non-exhaust emissions that are caused by wear on brakes, tyres and the road surface. EC is an abbreviation of ‘Elemental Carbon’ or ‘soot’ and is a component of $\text{PM}_{2.5}$ —exhaust emissions. VOC stands for ‘Volatile Organic Compounds’.

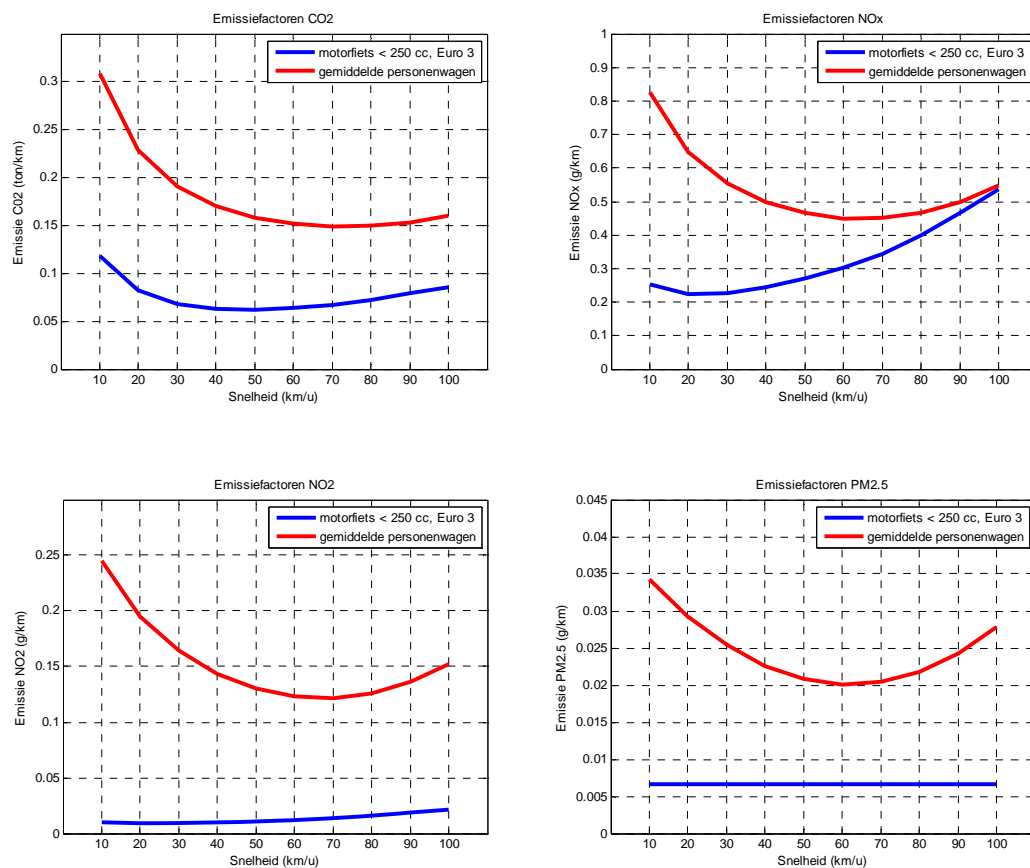
The emission factor of an ‘average’ car is compiled from the emission features that are available for each type of fuel, engine capacity and emissions class (Euro1, Euro2, etc...). These emission features are then weighted in accordance with the mileage of vehicles on the Belgian motorway network within certain sub-categories (fuel type, engine capacity and emissions class).

The emission features that we use are the most recently available COPERT IV emission features (Ntziachristos et al., (2010)). The COPERT IV database is largely based on measurements of emissions obtained in rolling road test cycles in combination with emissions models. These driving cycles are as far as possible representative of certain driving patterns in urban areas or on motorways and country roads. In this study we use the emission features that were prepared for motorways.

The number of kilometres driven on the Belgian motorway network by vehicles within the various subcategories (fuel type, engine capacity and emissions class) of the Belgian vehicle parc is derived from the transport model TREMOVE v3.3 (De Ceuster et al. (2010)).

In the remainder of this Section 3.1.1 we compare the emission factors of an ‘average’ car with the emission factors of a motorcycle subcategory 4-stroke, ≤ 250 cc, emissions class Euro 3. In the modal shift scenario it is assumed that average cars are replaced by new motorcycles of the type 4-stroke, ≤ 250 cc, emissions class Euro 3.

Emission factors are dependent on the average speed of the vehicles. Figure 16 shows the emission factors of the different pollutants for motorcycles and cars as a function of the average speed of vehicles on motorways:



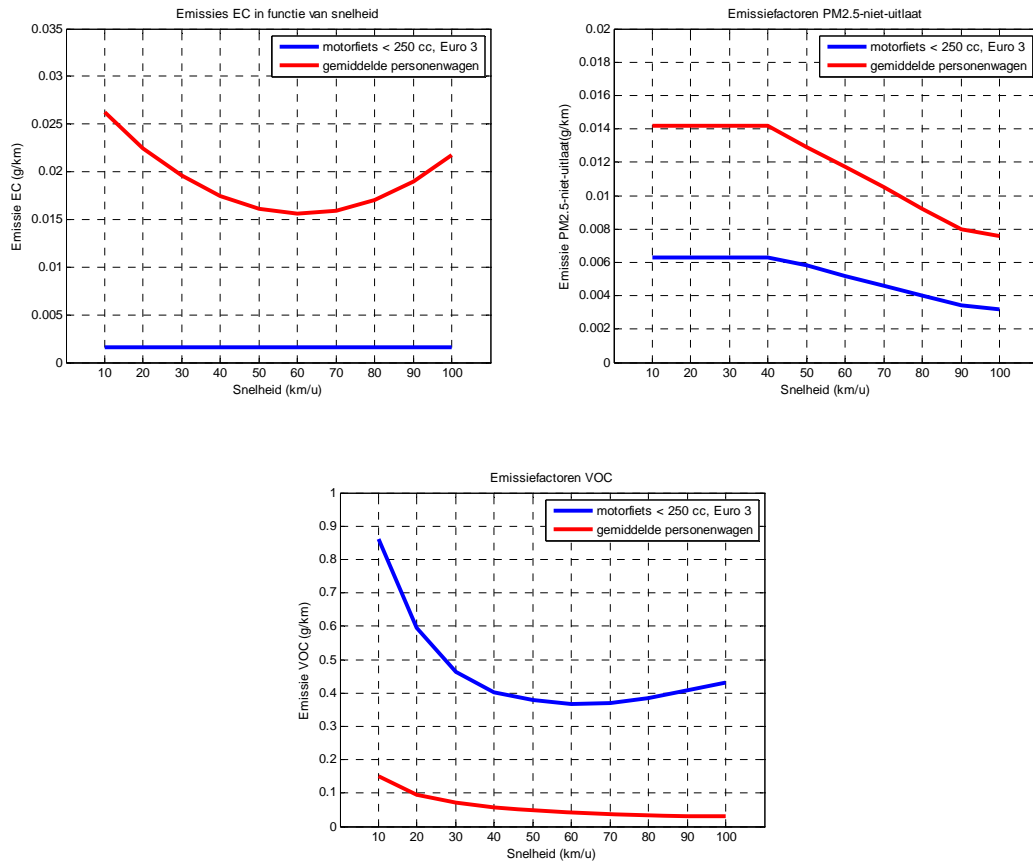


Figure 16: Emission factors for motorcycles and cars on motorways as a function of average speed

Most pollutants obtain minimum emission factors at an average speed of 60 to 70 km/h. At all speeds the emission factors of the pollutants CO_2 , NO_x , NO_2 , $\text{PM}_{2.5}$ and EC are higher for an average car than for a motorcycle (type 4-stroke, ≤ 250 cc, emissions class Euro 3). The emission factor of VOC is the only one that is higher for motorcycles. Figure 17 shows the emission factors of the different pollutants for motorcycles and cars next to each other. The emission factors in this case are those for motorway driving at an average speed of 90 km/h.

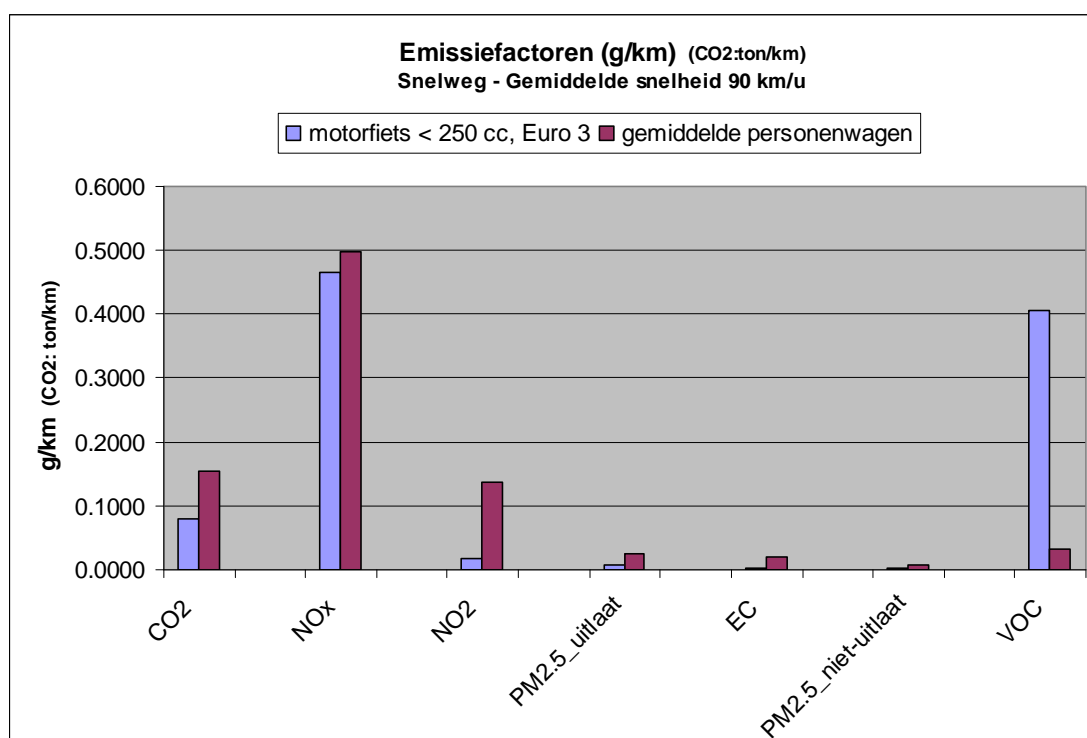


Figure 17: Emission factors of the different pollutants for motorcycles and cars for motorway driving at an average speed of 90 km/h

3.1.2 External emission costs

Emissions have a negative impact on public health, the climate, ecosystems, or more generally on the environment. Taking this environmental damage into account, emissions can be given a monetary value or linked to so-called ‘external emission costs’. External costs are those costs that result from a journey, but which the motorist does not take into account.

The link between emissions and external emission costs is made by means of a monetary valuation of these emissions. In this study we based the monetary valuation of the emissions on the results of the study ‘Update of external environmental costs - Actualisering van de externe milieuschadekosten’ by VITO (De Nocker et al. (2010)). In this study, the cost of environmental damage in Flanders is determined in accordance with the ExternE method. This method considers all steps from the emission to its impact on the environment. It takes account of the distribution of emissions, and their effect on people and the environment (increased symptoms of illness, reduced crop yields, erosion of building materials, contribution to the greenhouse effect, etc...). These effects are given a monetary value using the principle of ‘willingness-to-pay’, or how much someone would be prepared to pay in order to reduce the environmental impact.

Table 1 gives the emission values of the pollutants in question, which apply to traffic on the motorway:

Table 1: Value in 2010 in terms of €/kg (CO2 in €/ton), euro at 2009 value (source: De Nocker et al. (2010))

NO _x (€/kg)	PM _{2.5} (€/kg)	VOC (€/kg)	CO ₂ (€/ton)
0.577	135.503	7.535	20.000

Note that values are available for NO_x and PM_{2.5}, but not for the subcategories NO₂ and EC.

When we multiply the above emission valuations by the emission factors for motorcycles and cars, we can determine the total external emission costs (of all pollutants combined) for both vehicle categories as a function of the average speed. Figure 18 shows the results.

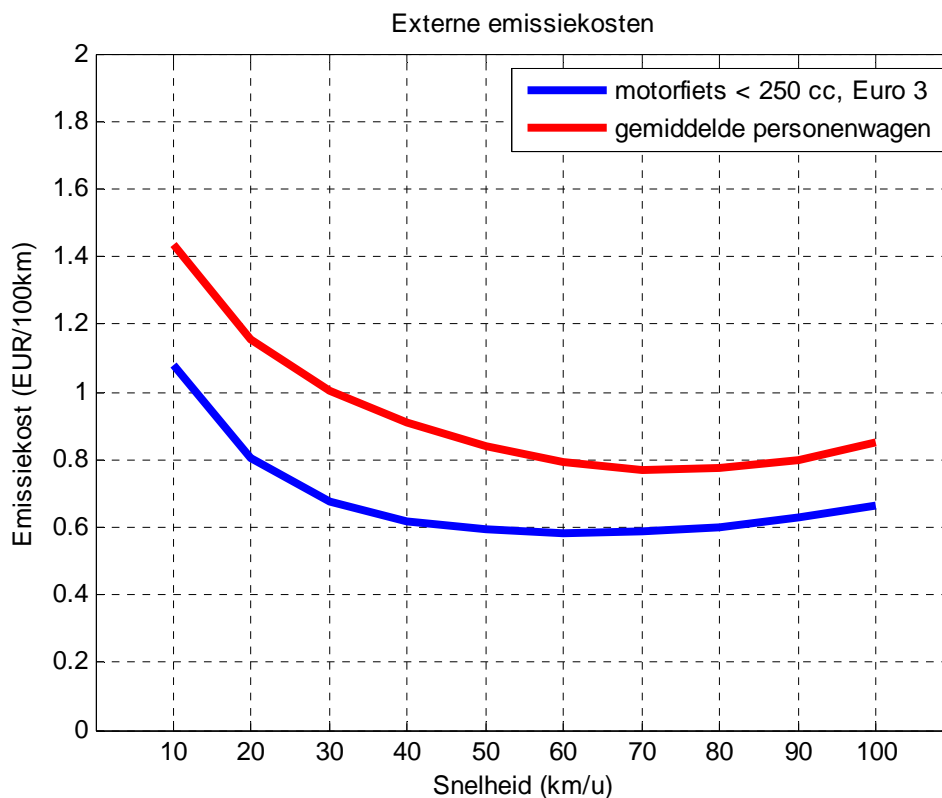


Figure 18: External emission costs for motorcycles and cars on motorways as a function of average speed

The external emission costs of motorcycles (type 4-stroke, ≤ 250 cc, emissions class Euro 3) are lower than those of an average car at all speeds. For both vehicle categories the external emission costs are at their lowest at an average speed of 60 to 70 km/h.

Figure 19 compares the external emission costs of the different pollutants for motorcycles and cars are compared with each other. The emission factors applied in this case are for motorway driving at an average speed of 90 km/h.

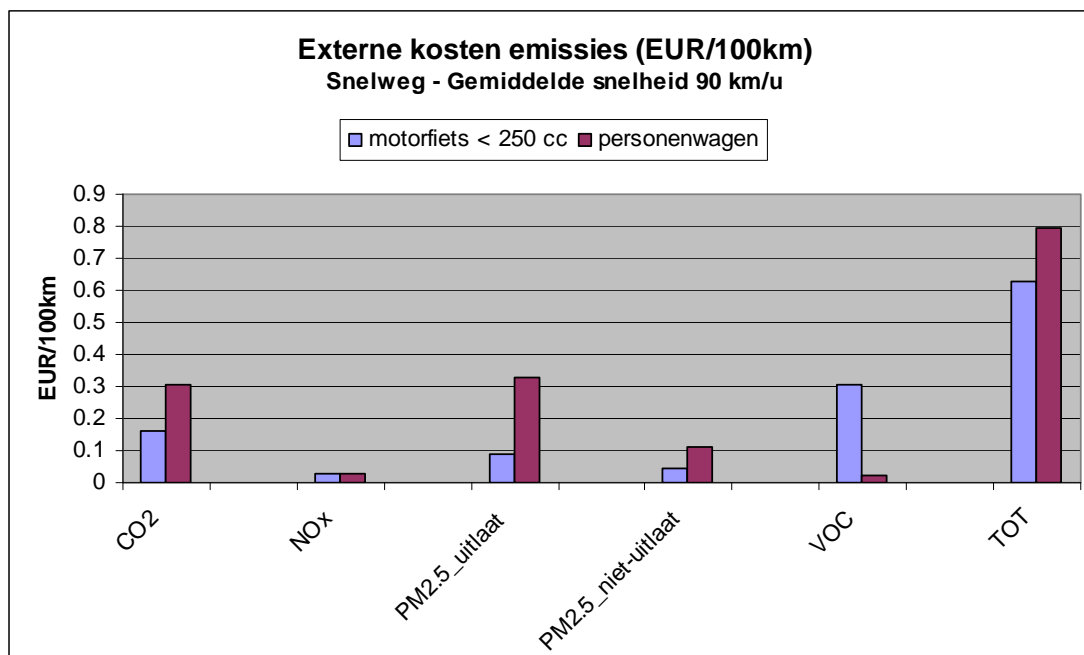


Figure 19: External emission costs of the various pollutants for motorcycles and cars

The external costs of CO₂, PM_{2.5} and VOC emissions are especially relevant. Cars generate higher costs in comparison with motorcycles in respect of CO₂ and particulates, but lower costs in respect of VOC. The total external emission costs of motorcycles (type 4-stroke, ≤ 250 cc, emissions class Euro 3) is **21%** lower than that of an average car.

3.2 Leuven-Brussels case study: emission costs

For the Leuven-Brussels case study under consideration (see Section 2.1) we determine external emission costs in the reference scenario and in the modal shift scenario. By comparing both scenarios we can then determine the effect of the modal shift on the external emission costs.

First we work out the external emission cost for each individual vehicle in both scenarios, taking account of the average speed of this vehicle during the journey from Leuven to Brussels. External emission costs are determined by multiplying emission values by emission factors (see Section 3.1.2). Figure 20 shows the total external emission cost as a function of the average speed for all vehicle categories.

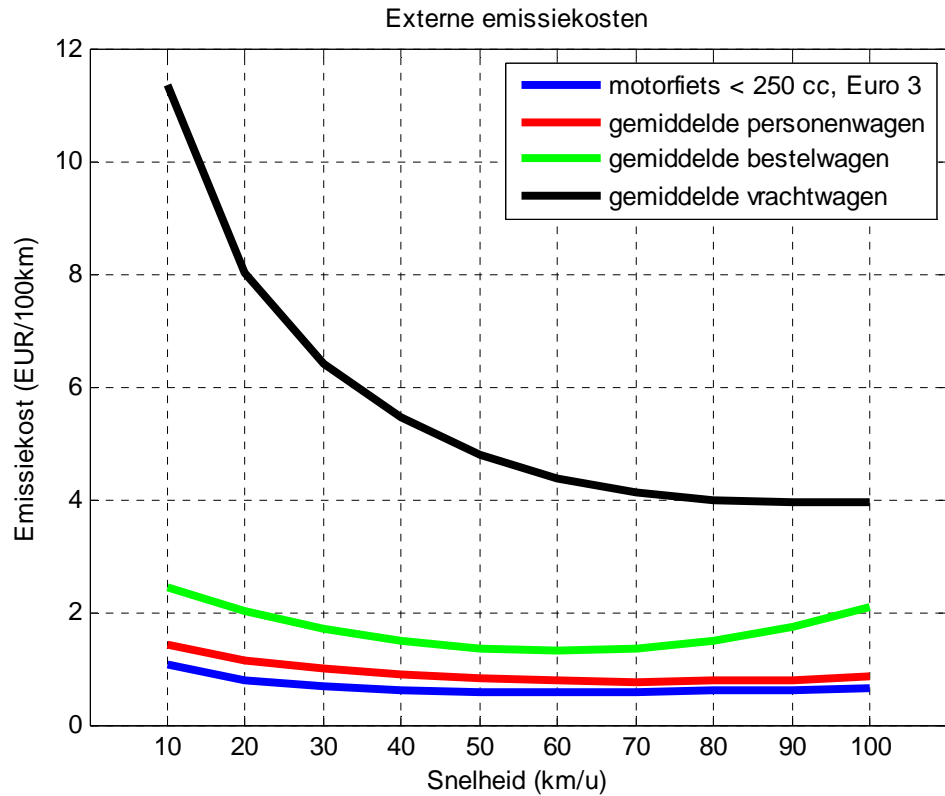


Figure 20: External emission costs for all vehicle categories on motorways as a function of average speed

When the emission cost has been worked out for each vehicle, we sum up the emission costs of all vehicles that make the journey from Leuven to Brussels during the morning rush hour (6.30 – 9.30 a.m.). The result is the total emission cost of all vehicles combined travelling from Leuven to Brussels. We now calculate these total emission costs both for the reference scenario and for the modal shift scenario.

Figure 21 compares the total emission costs by vehicle category in both scenarios:

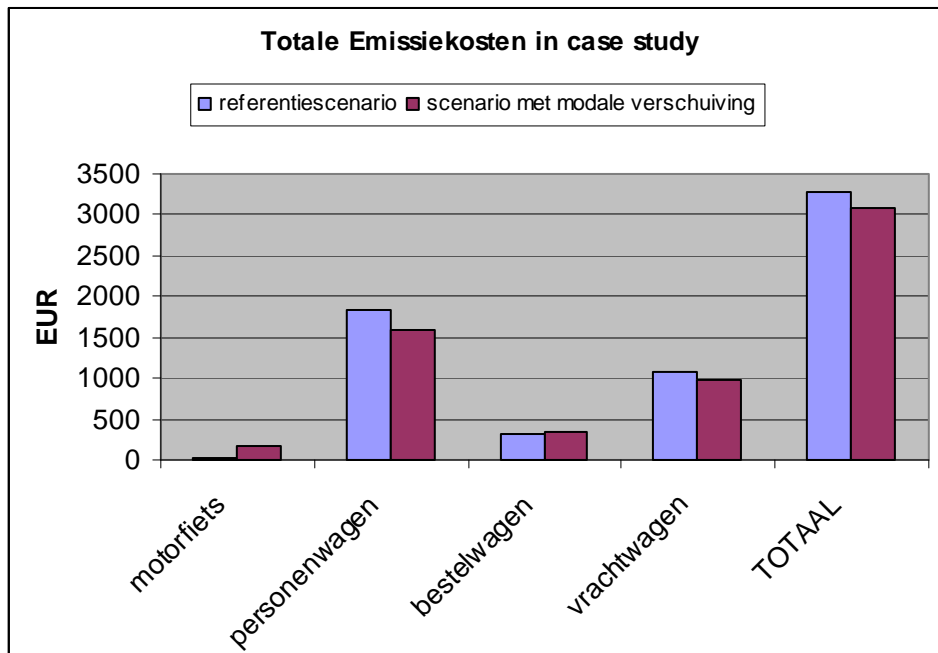


Figure 21: Total emission costs by vehicle category for the Leuven-Brussels journey during the morning rush hour

The total emission costs in the modal shift scenario are 6% (or €180) lower than in the reference scenario. There are two causes for this: in the modal shift scenario a number of cars are replaced by motorcycles, which have a lower external emission cost, while the modal shift scenario also results in a smoother traffic flow with higher average speeds in congestion.

Let us just examine these effects a little more closely:

Because of the increase in the number of motorcycles in the modal shift scenario the emission cost of motorcycles increases by €150 compared to the reference scenario.

The emission cost of cars falls in the modal shift scenario by €240. Of this, €180 can be attributed to the reduced number of cars and €60 to the higher average speed in congestion of the remaining cars. The replacement of cars by motorcycles therefore delivers a gain of €30 ($€180 - €150 = €30$).

The emission cost of trucks falls in the modal shift scenario by €90 (or 10%) compared to the reference scenario. The number of trucks remains the same, but in the modal shift scenario they travel faster when there is congestion, with the result that their emission cost falls. The smoother traffic flow with higher average speeds in congestion generates a total gain of €150 ($€60 + €90 = €150$).

From the total 6% (or €180) reduction in emission costs in the modal shift scenario, 1% (or 30 EUR) can therefore be attributed to the changed vehicle composition, and 5% (or €150) to the smoother traffic flow with higher average speeds in congestion.

Note that for the case study in question the emission benefits are 2 orders of magnitude lower than the time benefits. First, the total emission cost is an order of magnitude smaller than the total congestion cost and secondly the reduction in emission costs (modal shift scenario compared to reference scenario) is an order of magnitude smaller than the reduction in congestion costs.

Figure 22 shows how the total emission costs are distributed between the different pollutants.

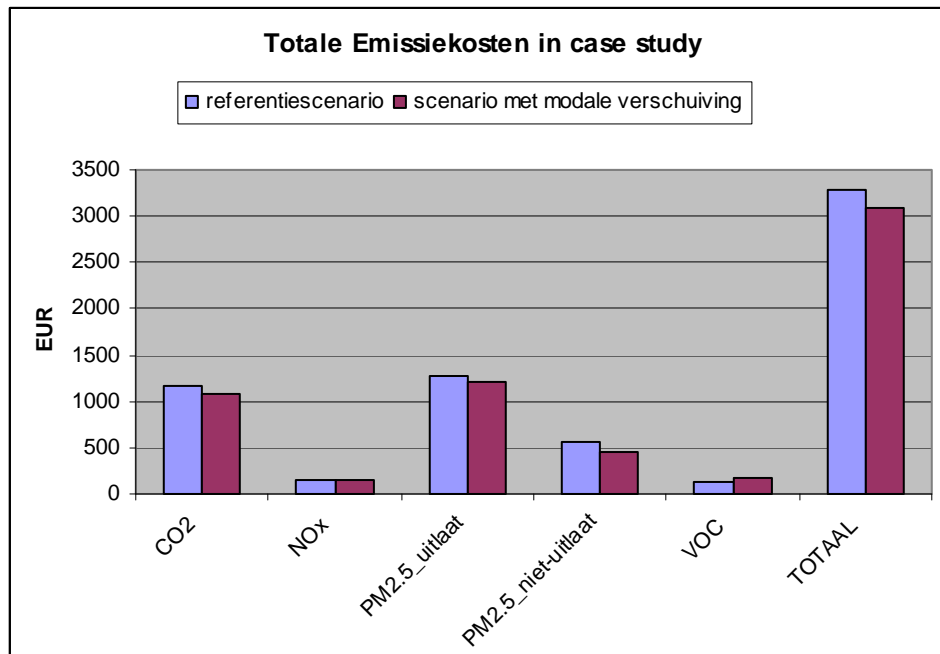


Figure 22: Total emission costs per pollutant for the Leuven-Brussels journey in the morning rush hour

Because of an increase in the number of motorcycles in the modal shift scenario the VOC emission cost increases by 36% compared to the reference scenario. The emission costs of all other pollutants are reduced in the modal shift scenario, partly because motorcycles have a lower external emission cost, and partly because of the smoother traffic flow with higher average speeds in congestion:

- CO₂: -7.5%
- NO_x: -5.5%
- PM_{2.5}_exhaust : -4%
- PM_{2.5}_non-exhaust : -16%

4 Conclusions

4.1 *Impact on traffic flow and congestion*

4.1.1 Leuven-Brussels case study

The impact of a modal shift on the traffic flow and traffic congestion has been examined using a case study in which the traffic on the Leuven-Brussels motorway journey was accurately simulated, first in a reference scenario and next in a scenario in which there is a modal shift from cars to motorcycles. By comparing both scenarios we can determine the effect of the modal shift on traffic flow and congestion.

The reference scenario shows the traffic flow in the current situation. Using a dynamic traffic model, realistic simulations were made of the traffic flows in the area of the study. These simulations show how a queue starts to form in Sterrebeek at 6.40 a.m. The queue grows with the result that the travel time for the Leuven-Brussels route increases. By 7.50 the queue stretches all the way back to Leuven. The journey from Leuven to Brussels then takes 14 minutes longer than during off-peak periods. The queue begins to disperse towards Brussels at 8.00. By 9.10 the queue has disappeared.

In the reference scenario there is a total of 1925 lost vehicle hours. This shows how much time is lost by all vehicles combined. This is a good indicator of traffic congestion.

In the modal shift scenario we assume that 10% of the cars are replaced by motorcycles. Simulations of this scenario also show that a queue begins to form at 6.40 a.m. in Sterrebeek. The queue grows more slowly and stretches less far at its peak, to around halfway between Sterrebeek and Bertem. The maximum travel time lost amounts to 6 minutes. The queue also dissipates more quickly in comparison with the reference scenario (the queue has disappeared by 8.30). In the modal shift scenario the total of lost vehicle hours is 706. Compared to the reference scenario this represents a reduction of 63%.

4.1.2 Overall effect on the primary road network

The impact on traffic congestion is also examined if a modal shift were to be achieved on the entire primary road network in Belgium. To this end, the results of the Leuven-Brussels case study are extrapolated to the entire primary road network. Because the relationship between the modal shift and the change in traffic flow, the reduction in travel times and the reduction in lost vehicle hours is strongly dependent on the location, the result of a rough calculation for the entire primary road network based on an extrapolation of the results of the case study can be taken as a purely indicative result.

In determining the impact account is taken of a knock-on effect on the primary road network. Because journeys on the primary road network become less expensive and therefore more attractive, they will on average attract approximately 2% extra traffic. Taking account of this knock-on effect, the Leuven-Brussels case study achieves a reduction in lost vehicle hours of 40% compared to the reference scenario. Extrapolating this figure to the entire primary road network suggests that 15,000 lost vehicle hours could be saved in Belgium every day, which is

equivalent to a total time-saving of around €350,000 per day. We emphasize that these figures only have an indicative value.

4.1.3 Overall effect on the secondary road network

Insufficient data is available for a quantitative analysis of a full modal shift on the secondary road network. Based on a number of partial reflections it can be expected that the time benefit is of the same order of magnitude as that of the primary road network. Additional research is needed to substantiate this statement.

4.2 *Impact on emissions*

The impact of a modal shift on emissions and emission costs is examined by means of the Leuven-Brussels case study. Emission costs are calculated in the reference scenario and in the modal shift scenario. By comparing both scenarios we can determine the effect of the modal shift on the emission costs.

Emission costs are worked out for each vehicle category. The emission cost of the pollutants CO₂, NO_x, NO₂, PM_{2.5} and EC is higher for an average car than for a motorcycle (type 4-stroke, ≤ 250 cc, emissions class Euro 3). Only the emission cost of VOC is higher for motorcycles. The total external emission cost of motorcycles (all pollutants combined) is 21% lower than that of an average car.

In the modal shift scenario, the total emission cost is 6% lower in comparison with the reference scenario. Of this, 1% can be attributed to the replacement of cars by motorcycles that have a lower external emission cost, and 5% to the smoother traffic flow with higher average speeds in congestion.

References

Yperman, I. (2007), *The Link Transmission Model for Dynamic Network Loading*. PhD Thesis, Katholieke Universiteit Leuven, Leuven, Belgium.

Frederix, R., C.M.J. Tampère, F. Viti and L.H. Immers (2010), *The effect of dynamic network loading models on DTA-based OD estimation*. In: Tampère C.M.J., Viti F. & Immers L.H. (eds): *New Developments in Transport Planning: Advances in Dynamic Traffic Assignment*. Edward Elgar, Cheltenham, UK - Northampton, MA, USA.

Federaal Planbureau (2009): *Traffic censuses - Federal Planning bureau 2009*,
[http://www.plan.be/databases/PVar.php?VC=TRAF001&D1\[\]=ZZTOT&D2\[\]=W40MOTO&D2\[\]=W50PRIVATE&D2\[\]=W60LDV&D2\[\]=W70HDV&D2\[\]=W80BC&D2\[\]=W90SPEC&D3\[\]=WW10SNEI&DB=TRANSP&lang=nl&XT=0](http://www.plan.be/databases/PVar.php?VC=TRAF001&D1[]=ZZTOT&D2[]=W40MOTO&D2[]=W50PRIVATE&D2[]=W60LDV&D2[]=W70HDV&D2[]=W80BC&D2[]=W90SPEC&D3[]=WW10SNEI&DB=TRANSP&lang=nl&XT=0),
consulted in August 2011

Ntziachristos, Samaras, et al., (2010) *EMEP EEA Emission Inventory Guidebook, Exhaust Emissions from Road Transport, Chapters 1.A.3.b.i, 1.A.3.b.ii, 1.A.3.b.iii, 1.A.3.b.iv*, 2009 (version of June 2010)

De Nocker L. et al. (2010) *Actualisering van de external milieuschadecosts (algemeen voor Vlaanderen) met betrekking tot luchtverontreiniging en klimaatverandering – Update of external environmental costs (general for Flanders) in relation to air pollution and climate change*, study commissioned by the Flemish Environmental Company - Vlaamse Milieumaatschappij, MIRA, VITO.

Lee Tzu-Chang (2007), *An Agent-Based Model to Simulate Motorcycle Behaviour in Mixed Traffic Flow*, PhD thesis, Imperial College London

Ellis T. (2005), *Inquiry into managing transport congestion Victoria*, Motorcycle Riders' Association (MRA) Submission, December 2005.

UK Department for Transport (2004), *Motorcycles and Congestion: The Effect of Modal Split*, London UK, 2004

Minh C. (2005), *The Speed, Flow and headway analyses of motorcycle traffic*, Journal of the Eastern Asia Society for Transportation Studies, vol. 6, pp. 1496-1508.

Holroyd, E. M. (1963) *Effect of Motorcycles and Pedal Cycles on Saturation Flow at Traffic Signals*. Roads and Road Construction, Oct., 315 – 316.

Powell, M. (2000) *A model to represent motorcycle behaviour at signalized intersections incorporating an amended first order macroscopic approach*, Transportation Research Part A, No. 34, 497 - 514.

Wigan, M. R. (2000) *Motorcycles as Transport*: Vol. 1 – Powered Two Wheelers in Victoria. VicRoads, Melbourne, Australia.

OVG Vlaanderen (2010) *Onderzoek Verplaatsingsgedrag Vlaanderen – Research into travel behaviour in Flanders, Sept. 2009 – Sept. 2010*, Instituut voor Mobiliteit, Hasselt, 2010

Agentschap voor binnenlands bestuur (2011) Kilometervergoeding bij dienstverplaatsingen – Mileage allowance for business travel, <http://binnenland.vlaanderen.be/kilometervergoeding>, consulted September 2011

De Ceuster, G. et al. (2010) *TREMOVE v2.3 Model and Baseline Description*, report by the European Commission, DG Environment, 2005; Update naar *TREMOVE v3.3*, 2010

Mayeres, I. (1999) *The control of transport externalities: A general equilibrium analysis*. PhD Thesis, Katholieke Universiteit Leuven, Leuven, Belgium.

Maerivoet S. en I. Yperman (2008) *Analyse van de congestie in België – Analysis of congestion in Belgium*, Final report for Federale Overheidsdienst Mobiliteit en Vervoer, October 2008.

Appendix A: Description of the Link Transmission Model

The Link Transmission Model is a dynamic traffic simulation model. Traffic simulation models determine travel times and travel costs in a traffic network, given the routes taken by all travellers.

Properties of the Link Transmission Model

The Link Transmission Model (LTM) is a macroscopic traffic simulation model, in which vehicles move as a continuum. Traffic streams are realistically modelled in large practical networks that include both motorways and urban areas. The LTM has the following characteristics:

- Traffic streams are placed in links in the same way as happens in first order kinematic wave theory. The build up and dispersal of the queuing process in LTM is closer to reality than in state-of-the-art macroscopic traffic assignment models.
- The LTM solution algorithm is computationally efficient, so that traffic streams in large networks can be simulated in a short calculation period.
- Vehicles are disaggregated to their routes. During their journey through the network the routes of the vehicles are constantly maintained, so that the information from the route choice model can also be used.

Solution algorithm

Traffic networks are composed of homogenous links a , which are defined by a start point x_a^0 and an end point x_a^L . These links have an arbitrary length L_a and are connected together with nodes n . Nodes have no physical length and act as exchange locations for traffic entities. Each node has a number of incoming links i and a number of outgoing links j .

The cumulative number of vehicles $N(x,t)$ is the total number of vehicles that pass location x at time t . For each time interval LTM determines the cumulative number of vehicles that pass the start and end points (x_a^0 and x_a^L) of each link a . Only when vehicles have left the link is their travel time determined.

The transmission stream $S_i(t)$ of link i at time t is the maximum quantity of vehicles that can leave the link during the time interval $[t, t+\Delta t]$, if this link fed into a reservoir with an infinite capacity. The receiving stream $R_j(t)$ of link j at time t is the maximum quantity of vehicles that could flow into the link during the time interval $[t, t+\Delta t]$, if infinite flow of traffic were to be released into this link.

The transfer stream $G_{ij}(t)$ is the quantity of vehicles that actually moves from link i to link j during time interval $[t, t+\Delta t]$. The LTM solution algorithm divides the total simulation period into time intervals Δt . For each time interval Δt the algorithm involves three steps:

For each time interval Δt ,

For each node n ,

Step 1: Determine the transmission stream S_i at the downstream end (x_i^L) for each successive link $i \in I_n$ and determine the receiving stream R_j at the upstream end (x_j^0) for each outgoing link $j \in J_n$.

I_n (J_n) is the set of successive (outgoing) links of node n .

Step 2: Determine the transfer streams $G_{ij}(t)$ of the successive links $i \in I_n$ to the outgoing links $j \in J_n$, i.e. determine which proportion of the transmission and reception streams are actually sent and received.

Step 3: Adjust the cumulative number of vehicles $N(x,t)$ for the downstream end (x_i^L) of each successive link $i \in I_n$ and for the downstream end (x_j^0) of each outgoing link $j \in J_n$:

$$N(x_i^L, t + \Delta t) = N(x_i^L, t) + \sum_{j \in J_n} G_{ij}(t) \quad \text{for all } i \in I_n$$

$$N(x_j^0, t + \Delta t) = N(x_j^0, t) + \sum_{i \in I_n} G_{ij}(t) \quad \text{for all } j \in J_n$$

Link model

In LTM traffic flows are reproduced on links as happens in kinematic wave theory. Traffic is characterised by three macroscopic variables: intensity q , density k and average speed v . The following relationship exists between these three variables:

$$v = q/k$$

The intensity q is the number of vehicles that pass by a particular place during a particular time interval dt .

The density k is the number of vehicles that are observed at a given point in time at a particular location dx .

Furthermore, kinematic wave theory assumes that a functional relationship exists between the intensity q and density k , also known as the fundamental diagram. By analogy with Newell (1993) in LTM a triangular fundamental diagram is used, as shown in Figure S.2.

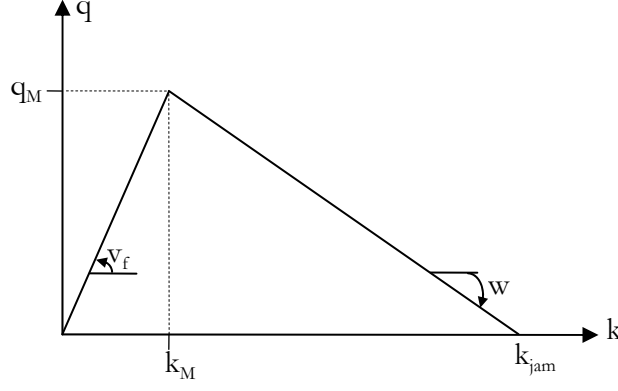


Figure S.1: Triangular fundamental diagram

The intensity q is zero for a nul density and for the maximum density k_{jam} . In between, the function reaches a maximum intensity q_M , which is also called the capacity. The rising section of the fundamental diagram shows the traffic situations in the ‘free-traffic’ regime, the falling section suggests the traffic situations in ‘congestion’.

Kinematic wave theory is based on the combination of the assumed fundamental diagram and the law of retention of vehicles. This traffic retention law describes the evolution of a traffic situation over place and time:

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0$$

Traffic situations in the ‘free-traffic’ regime propagate with speed v_f and traffic situations in ‘congestion’ move with negative speed w (see Figure S.2).

Cumulative vehicle numbers are derived from kinematic wave theory. Newell (1993) developed a method for determining the cumulative number of vehicles in links directly from the start and end values. An efficient method was developed based on Newell’s theory to determine transmission and reception streams, the first step in the LTM solution algorithm:

$$S_i(t) = \min((N(x_i^0, t + \Delta t - \frac{L_i}{v_{f,i}}) - N(x_i^L, t)), q_{M,i} \Delta t)$$

$$R_j(t) = \min((N(x_j^L, t + \Delta t + \frac{L_j}{w_j}) + k_{jam} L_j - N(x_j^0, t)), q_{M,j} \Delta t)$$

By determining transmission and reception streams in this way we ensure that the traffic in the links will propagate in the same way as in kinematic wave theory.

LTM has higher calculation efficiency than the Cell Transmission Model (CTM). CTM is a widely used traffic model with a different numerical solution scheme for the same kinematic

wave model. The CTM requires considerably more calculation time in order to achieve the same accuracy.

Node models

Node models determine the transfer flows $G_{ij}(t)$ of the successive links i to the outgoing links j of a node n , the second step in the LTM solution algorithm. Node models satisfy the traffic retention law. Each node model has defined rules of priority and behaviour that restrict the transitional flows and that finally determine which proportion of the transmission and reception flows are actually sent and received.

The following node models were used to model motorway networks:

- **Non-homogenous node**
Non-homogenous nodes are used to model a change in capacity or speed limit. These nodes connect 1 incoming link with 1 outgoing link (see Figure S.3).



Figure S.2: Non-homogenous node

- **Source node**
In a source node, traffic is released into the network. These nodes operate as feeding points for network traffic. These nodes consist of 1 outgoing link (see Figure S.4).

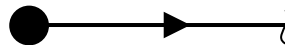


Figure S.3: Source node

- **Destination node**
Traffic leaves the network in a destination node. 1 link feeds into a node of this sort (see Figure S.5).



Figure S.4: Destination node

- **Split node**
Split nodes are used to model exits from a motorway. 1 link feeds into a split node and exactly 2 links exit from it (see Figure S.6).

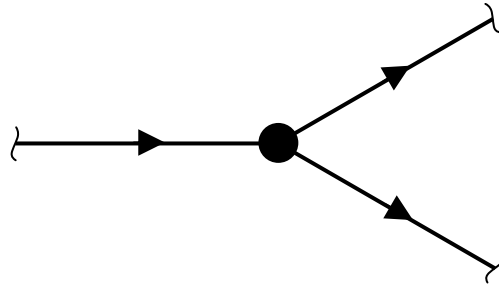


Figure S.5: Split node

- Aggregation node
Aggregation nodes are used to model entrances onto a motorway. 2 links feed into an aggregation node and 1 link departs from it (see Figure S.7).

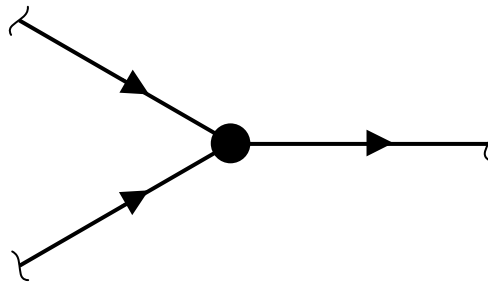


Figure S.6: Aggregation node