Impact of individual traffic management on liveability

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by

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Cover picture retrieved from http://helpspread.net/2017/08/29/4-traffic-does-not-come-from-no-where/

Preface

This thesis is the final product of my graduation of the master Transport, Infrastructure and Logistics at the TU Delft. It marks the end of an educational seven years, both regarding the content of my studies, and my own strengths and weaknesses.

I would like to thank Antea Group, for giving me the opportunity to carry out this graduation work, for being open to a more future-oriented research, and for letting me get to know the company. I would like to thank the experts that helped me gain insight in their field of knowledge. Furthermore, I am grateful for the colleagues at Antea Group for their support, interest, and making me feel part of their team for a few months.

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Bernice Noëlle den Haan
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Introduction

This chapter gives an introduction on externalities caused by traffic and possible solutions for them. Furthermore, the research gap and corresponding research objective and questions are described and the methodology to answer these questions is discussed.

1.1. Context

Marchetti's constant, or in Dutch the *'BREVER-wet'*, describes that over time, people keep spending the same amount of their time on transport. However, people travelling from A to B causes several negative externalities, such as congestion, pollution, noise, and accidents. These externalities can have consequences for the liveability of the environments of roads, causing nuisance, reduced safety, or mental and physical health issues (Ising, Dienel, Günther, & Markert, 1980, Künzli et al., 2000, Laumbach & Kipen, 2012). Furthermore, congestion can be seen as a loss of money (Hoogendoorn et al., 2012).

There are multiple options to reduce these effects. For example, building extra infrastructure can temporarily alleviate congestion, technological advancements can reduce pollution and noise from cars and asphalt, and seat belts have caused a significant reduction in fatal car accidents. Another approach for reduction of these externalities is traffic management. Within traffic management, multiple solutions are possible: increase of throughput, better distribution of traffic across the network, regulation of the inflow of traffic, and prevention of spillback (Hoogendoorn et al., 2012).

When deciding on a route to their destination, travellers usually opt for the fastest route, leading to a user equilibrium (UE). However, as most users do this, in case of high demand the originally fastest route is likely to be congested, while an alternative route might be free flowing. Individual traffic management can focus on a better distribution of vehicles over the network, yielding a system optimum (SO). However, an alternative route might take a few minutes of extra travel time for some people. Whether users are willing to comply with the social route advice as opposed to the selfish route can depend on several factors, such as their level of altruism and familiarity with the network (Bonsall, 1992, Van den Bosch, Van Arem, Mahmod, & Misener, 2011).

In case of congestion, using their in-vehicle navigation, some travellers already choose alternative routes. Although this could improve conditions on the main route, if the alternative route uses local roads, this might reduce liveability there. Therefore, it is important to not only consider travel time in distributing traffic over a network, but also take liveability into account.

1.2. Individual Traffic Management

Individual traffic management (ITM) gives road users individual routing advice, via in-car systems such as an app on a mobile phone. This allows to give routing advice at any point in space or time, as opposed to the fixed variable message signs (VMS). Furthermore, not all routing advice has to be the same, allowing traffic to be spread more evenly over the network. Individual traffic management can also be extended into personal traffic management. This means the advice is personalised to consider characteristics and preferences of the traveller.

1.3. Research gap

Currently, as is illustrated further in Chapter 2, quite some research exists on the emissions resulting from a system optimum versus a user equilibrium. Although limited, some literature considers the effects on noise and safety as well. Wismans et al. (2012) consider the impact of Dynamic Traffic Management (DTM) on multiple externalities of traffic such as emissions, noise, and safety. However, they consider VMS as a means to communicating the advice, which can only give the same message to all drivers currently on that section of the road. Individual traffic management allows to advise road users at any location or time, and vary this advice from vehicle to vehicle. This brings about the opportunity to give more detailed and accurate advice. However, currently, no research has considered the effects of individual traffic management on travel time as well as air quality, noise and accident risk yet.

1.4. Research objective

This research aims to take the effects on the liveability of roads into account. It aims to quantify the relations between traffic conditions such as capacity, speed, and density on the one hand, and externalities such as congestion, emissions, noise, and accidents on the other hand. Assessing the effects individually allows to reveal existing trade-offs between the different objectives. From a practical perspective, this allows to obtain an insight in the effects achievable, and what conditions are required to obtain impact.

1.5. Research questions

This research objective can be captured in the following research question:

How can negative effects on liveability be improved using individual traffic management,
considering users willingness to comply with the given advice?

Two important terms in this question are liveability and individual traffic management. The first, liveability, comprises air quality, noise, and accident risk. Individual traffic management in this research considers in-car route advice, that can differ among travellers with the same origin, destination, and departure time.

To answer this main research question, several sub questions have to be answered. First, the relations between what happens on the road and the effects on different aspects of the liveability have to be determined. This can be captured in the following sub question:

1. What are the relationships between traffic conditions and effects on the liveability regarding travel time, air quality, noise, and accident risk?

As a system optimum often requires some travellers to sacrifice some travel time, distance, or comfort, not all travellers might be willing to follow the given advice. As the amount of road users complying with the route guidance impacts the effects achievable, it is important to be aware of the aspects affecting the compliance behaviour. This is captured in the following sub question:

2. Which personal and context factors influence the compliance of users with route advice?

Next, it can be assessed what aiming to reduce the externalities means for the required traffic conditions and thus the required route advice. This is expressed in the following sub question:

3. What is the required route advice when aiming to achieve goals for travel time, air quality, noise, and accident risk?

This yields the ideal traffic situations and distribution over the network.

Finally, to compare the individual effects that can be obtained, they have to be evaluated. This allows to get an insight in the trade-offs between the different objectives. The corresponding sub question can be formulated as:

4. What trade-offs exist between travel time, air quality, noise and accident risk when using individual traffic management aiming for a different liveability and travel time goals?

Using these sub questions, the main research question can be answered.

1.6. Methodology

Below, the approach for answering the research questions is described.

1.6.1. Literature research

First, the relationships between traffic conditions and externalities have to be determined, relating to the first sub question. As some studies and national guidelines on this already exist and conducting real-life experiments would be out of scope for this research, these relationships are defined using literature research. Definitions of the effects considered are also delineated. Another aspect that can be examined using existing literature is the influences on compliance of users of the second sub question. Existing literature on this is fairly large, so the answer to this question serves more as context information. The literature is discussed in Chapter 2

1.6.2. Model building

When the relationships between traffic conditions and externalities are known, minimising these externalities represent multiple objectives. To achieve these objectives, an optimisation model has to be developed. First, this is described in a mathematical model, using the relations between traffic conditions and externalities found earlier. This mathematical model is described in Chapter 3. A fictional network is described in terms of link lengths, speed, capacity, demand, and vehicle type distribution, as well as the number of people in the surroundings that are affected, to be able to change and test the impact of these variables. Limits on additional travel time and the externalities on air quality, noise, and accident risk will serve as constraints. Combined, this forms an optimisation model that is solved in Excel. How this is set up, is described in Chapter 3 as well.

1.6.3. Effect estimation

To be able to assess the different factors that can be of influence on the impact reduction attainable, various cases and scenarios are set-up, as are described in detail in Chapter 4. Within these cases and scenarios, the model is optimised for multiple objectives: minimising experienced travel time, minimising negative effects on air quality, minimising noise, minimising accident risk, and minimising all these effects at once. By determining the ideal traffic advice to achieve the different goals, the third sub question can be answered. The results of this optimisation across the different cases and scenarios are discussed in Chapter 5

1.6.4. Effect appraisal

Finally, these solutions to the optimisation are evaluated in Chapter 6. By attaching a monetary value to each of the individual effects, the effects can be appraised and compared in the same unit. Furthermore, trade-offs between the different objectives can be made explicit, answering the fourth sub question. As individual traffic management uses existing infrastructure, it is assumed there is no significant investment needed. Therefore, the ratios of effects can be assumed to be the same every year, so discounting the effects over the years is not necessary.

1.6.5. Visual summary

A visual overview of the methodology is given in Figure 1.1. The colours of the segments indicate the related sub question.

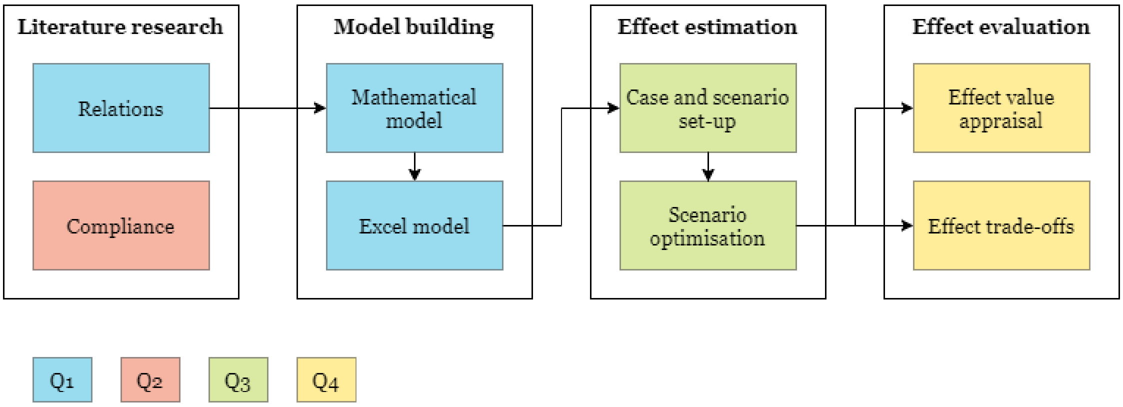

Figure 1.1: Visual summary of approach

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Theories and literature review

In this chapter relevant theories and existing literature are discussed. Traffic flow theories are described, research on liveability effects is examined, and factors influencing compliance are analysed.

2.1. Traffic flow theory

In traffic flow, three important macroscopic variables are flow (q), being the number of vehicles passing a reference point per unit of time, speed (u), being the average speed on a road section, and density (k), describing how close vehicles are to each other. These are related in the well-known formula $q = k*u$, and can be presented in the fundamental diagram. An important aspect of this fundamental diagram is the capacity, being the maximum flow at a road. Related to this maximum flow are the critical density and the critical speed. Traffic is in an uncongested state when the density is lower than the critical density, it is congested for higher densities. The free flow speed can be described as the speed of the vehicle at zero density, the jam density is when vehicles have no speed (Knoop, 2018).

Several causes exist for congestion. Fixed and moving bottlenecks block one or more lanes, decreasing the total capacity of the road or the average speed, causing shock waves upstream from the bottleneck. Furthermore, in dense traffic, when traffic demand is near capacity, local instabilities in traffic can cause stop-and-go waves. Here, traffic comes (almost) to a complete stop, with the density being jam density. Often, these jams occur so short after one another, that the outflow of the first stop-and-go wave is the inflow of the second (Knoop, 2018).

2.2. User Equilibrium versus System Optimum

Two well-known principles regarding travel times and the distribution of traffic over a network are described by Wardrop (1952). The first is the User Equilibrium principle, where traffic distributes itself in such a way, that travel times on all routes in a network from an origin to a destination are equal. The travel times of unused routes are equal to or greater than these shortest routes. In this situation, travellers can not decrease their travel time by unilaterally switching their route. The second is the System Optimum principle, where the total travel time in the network is minimal (Kerner, 2011)

In case of congestion, these two principles are in conflict with one another: the choice of the drivers for the shortest route increases the total travel time in the network, with the negative marginal impact on the network often being greater than the gain for the individual driver. Literature on the UE versus the SO is extensive. Mahmassani & Peeta (1993) for example compared the cost and performance under time-dependent SO and UE assignment, considering the effectiveness of advanced traveller information systems (ATIS). ATIS supply travellers with real-time traffic information or navigation instructions. They found that ATIS information supply strategies based on SO route guidance could perform better than non-cooperative information strategies. With low loading levels, UE and SO perform similarly. The higher the congestion levels, the greater the improvement achieved under SO that is observed compared to UE. Average travel distance was increased under SO compared to UE. When all links in the network are highly congested, the options for rerouting are lowered, decreasing the benefit of SO over UE (Mahmassani & Peeta, 1993).

Wie, Tobin, Bernstein, & Friesz (1995) have described the cost difference between a UE and a SO as well. In their costs, they considered the number of vehicles that did not reach their destinations by the end of the planning horizon, the total travel time, and the schedule delay. In their research, arriving one minute early or late at a destination is preferred over one minute of driving. The SO was found to have lower generalised travel costs than the UE (Wie et al., 1995).

Boyce & Xiong (2004) found a decrease of 5% in total travel time could be achieved, however leading to an increase in the travelled distance of 1.5% for their test network. For some travellers, travel time increased. For some users, this increase could be fairly large.

Jahn, Möhring, Schulz, & Stier-Moses (2005) consider this unfairness in their research, by limiting the allowed travel time on an advised route to a predefined "normal length" plus a tolerable factor. This approach ensured fairness of the routing advice compared to an unconstrained SO, while still yielding a total travel time close an unconstrained SO.

2.3. Individual traffic management

Currently, most route guidance for cars is done via road signs, Variable Message Signs, or in-car navigation. These options have in common that the same route advice is given to all drivers with a similar origin and destination. Although some in-car navigation offers the option to choose for example between the fastest, the shortest, and an environmentally friendly route, most users will pick the first option, again causing the same route to be used by all drivers with a similar origin and destination. With individual traffic management it is possible to give drivers with similar origins and destinations a different routing advice, allowing traffic to be distributed over the network into a SO. This advice is updated depending on the current situation on the road. Ma, Zhou, & Lee (2016) for example proposed a personalised system optimum traveller information (PSOI) system comprising personal attributes such as value of time and willingness to take detours, that reduces average travel time in the network.

2.4. Impact on the environment

As shown in Section 2.2, the conflict in travel time between the UE and the SO is well-described. But besides an increase in travel time, congestion can bring about a change in emissions, noise, and safety as well. Some examples of existing literature on these effects are described below.

2.4.1. Emissions

Routing to minimise emissions is considered more and more in research. Rilett & Benedek (1994) for example assessed the possibilities of an intelligent vehicle-highway system (IVHS) in reducing traffic congestion and air pollution. They calculated the CO emissions produced per vehicle on a given link. They found that the seemingly corresponding objectives of the reduction of system travel time and the reduction of pollution, could conflict.

Benedek & Rilett (1998) also studied the effects of different routing objectives on emissions, while taking equity of the effects into account. They used two different approaches in their model: the first is charging the users of the system for their CO emissions of their trip, yielding a UE where drivers try to minimise their emissions, the second uses intelligent transportation systems (ITS) to minimise the total CO emissions in the entire network, aiming for a SO. However, only small differences between the environmental objectives and travel time objectives were found, which the researchers attributed to characteristics of the case study network. Furthermore, when equal distribution of the pollution over the network was considered, an increase in CO emissions was found.

Van den Bosch, Van Arem, Mahmod, & Misener (2011) considered social cost comprising travel time loss for other drivers, extra fuel consumption of other drivers and CO_2 emission. They calculated the emission of CO_2 per meter, dependent on speed. It was found that the higher the share of people following the social advice, the lower the average travel time. Compared to time savings, the reduction of CO_2 emissions and fuel consumption they found to be relatively small.

Aziz & Ukkusuri (2012) integrated an emission-based objective into the traditional travel time based dynamic traffic assignment (DTA) framework. They considered the effect on travel time and CO emission, route choice behaviour, and speed profiles. CO emission concentrations were calculated per cell, as well as per vehicle per second, to compute emissions for the full network. If more importance was assigned to CO emissions in the DTA model, they found higher travel times.

Bandeira et al. (2018) assessed the impacts of eco-routing on the reduction of pollutant emissions and considered the resulting variations in travel time. They calculated NO_x, CO, HC, and CO_2 per road segment. When routing advice was given to minimise the total system environmental impact, a reduction of 9% of CO_2 and NO_x could be achieved in their case study. However, when advice was given to minimise the emissions per driver, the total emissions could be higher than the standard UE, because travellers then could be navigated to lower capacity roads.

2.4.2. Noise

Most noise of traffic is originating from the rolling of the tires, aerodynamics, and propulsion, for example the engine and exhaust. The amount of this noise can be influenced by vehicle characteristics and driver behaviour at the vehicle level, and traffic volume, road design, composition of traffic, and speed at the road level (Wismans, Van Berkum, & Bliemer, 2011).

For quantifying the amplitude characteristics of noise, often the equivalent sound power level L_{eq}, is used, or L_{den}, which considers the different experience of noise during the evening and the night. Here noise is calculated as a steady flow. However, fluctuation and the time pattern of noise can influence annoyance as well. Therefore, De Coensel, De Muer, Yperman, & Botteldooren (2005) developed a model for dynamic traffic noise prediction. This showed local variations in noise, and allowed to assess the effect of traffic on the urban soundscape more accurately.

Johnson & Saunders (1968) described different relations between traffic characteristics and noise levels in free flowing conditions. Noise increases with flow, and decreases with distance from the road. Furthermore, a higher speed also causes an increase in noise.

Calvo, Álvarez-Caldas, San Román, & Cobo (2012) measured which variables influence vehicle noise. They found that aggressive driving behaviour, which they defined as driving fast and using lower gears than normal to increase acceleration, increases engine noise significantly, especially for gasoline cars as they accelerate faster. Under similar conditions, however, for diesel vehicles the engine noise is greater than for gasoline vehicles.

2.4.3. Safety

Several factors influencing traffic safety can be distinguished. First, speed influences crash risk: higher speeds lead to an exponential increase in risk (Kloeden, McLean, Moore, & Ponte, 1997, Kloeden, Ponte, & McLean, 2001), as drivers have less time to react to their environment and vice versa (Hakkert, Gitelman, & Vis, 2007). Furthermore, as kinetic energy is dependent on speed and mass, these factors influence crash severity. Differences in mass cause higher impact on the lighter party (Wegman, Aarts, & Bax, 2008). Another factor contributing to accident risk is the difference in speeds between vehicles. Furthermore, road types can influence accident risk as well. For example, roads intended for higher speeds often have wider lanes, fewer junctions, and separate driving lanes (Hakkert et al., 2007).

Brownfield et al. (2003) found that, on the motorway, more accidents occurred in case of congestion. On urban and peri-urban roads, however, fewer accidents were found to occur. This may partially be attributed to the high share of users that are familiar with the road conditions during congestion periods. Another plausible explanation is the lower speeds of the vehicles. For two-wheeled motor vehicles, cyclists, and pedestrians the share of fatal or serious accidents was found to be similar in congested and non congested situations, which they assigned to the vulnerability of these road users.

In The Netherlands, most deadly accidents occur on road with a speed limit of 50 km/h (27%), 80 km/h (22%), and 60 km/h (14%). Most deadly accidents occur outside city limits (SWOV, 2019).

A new attitude is the risk-based approach, where the safety of a road section is assessed based on risk factors, such as road characteristics, circumstances, or behaviour. The Safety Performance Indicators (SPI) mentioned by Kennisnetwerk SPV (2019) for which policy can be designed are shown in Table 2.1.

Furthermore, Dijkstra & Drolenga (2007) describe nine criteria to evaluate the safety of different routes. These are shown in Table 2.2.

Chatterjee & McDonald (1999) assessed the effect of driver information on accident risk. They found no significant reduction in accident occurrence, both for drivers using dynamic route guidance systems (DRG) and for the full network. The fastest route usually was found to be the safest route, except when in case of high congestion minor roads are used in alternative routes, which could have higher accident risk. They found accident risk to be highly dependent on the travelled distance and the number of junction crossings.

Abdulhai & Look (2002) discussed the influence of DRG on accident occurrence in an urban network. They found that, up to a transition point, more accidents occurred when the usage of DRG was higher. This

Table 2.1: Safety Performance Indicators

Traffic safety domain	Safety Performance Indicator
1. Safe roads	**1a. Safe roads (general)** Share of motorised traffic on roads qualified as 'sufficiently safe' **1b. Safe bicycle infrastructure** Share of cyclists on roads or bicycle facilities qualified as 'sufficiently safe'
2. Safe speed	Share of motorised traffic that does not exceed a safe speed and the speed limit
3. Safe vehicles	Share of new vehicles with the highest (Euro) New Car Assessment Programme score
4. Safe road users	**4a. Sober drivers** Share of drivers not under influence of alcohol or drugs **4b. Use of safety measures** Share of road users wearing a seat belt; share of use of approved helmets and child seats **4c. Light use in reduced visibility** Share of vehicles that uses light (per visibility condition) **4d. Attention to traffic** • Share of drivers not using a phone while driving • Share of drivers that indicate there was no risk of falling asleep while driving in the past year
5. High quality trauma care	Share of traffic victims that receives professional medical care within 10 to 15 minutes

Table 2.2: Criteria for safe routes

Criterion	Unit
Limited transitions of road categories	Number of additional transitions
Correct type of transition	Number of erroneous transitions
Number of missing road categories as low as possible	Number of mission road categories
Share in length of access roads as low as possible	Percentage of total distance
Share in length of distributors as low as possible	Percentage of total distance
Travelled distance	Meter
Travel time	Seconds
As little as possible left turns	Number of left turns
Limited junction density between junctions of access roads	Number per km

can be explained as DRG improves network efficiency and utilisation, increasing throughput. As more traffic was handled and more manoeuvres and turns were made, more accidents occurred. However, as more traffic reached their destination sooner due to the efficient routing in the previous period, the traffic demand decreased below congestion level after the transition point, causing a decline in the number of accidents. In their study, the researchers found that a 60% share of DRG use led to the highest number of accidents during the congestion period, and the lowest number after the transition point.

2.4.4. Multiple effects

Wismans et al. (2011) reviewed existing literature on modelling traffic safety, emissions, and noise combined with DTA models. They argue that, as relations exist between traffic dynamics and externalities, DTA models producing output on flow, speed, and density are most suitable to determine effects. Furthermore, they describe appropriate methods for determining the effects of traffic on safety, emissions, and noise.

Wismans, Van Berkum, & Bliemer (2013) formulated an optimisation problem comprising objectives related to externalities as a discrete multi objective (MO) network design problem (NDP). This was solved as a bilevel optimisation problem and yielded a Pareto optimal set of solutions. They defined efficiency by the total travel time in the network. Safety was described as the total number of injury accidents. The total emission of CO_2 was used to depict climate, and the weighted total amount of NO_x emissions was used as air quality. Noise is described as the average weighted sound power level. Of their used objectives, they found that efficiency, climate, and air quality are aligned, while they are opposed to traffic safety and noise. Safety and noise were found to be neither aligned nor opposed. This can be explained as efficiency aims at maximising throughput and therefore minimising congestion, at which both climate and air quality aim as well. For traffic safety, the use of the relatively safe routes needs to be maximised, and reducing noise aims at lowering driving speeds and using rural roads. However, no solution could be found that optimised the three aligned objectives. Using the set of Pareto optimal solutions, they established a trade-off for their case study of 2 kg CO_2 emission reduction in exchange for an increase of 1 vehicle lost hour.

2.4.5. Definition liveability effects

As can be concluded from the literature described above, various definitions can be used for the effects on the liveability. Firstly, regarding the environment, one can make a distinction between pollutants affecting health, such as particulate matter (PM), nitrogen dioxide (NO_2), and ozone (O_3), which results from volatile organic compounds (VOCs) and nitrogen oxides (NO_x), and those affecting the environment, including carbon dioxides (CO_2), O_3, and NO_2. Additionally, pollutants can be emissions from the exhaust pipe of a car, but can also be attributed to wear. For PM, about 80% is originating from combustion of fuel, the rest is wear of for example the road, wheels, or engine (RIVM, 2018). Finally, one can consider local effects as well as network wide effects. This research will focus on the effects at vehicle level.

Noise can be considered as the amount of dB, for which several measurements such as L_{eq} or L_{den} are used, or as the annoyance experienced from the noise. The preferred value for noise to reach houses is no higher than 50 dB during the day, the maximum is 65 dB (Rijkswaterstaat, n.d.-a). During the evening, these values are 5 dB lower, at night, they are lowered with 10 dB (Rijkswaterstaat, 2018) Furthermore, the distribution of noise could be considered as well.

For safety, both the amount of accidents and the severity can be taken into account. In contrast to emissions and noise, the number of accidents can not be predicted, only the risk associated.

2.4.6. Conclusion

All existing literature described above provides a relevant context, however, up to this point, no literature exists where individual traffic management is used to obtain a system optimum while minimising externalities of traffic such as polluting emissions, noise, or reduced safety. This research aims to fill this research gap.

2.5. Compliance

An important aspect of route guidance is the extent to which drivers follow up the advice. In the literature, several factors that influence compliance are distinguished.

Bonsall (1992) for example describes that compliance of users depends on the extent to which other factors, such as the alignment of the advised exit to the destination, the congestion level on the suggested exit, or the behaviour of preceding drivers, corroborate the advice. Furthermore, it is dependent on how familiar drivers are with the network, and on the quality of previous advice. If drivers are asked to leave a route they normally use, or adversely, sent via a route which is usually congested, they are less likely to comply. It was also found that both young drivers and experienced drivers were less likely to comply, as well as users with time minimisation as main criterion as opposed to for example distance minimisation as main objective.

Bonsall & Joint (1991) further emphasise the importance of credibility of the advice. For example, they mention that the exclusion of short cuts is quickly noticed by the users, often leading to rejection of the advice. "External" evidence, such as the actions of other drivers, or alignment with the compass direction of the destination, increased the compliance. Furthermore, a system optimising an environmental objective is more likely to be rejected than one aiming for efficiency, as the latter usually yields congestion-avoiding routes, which is an important criterion for many users.

P. S.-T. Chen, Srinivasan, & Mahmassani (1999) analysed the compliance of travellers with ATIS and found several factors of influence. Drivers comply less with inaccurate and unreliable advice. If the route advised is different from the currently followed route, drivers experience a cost for switching, consisting of the distance needed to switch to the advised path. This induces a lower compliance rate. Furthermore, if drivers recently experienced congestion, the compliance with real-time information is lower. Additionally, prescriptive information caused drivers to be more likely to comply than descriptive information. Finally, the authors found a hierarchy of information systems with different compliance rates. Travellers were most likely to comply with predicted information, followed by information based on prevailing travel times, perturbed information, where random errors are added to the predicted travel times, then differential predicted, and differential prevailing information, where travellers have no information on one of the alternatives. They found the lowest compliance with random information.

Srinivasan & Mahmassani (2000) found that larger travel time savings induce higher compliance, while higher switching cost reduces compliance. Furthermore, more traffic on the current day compared to the base situation yielded higher compliance. Additionally, when travel time was overestimated, compliance was reduced. If travel time was underestimated, travellers were less likely to continue the current path.

W.-H. Chen & Jovanis (2003) assessed factors influencing compliance with en route guidance, especially at intersections. A factor that was found of significant influence regarding the advised link is whether this link is on the motorway or approaching the motorway: drivers are more likely to comply with motorway advice. Additionally, if a turn is required to follow the advice, the compliance rate is lower. If the suggested route is congested or an incident has occurred on this link, drivers were also less likely to comply. Personal characteristics found to be of influence were subjects' spatial experience at the same intersection, temporal experience with the system in the same day, and education level.

Chorus, Molin, & van Wee (2006) describe several other factors influencing compliance with route advice. Because drivers' generally perceive the benefits of route information to be small, they have a very low willingness to pay for advice in monetary costs. In non-monetary costs, the service should be easily usable and readable and comprehensible while travelling. Furthermore, they showed a learning effect, where information on the route normally chosen by the driver might reduce the user's misconceptions on that route. It was also found that information is effective when the other alternative is more attractive than the currently chosen route. This alternative route may however benefit from more extensive information than the current route. Additionally, the effect of information is higher when the driver is unfamiliar with the network, in case of high variability of conditions in parts of the network the driver is familiar with, or in case of long or complex trips or trips with an important purpose. Finally, the earlier the route information is given, the more likely it is the information will be used.

Dia & Panwai (2007) analysed data from a field survey on commuters' route choice behaviour. They found that prescriptive, predictive, and quantitative real-time information on delays yielded the highest compliance. Furthermore, the familiarity with the network was found to be of influence. Additionally, if the expected travel time improvement of a route exceeded a person's delay threshold, they were more willing to switch routes.

Van den Bosch et al. (2011) assessed the effect of altruism on reduction of the average travel time. Furthermore, they translated fuel consumption and CO_2 emissions into travel time, allowing to consider these effects in the social cost. Altruism indicates the extent to which a driver is willing to trade off their own travel time to benefit the travel time other drivers. They varied altruism from 0, where the driver does not take travel times of others into account, to 1, where the driver values travel times of others equal to their own travel time. The higher the factor of altruism of drivers, the lower the average travel time. In their case study, 20% of social navigation yielded 10% of travel time reduction.

Kerkman, Arentze, Borgers, & Kemperman (2012) conducted a stated choice experiment to examine the compliance of drivers with route advice and willingness to consider social objectives in route choice. They found personalised advice to have a higher compliance rate than non-personalised. Furthermore, contrary to the researchers' expectations, compliance was higher when the objective of the advice was traffic management, compared to the individual objectives of the driver. The authors attribute this to the fact that advice is discarded when users received extensive information on the outcomes of the route alternatives, so they could determine their own preference based on the attributes of the alternatives. Therefore, advice from an individual perspective was redundant, whereas advice from a traffic management perspective was complementary. Additionally, it was found that importance of comfort was lower for users receiving personalised advice, while 'environment and burden' was more important. This could be attributed to drivers wanting to compensate for the fact that personalised advice discarded environmental effects, by increasing their own value attached to this attribute.

Klein, Levy, & Ben-Elia (2018) developed an agent-based model aiming for a SO by driver cooperation. It was found that time or monetary punishments work best in increasing compliance, followed by rewards. Furthermore, route alternatives with absolute dominance were complied with more than those with relative dominance, as they do not have any strong resistance to the self-interest of the driver.

Ringhand & Vollrath (2018) used a survey and a driving simulation study to assess the effect of recommendations for system-optimal routes. It was found that recommendation increased the compliance with the SO alternative compared to no advice, independent of other route choice attributes. In-depth information on traffic management was found to have no further effect on compliance.

Van Essen, Thomas, Van Berkum, & Chorus (2018) assessed the possibilities of using travel information to direct drivers to SO routes. Their results suggest that travellers have an intrinsic preference for either compliance or non-compliance, varying between respondents. Furthermore, they found nudging, social reinforcement, and education to be more effective in increasing compliance than just a recommendation. Additionally, they found compliance was greater when information was aimed at alleviating congestion than increasing safety or reducing emissions. This could be attributed to the fact that travellers perceive travel time and congestion to be directly related, making it a more achievable goal in the eyes of the user. Moreover, a higher travel time sacrifice yielded a lower compliance. It was also found that travellers are inclined to follow the advice when they are cooperatively oriented, and when they make their route choices non-habitual. Finally, older users were more likely to comply in comparison with younger travellers. When asking participants of the experiment for their reasons for choosing a certain route, the researchers found that users are less likely to comply with advice for the social route if their usual route is not congested or if they believe social route will be congested. This reveals travellers do not always fully trust the system and need to believe their action has an influence on the traffic conditions.

Zhong, Zhou, Ma, & Jia (2012) assessed the factors of influence on drivers' compliance with VMS information, using a survey. They found that older drivers were more likely to comply with the advice. Furthermore, people with less than one year of driving experience had the highest compliance rate, whereas drivers with more than 5 years of experience complied the least. The authors attribute this finding to the fact that novice drivers have not enough experience to know what the best route is. Additionally, a higher average annual mileage corresponded to more trust in the VMS and a higher compliance. The authors also found that a larger monthly income correlated with more compliance with the given advice. Moreover, steady drivers appeared to comply with the advice the most, as did drivers that trusted the VMS based on previous advice. As was also mentioned in other researches (Bonsall, 1992, Chorus et al., 2006), people that were more familiar with the network were less likely to follow the advice.

2.5.1. Bandwidths

Aziz & Ukkusuri (2014) analysed the trade-offs between greenhouse gas emissions and travel time students in their study were willing to make. They found that females in their sample traded off a higher additional travel time per lb of greenhouse gas emissions compared to males. This was found to be the case for both work and non-work trips. Furthermore, students from high income households were willing to trade off more additional minutes compared to the found average. Finally, students were considering larger changes in departure time than in the travel time of their routes.

Mouter, Van Cranenburgh, & Van Wee (2017) assessed the trade-offs between travel time and safety people considered, both as citizen and as consumer. They found that the travel time people were willing to trade for a traffic casualty was much larger when assessed in a citizen role than in a consumer role. As a consumer, participants traded between 2.5 and 5.4 minutes of travel time savings for a reduction of one casualty on a road per year. In a citizen role, the travel time savings considered were between 10.7 and 16.4 minutes for one traffic casualty reduction.

2.5.2. Conclusion

Multiple factors are described that are of influence on the extent to which travellers comply with given route advice. An important aspect regarding the advice is the credibility of the advice. Road users are more likely to follow the suggested route if other traveller use that route, it is in the same compass direction as the destination, the suggested route is uncongested, and the quality of the previously received advice was good. Furthermore, travellers are found to be more likely to follow advice that aims at congestion alleviation, than advice that has an environmental or safety objective. Additionally, if the road user is already on the suggested route, they are more likely to comply. If turns are required to follow the advice, however, compliance is less likely. Larger travel time savings, or at least savings larger than the delay limit of the driver, increase compliance on the other hand. Furthermore, predictive and personalised advice yields higher compliance as well. Nudging, social reinforcement, education, monetary punishments or rewards finally are mentioned to increase compliance as well.

Several personal factors influencing compliance are discussed as well. The most important one is the familiarity of the driver with the network: the more familiar, the less likely to follow the given advice. Furthermore, young and experienced drivers were found to be less likely to comply, while older drivers complied more. Finally, education level and a larger income were found to be of influence as well.

Taking these factors into account can increase compliance and thus improve the impact of individual route guidance.

Regarding the trade-offs between different effects, females were found to trade-off more additional travel time for greenhouse gas emissions than males. A difference in trade-off values can also be observed when comparing travel time and safety: in the role of citizen, travellers are willing to trade more travel time for a traffic casualty than in the role of consumer.

3

Mathematical model

In this chapter the mathematical model is described. First, the model requirements are outlined. Then, the relationships between traffic conditions and the externalities travel time, reduced air quality, noise, and accident risk are explained. Afterwards, the mathematical model is specified, comprising the Link Transmission Model, individual route guidance, and the determination of the liveability effects. Then, this model is constructed in Excel and the related assumptions and operationalisations are described. Finally, the validity of the model is discussed.

3.1. Requirements

To be able to answer the research questions, several requirements on the model exist. First of all, the model should describe the traffic propagation. It has to determine the number of vehicles that are currently on a link, the available capacity on a following link and what the speeds on the different links are. To allow to consider variations in these variables over time, a Dynamic Traffic Assignment is required. To be able to determine the effects of the traffic through the network, the instantaneous travel time should be calculated, as should the production of NO_x, PM_{10}, dB, and the accident risk. To determine the impact on the liveability of the effects, the surroundings have to be taken into consideration as well. Furthermore, given a certain penetration and compliance rate, and a fixed split of unguided traffic, the model should determine the optimal split advice for the guided traffic, for a certain objective. Additionally, requirements exist to allow for testing of different cases and scenarios. Because different weight classes of vehicles yield different emissions and noise, the model should distinguish between light, medium heavy, and heavy traffic. Furthermore, different routes should be able to have different speeds and different lengths.

3.2. Relationships between traffic conditions and externalities

Before the effects of traffic conditions on the liveability can be minimised, first, it is necessary to describe the relationships between these traffic conditions and the liveability. This is done below.

3.2.1. Air quality

In this research, air quality is depicted by PM_{10} and NO_x. Every year, the Dutch government publishes emission factors (Rijksoverheid, 2019). They distinguish between light, medium heavy, and heavy traffic, types of roads, and speeds. They describe factors in g/km for CO, PM_{10}, $PM_{2.5}$, NO_2, and NO_x, for 2014, 2017, 2018, and 2019, and include predictions up to and including 2030. The factors for PM_{10} and NO_x will be used to calculate the air quality resulting from the traffic conditions.

3.2.2. Noise

For noise, the government has established rules for the calculation of noise levels (Staatssecretaris van Infrastructuur en Milieu, 2012). This comprises the noise production and several correction and deduction factors considering for example the effect of the car pulling up or the reduction caused by the air. For this research, only the noise production will be considered:

$$E = 10 * \log\left(10^{\frac{E_l}{10}} + 10^{\frac{E_m}{10}} + 10^{\frac{E_h}{10}}\right) \tag{3.1}$$

with:

$$E_l = 70.0 + 29.8 * \log\left(\frac{v_l}{v_0}\right) + 10 * \log\left(\frac{q}{v}\right)_l + C_{roadsurface,l} \tag{3.2}$$

$$E_m = 73.2 + 19.0 * \log\left(\frac{v_m}{v_0}\right) + 10 * \log\left(\frac{q}{v}\right)_m + C_{roadsurface,m} \tag{3.3}$$

$$E_h = 76.0 + 17.9 * \log\left(\frac{v_h}{v_0}\right) + 10\log\left(\frac{q}{v}\right)_{ht} + C_{roadsurface,h} \tag{3.4}$$

Here v_l, v_m, and v_h are the speeds of respectively light, medium heavy, and heavy traffic. v_0 is the reference speed for the different vehicle categories, respectively 80 km/h for light traffic and 70 km/h for medium and heavy traffic. q is the flow in veh/h. The correction for the road surface is calculated as follows:

$$C_{roadsurface,cat} = \sigma_{cat} + \tau_{cat}\log\left(\frac{v_{cat}}{v_{0,cat}}\right) \tag{3.5}$$

Here cat is the vehicle category l, m, or h, σ_m is the difference in dB(A) at reference speed v_0, and τ_m is the speed index in dB(A) per decade change in speed.

3.2.3. Safety

Originally, the safety of a road section is assessed by the number of accidents that has occurred in the past, and this influences safety improving measures. The expected number of accidents on a road section is for example described by Reurings & Janssen (2007) as:

$$\mu = \alpha * L^{\beta} * q^{\gamma} * e^{\sum_{i=1}^{n}\delta_i x_i} \tag{3.6}$$

Here μ is the expected number of accidents on a road section in a given period, L is the length of the road section, and q is the traffic flow per 24 hours. x_i indicates other explaining variables, such as the width of the road. α, β, γ, $\delta_1 ... \delta_n$ are parameters that are fitted to the observed number of accidents.

Reurings & Janssen (2007) adapted this general formula to fit data of different types of roads in the city region Haaglanden, the province of Gelderland, and the province of North-Holland. Although this study is from 2006, this is currently the best available data and is used in this research.

3.3. Model

Now that the relationships between traffic conditions and effects are defined, the mathematical model used to minimise the effects can be described. The model comprises traffic propagation, route advice, and effect determination. The Link Transmission Model is used to describe traffic propagation in the network (Verschelling, 2017, Yperman, 2007), as this takes spillback into account. The LTM uses Newell's triangular fundamental diagram, comprising only two wave speeds: a positive forward one for free-flow traffic v_f, and a negative backwards one for congestion w. The values describing the traffic situation can then be used to determine the effects on travel time, air quality, noise, and accident risk. Depending on the objective, the individual route advice has to be determined. Below, this is described in a mathematical model.

3.3.1. Sets

V	Set of nodes
A	Set of links
I_n	Set of incoming links into node n, $I_n \subset A$
J_n	Set of outgoing links of node n, $J_n \subset A$
O	Set of all origins in the network, $O \subset V$
T	Set of simulation time step indices
X	Total network space

3.3.2. Indices

t	A certain time interval, $t \in T$
n	Node, $n \in O$
r	Origin node, $r, \in R \subset O$
a	Link, $a, \in A$
i	Incoming link, $i \in I_n$
j	Outgoing link, $j \in J_n$
x	Point in network space, $x \in X$
x_a^0	Entrance point (upstream end) of link a
x_a^L	Exit point (downstream end) of link a
p	A path between a node and the destination
r	A path between a node and the destination, other than p

3.3.3. Decision variable

β_{ij}	The split fraction at a node connecting link i and j.

3.3.4. Model variables

Δt	Time interval length, simulation time step
$v_{f,a}$	Free flow speed (forward wave speed) of link $a[km/h]$
w_a	Backward shock wave speed (negative number) of link $a[km/h]$
$q_{M,a}$	Link capacity of link $a[veh/h]$
$k_{M,a}$	Critical density of link $a[veh/km]$
$k_{jam,a}$	Jam density of link $a[veh/km]$
L_a	Length of link $a[km]$
$N(x,t)$	The cumulative number of vehicles that has passed location x at time $t[veh]$
$N_r(t)$	The cumulative number of vehicles that has passed origin r at time t. This can be derived from the demand profile $[veh]$
$S_{ij}(t)$	Sending flow of link i to link j during time interval $[t, t+\Delta t][veh]$
$R_{ij}(t)$	Receving flow of link j from link i during time interval $[t, t+\Delta t][veh]$
$G_{ij}(t)$	Transition flow of link i to link j during time interval $[t, t+\Delta t][veh]$
x_a^t	The total number of vehicles on link a at time interval t. This is not the flow rate, but the link vehicle count [veh]
$T_a^t(x_a^t)$	The travel time on link a at time interval t, as a function of the number of vehicles on that link on that time [s]
$\tau_{f,a}$	Free flow travel time on link a [s]
η	The share of vehicles arriving at a decision node that requires guidance and complies to it. This value is between 0 and 1 and represents the penetration rate multiplied by the compliance rate. This variable ensures the distinction between guided and unguided traffic and reflects the compliance behaviour of guided drivers
γ_{ij}	The fixed split fraction of unguided and non-complying guided individuals from link i to link j
EX_a^t	Emitted NO_x on link a at time t
EP_a^t	Emitted PM_{10} on link a at time t
EN_a^t	Emitted dB on link a at time t
EA_a^t	Accident risk on link a at time t
Y_a	Number of local residents at link a
BT	Benchmark value for experienced travel time
BX	Benchmark value for experienced NO_x
BP	Benchmark value for experienced PM_{10}
BN	Benchmark value for experienced noise
BA	Benchmark value for accident risk
WT	Weight attached to travel time in the combined objective
WX	Weight attached to NO_x in the combined objective
WP	Weight attached to PM_{10} in the combined objective
WN	Weight attached to noise in the combined objective
WA	Weight attached to accident risk in the combined objective

LX_a^t	Limit for the emitted NO_x on link a at time t
LP_a^t	Limit for the emitted PM_{10} on link a at time t
LN_a^t	Limit for the emitted dB on link a at time t
LA_a^t	Limit for the accident risk on link a at time t
HT_n	Maximum travel time difference between two paths to a destination for guided travellers passing node n. [s]
HA_n	Maximum difference in accident risk between two paths to a destination for guided travellers passing node n
HX_n	Maximum difference in NO_x between two paths to a destination for guided travellers passing node n
HP_n	Maximum difference in PM_{10} between two paths to a destination for guided travellers passing node n
HN_n	Maximum difference in dB between two paths to a destination for guided travellers passing node n
ψ_a^t	The number of queueing vehicles on link a at time interval $t[veh]$
m_n^t	The transition flow that arrives at decision node n at time interval $t[veh]$

3.3.5. Traffic flow propagation description

Before the objectives and constraints are discussed, the calculation of the traffic propagation is described. The potential sending and receiving flow of every link in the network can be described as follows:

$$S_i(t) = \min([N(x_i^0, t+\Delta t - \frac{L_i}{v_{f,i}}) - N(x_i^L, t)], q_{M,i} * \Delta t) \tag{3.7}$$

Here S_i is the sending flow of link i during time step t. $\frac{L_i}{v_{f,i}}$ is the travel time of the link at free flow speed, so $N(x_i^0, t+\Delta t - \frac{L_i}{v_{f,i}})$ is the cumulative number of vehicles that passed the beginning of the link one free flow travel time period ago. $N(x_i^L, t)$ is the cumulative number at the end of the link at the current time step. $q_{M,i} * \Delta t$ is the capacity of the link. The flow a link can potentially receive, $R_j(t)$,is described as:

$$R_j(t) = \min([N(x_j^L, t+\Delta t - \frac{L_j}{w_j}) + k_{jam,j} * L_j - N(x_j^0, t)], q_{M,j} * \Delta t) \tag{3.8}$$

$\frac{L_j}{w_j}$ is the duration of a backwards shock wave travelling back one link, so $N(x_j^L, t+\Delta t - \frac{L_j}{w_j})$ is the cumulative number of vehicles that have passed the link end one time step minus one shock wave period ago. $k_{jam,j} * L_j$ is the number of vehicles on the link at jam density, $N(x_j^0, t)$ is the cumulative number currently at the link start. The potential receiving flow therefore is the minimum of the number of vehicles that can still enter the link until a jam occurs, and the capacity of the link.

Transition flows are flows from an incoming link to the outgoing link of the node. In the LTM, different node types have different rules for the transition flow. Inhomogeneous nodes are nodes with one incoming and one outgoing link, where there is a change in the infrastructure, such as a lane drop. The transition flow between two links is the minimum of the sending and the receiving flow:

$$G_{ij}(t) = \min(S_i(t), R_j(t)) \tag{3.9}$$

Origin nodes have only an outgoing link and ensure the demand is loaded to the network. The flow is the minimum of the demand and the potential receiving flow of the link:

$$G_j(t) = \min([N_r(t+\Delta t) - N(x_j^0, t)], R_j(t)) \tag{3.10}$$

Vehicles can exit the network in destination nodes. These have no capacity restrictions, therefore the transition flow is equal to the sending flow of the previous link:

$$G_i(t) = S_i(t) \tag{3.11}$$

In diverge nodes, one incoming link splits into two outgoing links. Therefore, the sending flow must be split. A distinction is made between guided and unguided traffic. η is the penetration rate multiplied with the compliance rate, and indicates the share of people that will follow the advice given to them. β_{ij} describes the split fraction advice from the incoming link i to one of the outgoing links j.

$$S_{ij,guided}(t) = S_i(t) * \eta * \beta_{ij}, \forall i \in I_n; j \in J_n \tag{3.12}$$

$$S_{ij,unguided}(t) = S_i(t) * (1-\eta) * \gamma_{ij}, \forall i \in I_n; j \in J_n \tag{3.13}$$

If one of the two outgoing links is restricted and spillback occurs, this affects the flow from the incoming link to the other outgoing link as well. This is described as follows:

$$G_{ij}(t) = \min_{j \in J_n} \left(\frac{R_j(t) * S_{ij}(t)}{S_{ij'}(t)}, S_{ij}(t) \right), \forall j \in J_n \tag{3.14}$$

Here, R_j is multiplied by the ratio of the specific vehicle type of all vehicle types on the previous link, to ensure that all vehicle types are continued evenly.

In merge nodes, two incoming links are combined into one outgoing link. If the outgoing link is restricted, this affects both incoming links. This can be described as:

$$G_{ij}(t) = \min \left(\frac{R_j(t) * S_{ij}(t)}{\sum_{i' \in I_n} S_{i'j}(t)}, S_{ij}(t) \right) \forall i \in I_n \tag{3.15}$$

When all transition flows are determined, the cumulative number of vehicles on each link can be updated. The cumulative number of vehicles in the current time step is increased by the transition flows to determine the cumulative number of vehicles in the next time step:

$$N(x_j^0, t+\Delta t) = N(x_j^0, t) + \sum_{i \in I_n} G_{ij}(t), \forall j \in J_n \tag{3.16}$$

The cumulative outflow of the link is dependent on the transition flow to the following link:

$$N(x_i^L, t+\Delta t) = N(x_i^L, t) + \sum_{j \in J_n} G_{ij}(t), \forall i \in I_n \tag{3.17}$$

The number of vehicles currently on a link can be determined by the difference between the cumulative inflow and outflow:

$$x_a^t = N(x_a^0, t) - N(x_a^L, t), \forall a \in A; t \in T \tag{3.18}$$

The number of queueing vehicles can be described as the difference between the current cumulative number of vehicles that has entered the link, and the cumulative number of number of vehicles that has left the link at one free flow travel time period later:

$$\psi_a^t = N(x_a^0, t) - N(x_a^L, t + \frac{L_a}{v_{f,a}}), \forall a \in A; t \in T \tag{3.19}$$

The instantaneous travel time of link a at time t is described by the link length divided by the current speed.

$$T_a^t = \frac{L_a}{v_a}, \forall a \in A; t \in T \tag{3.20}$$

Finally, the number of vehicles at node n at time t is the sum of the transition flows:

$$m_n^t = \sum_{j \in J_n} G_{ij}(t), \forall i \in I_n; n \in V; t \in T \tag{3.21}$$

To determine the values of the above described variables for the three different vehicle weight classes light, medium, and heavy traffic, the total values are multiplied with the respective passenger car unit (PCU) and vehicle share ratio.

3.3.6. Objective functions

Per effect an objective can be described. This considers the produced effects and weighs this by the amount of people affected, either on or surrounding the road.

The objective to minimise the effect on travel time can be described as:

$$\min \sum_{a \in A} T_a^t(x_a^t) * x_a^t, \forall t \in T \tag{3.22}$$

The total travel time on a route is dependent on the amount of people using the links on that route. The total experienced effect is calculated by multiplying the travel time of a link with the amount of people present on that link in that time step.

Contrary to the experienced travel time, the air quality and noise are mainly perceived by people surrounding the road instead of the drivers themselves. The objective to minimise the effect on air quality is therefore described as:

$$\min \sum_{a \in A} (EX_a^t + EP_a^t) * Y_a, \forall t \in T \tag{3.23}$$

This comprises both the emitted NO_x and PM_{10}.

The objective to minimise the effect on noise is:

$$\min \sum_{a \in A} EN_a^t * Y_a, \forall t \in T \tag{3.24}$$

Finally, the objective to minimise the effect on accident risk is again dependent on the amount of drivers on the link, and is therefore described as:

$$\min \sum_{a \in A} EA_a^t * x_a^t, \forall t \in T \tag{3.25}$$

These four individual objectives can be combined into one all encompassing objective. As the effects are measured in different units, they first all have to be normalised. This can be done by expressing all effects relative to a certain value. This value is determined by sending all traffic via the route that is worst for that effect, and then taking the resulting maximum over the full hour assessed. This is not necessarily the absolute worst result of the effects, but functions merely as a benchmark.

For travel time, the worst situation is where all traffic uses the same, longest route. This is then multiplied by the resulting number of vehicles in the network.

For both air quality and noise, the benchmark situation is where all traffic uses the route with the most people surrounding. The resulting number of vehicles in the network and the number of local residents is used to determine the effect.

For safety, the comparison situation is equal to the worst travel time: every vehicle uses the same, longest route. The resulting number of vehicles in the network is used to determine the accident risk.

Additionally, weights could be attached to the different effects, as some actor might value for example travel time as more important, while others might consider safety to be the most important aspect.

This all combined yields the following objective:

$$\min \sum_{a \in A} \frac{T_a^t(x_a^t) * x_a^t}{BT} * WT + \left(\frac{(EX_a^t) * Y_a}{BX} * WX + \frac{EP_a^t * Y_a}{BP} * WP \right) /2 + \frac{EN_a^t * Y_a}{BN} * WN + \frac{EA_a^t * x_a^t}{BA} * WA \tag{3.26}$$

As NO_x and PM_{10} together form the indicator for air quality, their total impact is divided by two, so they are not counted double.

3.3.7. Constraints

Several constraints have to be formulated before the objectives can be solved. First of all, if no traffic would be on the road, no effects would occur, but the demand must be fulfilled. This can be achieved by ensuring all traffic at a diverge node is assigned to a next link:

$$\sum_{j \in J_n} \beta_{ij} = 1 \forall i \in I_n; \tag{3.27}$$

When optimising for an effect, this might have adverse impact on the other effects. Therefore, those have to be constrained. The liveability effects caused may not be higher than set limits. For NO$_x$ this is formulated as:

$$EX_a^t \leq LX_a^t, \forall t \in T; a \in A \tag{3.28}$$

For PM$_{10}$ this limit is described in a similar fashion as:

$$EP_a^t \leq LP_a^t, \forall t \in T; a \in A \tag{3.29}$$

The noise limit is expressed as:

$$EN_a^t \leq LN_a^t, \forall t \in T; a \in A \tag{3.30}$$

For simplicity reasons, the correction factors are not considered when calculating the noise production, causing the noise level in this model to be much higher than the actual expected noise level, or than what would be calculated in a dedicated noise model. Therefore, the noise limit used as a constraint in the model is set at 110 dB, instead of the 50 dB described in the laws of environmental conservation (Rijkswaterstaat, n.d.-b).

Finally, the limit for the accident risk is formulated as:

$$EA_a^t \leq LA_a^t, \forall t \in T; a \in A \tag{3.31}$$

Furthermore, fairness must be ensured. The first type of fairness that should be considered is the difference between the travel time of users:

$$\left| \sum_{a \in A} T_{a,p}^t(x_a^t) - \sum_{a \in A} T_{a,r}^t(x_a^t) \right| \leq HT_n, \forall n \in V; t \in T \tag{3.32}$$

Here $T_{a,p}^t(x_a^t)$ and $T_{a,r}^t(x_a^t)$ describe the travel times of route p and r, respectively.

A similar constraint can be constructed for air quality, noise, and safety, by comparing the unweighted produced effects of the alternative routes for NO$_x$, PM$_{10}$, dB, and accident risk respectively:

$$\left| \sum_{a \in A} EX_{a,p}^t - \sum_{a \in A} EX_{a,r}^t \right| \leq HX_n, \forall n \in V; t \in T \tag{3.33}$$

$$\left| \sum_{a \in A} EP_{a,p}^t - \sum_{a \in A} EP_{a,r}^t \right| \leq HP_n, \forall n \in V; t \in T \tag{3.34}$$

$$\left| \sum_{a \in A} EN_{a,p}^t - \sum_{a \in A} EN_{a,r}^t \right| \leq HN_n, \forall n \in V; t \in T \tag{3.35}$$

$$\left| \sum_{a \in A} EA_{a,p}^t - \sum_{a \in A} EA_{a,r}^t \right| \leq HA_n, \forall n \in V; t \in T \tag{3.36}$$

Finally, there are some non-negativity constraints. The number of vehicles on a link a at time t must always be non-negative.

$$x_i^t \geq 0, \forall a \in A; t \in T \tag{3.37}$$

Due to the nature of the formulas, the advised split fractions should be larger than zero.

$$\sum_{j \in J_n} \beta_{ij} > 0 \forall i \in I_n; \tag{3.38}$$

3.3.8. Algorithm

The Link Transmission Model, Individual Route Guidance, and effects are combined into one model, which determines the situation in each time period of 30 seconds. Figure 3.1 shows how the advice is determined to optimise a certain objective. The grey boxes are input, the blue boxes are model variables, the green box contains the objective, and the red box is what can be changed to achieve the objective. The 'Number of vehicles on each link' at time t is indicated in both grey and blue, as the initial number of vehicles on each link is zero, but in the next time steps this is dependent on the previous periods. The current number of vehicles on each link, the given split fraction of unguided traffic, and the demand for the next time step determine the possible sending and receiving flows of the links. The transition flows are dependent on the sending and receiving capacity of the links, the compliance and penetration rate of guided traffic, and the split advice for guided traffic. The transition flows and number vehicles on each link in the current time period in turn influence the number of vehicles on each link in the next time period. This determines the speeds and resulting travel time and liveability effects for the next period. As these effects are what need to be optimised, they iteratively determine the best split advice.

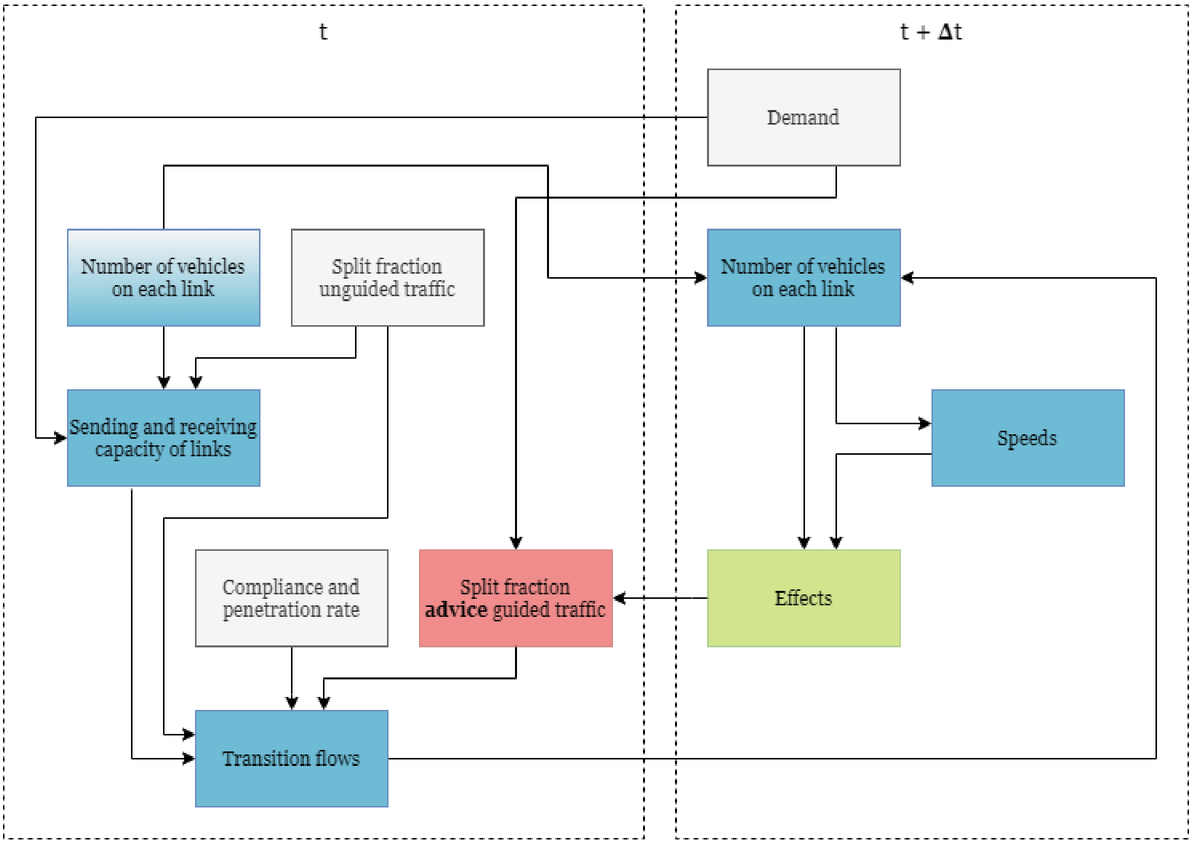


Figure 3.1: Algorithm

3.4. Description Excel model

The mathematical model described above is defined in an Excel file for a very basic network, as shown in Figure 3.2.

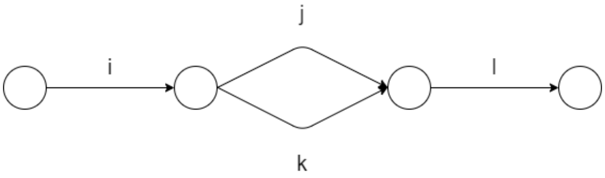


Figure 3.2: Basic network

Route X consists of link i, j, and l, route Y comprises link i, k, and l. Due to structure of this network, as is described as well in Section 3.3.5, if one of the two alternative routes is congested, the transition flow of both links is reduced and spillback occurs on link i. As link i is part of both routes, this then affects the travel time on both route X and route Y.

The traffic conditions and effects of the different links are described in different sheets, and are combined into route X and route Y, which are compared for the optimisation. The different objectives of travel time, air quality, noise, and safety can each be optimised by varying β_{ij}, the split between the two routes. The total time period examined is one hour.

The model is optimised per time step of 30 seconds, to be able to take into account variations in traffic characteristics such as speed, flow, and density over time, but also be able to operationalise the model in Excel. In every time step the current traffic situation and demand are evaluated to determine the best split to achieve the objective. Based on this split, the new traffic situation is determined.

Because the model is nonlinear, the solver used in Excel is the GRG nonlinear. This can at best guarantee a local optimum. The initial values for β_{ij} influence what the solver finds as the best result. Therefore, the "Multistart" function in the Excel solver is used, which uses different initial values within the given constraints for β_{ij}, and picks the one yielding the best result.

When using Multistart, the number of starting values has to be determined in the PopulationSize. These values are then generated using a seed, specified in RandomSeed. When using a fixed seed, the split is equal over time. While this split might be optimal for the first time period, for further time periods this might cause issues if there are capacity restrictions. To allow the solver to search the optimal split depending on the situations in each time step, a random seed is used.

3.5. Assumptions

For the scope of this research, some assumptions are made. First of all, the time steps considered are 30 seconds. To insure that links with different speeds can be compared over the same time period, all speeds considered are multitudes of 30 km/h. The length of the links is chosen in a way that it is a multitude of the distance that can be travelled in one time step when driving at free flow speed. For example, with a speed of 30 km/h the link lengths have to be a multitude of 0.25 km. The backwards shock wave speed is assumed to be -15 km/h. As the time steps are 30 seconds, with a link length of 0.25 km the shock wave uses two time periods to travel the link.

On different road types different shares of light, medium heavy, and heavy traffic are observed (Van der Brink, Brederode, & Wagenaar, 2010). The used vehicle shares are shown in Table 3.1.

Table 3.1: Shares of vehicle categories on different road types

	Light	**Medium**	**Heavy**
Inside built-up area	85.92%	11.77%	2.31%
Motorway	54.63%	27.67%	17.71%
Other outside built-up area	75.68%	19.93%	4.39%

If there is a difference in road type between the two alternatives, the shares of the first link in the network are assumed to be fixed.

Unguided traffic is assumed to be distributed according to a User Equilibrium, with the split being fixed over time.

As in the built model only produced effects are considered and reduction factors are omitted, the limits used in the constraints are adapted to allow the model to find a feasible solution.

While in reality emissions and noise could spread further over the network, for calculation purposes, the resulting effects are assigned to only one link.

3.6. Validation

As is the case for every model, the model described and developed in this research is a simplification of reality. Naturally, this brings about some limitations. However, the model should still allow to answer the research questions. Below, the validity of the developed model is discussed.

3.6.1. Model

The research questions the model should be able to answer consider the required traffic conditions and corresponding route guidance advice to achieve the different objectives for the liveability, and the trade-offs that exist between the objectives. The model determines the split advice that should be given to users of route guidance, given a certain penetration and compliance rate, a given split of unguided traffic, and the demand for that time period. The resulting effects for travel time, air quality, noise, and accident risk are calculated. When comparing these effects for the different objectives, the trade-offs between them can be determined. Therefore, the model allows to answer the relevant research questions.

Another important aspect is whether the model acts the way it is expected to do. The Link Transmission Model is used to describe the traffic conditions, considering traffic propagation and spillback. The formulas for the determination of the effects are retrieved from literature and national guidelines. Capacities and flows are obtained from guidelines for different road types. In case of a penetration rate of 0%, a fixed demand over time, and sufficient capacity, the effects are equal over the full simulation period. Furthermore, the route advice impacts the transition flows to both alternative routes. The transition flows in turn influence the experienced effects, allowing to compare these effects between routes and determine the route advice to be given.

3.6.2. Network

Another aspect to validate is the extent to which the modelled network corresponds with existing, real-world networks. The modelled network as shown in Figure 3.2 is very simple, with only one origin, one destination, and two alternative routes. This means that there is only one choice moment. Furthermore, once en route, there are no other inflow or outflow possibilities. Although in real world networks additional incoming and outgoing roads exist, in some situations the amount of traffic actually flowing in or out can be neglected. Additionally, in the modelled network a part of the total traffic is unguided and follows their own preferred route to the destination. Additional in- and outflowing traffic would have a similar impact, although they would flow in or out the network in the middle of the route. Despite its simplicity, the described network allows to consider the impact of the different variables more clearly.

4

Scenarios

In this chapter the different cases and scenarios that are used to answer the research questions are described. Three different cases are used, with for each different scenarios.

Based on the discussed literature and research questions, multiple aspects are interesting to vary to get an insight in their respective impact on the liveability effects, and to learn under what conditions individual traffic management could work. Some of these aspects are varied across the three cases that are set up. Others are changed in the scenarios that are tested for these three cases.

As discussed in Section 2.1, the relationship between capacity and demand determines the occurrence of congestion. Mahmassani & Peeta (1993) described that the amount of congestion determines the positive impact that a SO can have over a UE. Therefore, the first area for variations are the traffic conditions, such as capacity, speed, and demand.

Van den Bosch et al. (2011) described that the amount of people following the advice is of influence on the effects achievable. Therefore, the next aspect to vary is the combination of the penetration and compliance rate.

If a particular share of travellers follows the given advice, then the remaining part of travellers is unguided traffic. This unguided traffic already takes up some of the road space, influencing the remaining capacity for guided traffic. Therefore, the split fraction of unguided traffic is another element that is varied.

The goal of this research is to find the effects achievable on the liveability, which constitutes travel time, air quality, noise, and safety. As described in Section 3.3, the size of the effects of air quality and noise are dependent on the amount of people surrounding the roads. Thus, the surroundings are another aspect to be varied.

A final facet to change are the weights assigned to the different components of the combined objective. Aziz & Ukkusuri (2012) discussed that weight variations are of impact on the achieved effects.

4.1. Cases

Three cases are set up to assess the effects of individual traffic management in different situations. These cases vary in speed limit, road capacity, shares of vehicle classes, and surroundings. To fully test the impact of individual route advice, for all cases, one route should be more attractive for drivers, but less desirable from a liveability perspective.

To decide on the number of local residents surrounding the routes, an average of 0.5 residence per meter is assumed, with variations depending on the environment. The average household in the Netherlands in 2018 consisted of 2.1 people (Deuning, 2019), this is multiplied by the number of houses.

On average, there are 665 secondary school students per school location, with on average 225 primary school students per location. Combining this with the number of primary and secondary school location, an average of 300 students per school is assumed (Nederlands Jeugdinstituut, 2020, PO Raad, n.d.).

The first case considers two routes, where one route passes a school. An overview is shown in 4.1, the parameters used can be found in Appendix C. Due to the nature of the built-up area the school is in, speeds and capacity are low. The route passing the school has a lower speed limit but is the shortest. It has a relatively large number of people surrounding it, mainly the children in the school, and by nature has limited heavy traffic. The other route has a higher speed limit and has a limited number of local residents.

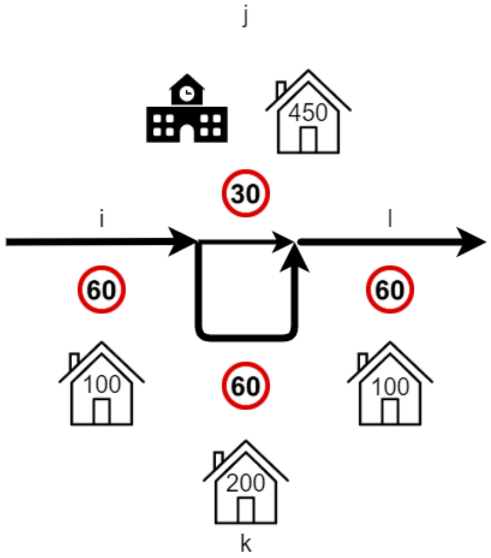


Figure 4.1: School route case

The second case, displayed in Figure 4.2, is situated outside the built-up area. It considers a motorway and a shorter parallel road, which has limited capacity. Speeds and capacity in this case are higher than in the previous case. It is assumed that for most of the road, the motorway has no local residents. However, in this case it is assumed that for about 20% of the road section there is 0.5 house per meter, representing for example a flat. The parallel road has limited surrounding residents as well, but compared to the motorway they are closer and more.

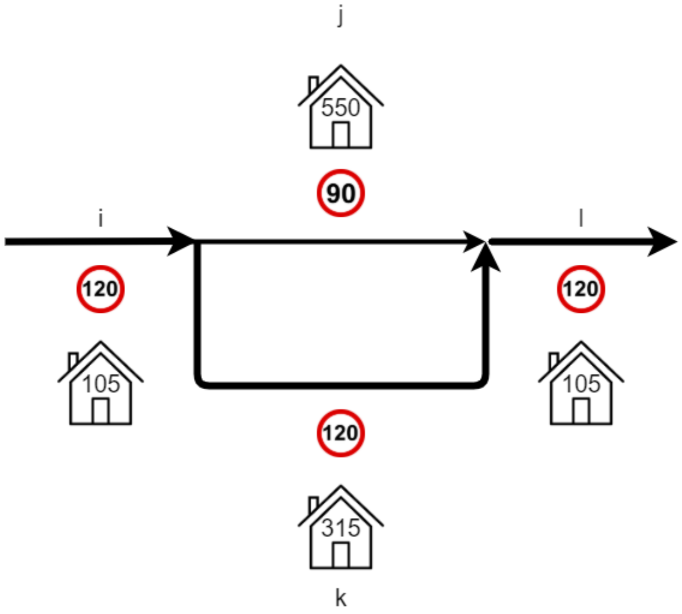


Figure 4.2: Parallel road case

The third and final case, shown in Figure 4.3, is in the built-up area, with consequently low speeds and capacity. Here, one of the two routes is restricted for heavy traffic, as often is the case in (historical) inner cities. This means that on link j, medium heavy and heavy traffic flow is limited to zero.

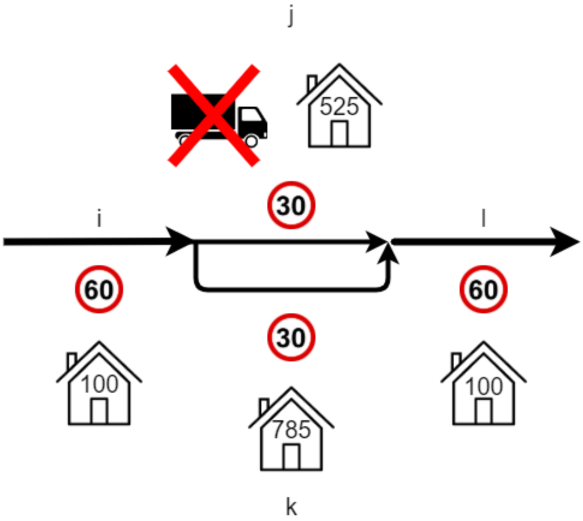


Figure 4.3: Road restricted for heavy traffic case

4.2. Scenarios

Of the discussed aspects to vary, capacity, speed, demand, and surroundings are covered within the cases. This leaves the effective compliance, split fraction of the unguided traffic, and the weights of the different effects to be changed in the scenarios. To analyse some interactions between these parameters, they are combined into the scenarios in Table 4.1. These scenarios are run for all three cases. The column 'Optimisation goal' shows the objective. For scenario 1 to 12 the four different effects are considered individually. In the last seven scenarios, the combined objective is used, both to assess the impact of the weight attached to the four effects, and to be able to analyse the influence of the unguided traffic. In scenario 17 to 19 extra weight is attached to the effects air quality and noise, as those primarily affect the local residents. In scenario 20 to 22, this extra weight is attached to the effects impacting road users, travel time and accident risk. In the final scenario, all weights are equal. The next column, 'Effective compliance', considers the penetration rate multiplied with the compliance rate. This ranges from limited, 0.1, to complete, 1, compliance. The 'Split unguided' column shows the fixed split fraction of unguided traffic using the fastest, but from a liveability perspective undesirable, route. In the first few scenario's this split is equal to what would be obtained with a UE. For the other scenarios this ranges from 50/50 to all unguided traffic via the undesirable route.

4.3. Determination of unguided traffic split

For the base cases and some of the unguided splits in the scenarios a fixed split fraction of the unguided traffic is to be determined. To get an idea of a somewhat realistic distribution, a deterministic user-equilibrium (DUE) is used. To be able to determine the split of this equilibrium in advance and use a fixed split for the unguided traffic over the assessed time period, the Method of Successive Averages (MSA) is used. In the simulation model developed, the travel time per link is determined in each time step using the ratio between the number of vehicles entering and leaving a link. The travel time used in this algorithm however is determined by a BPR function, to find the equilibrium instantly instead of having to fill the network and run a simulation. This function is described as follows:

$$t_a(q_a) = t_a^0\left(1+\alpha\left(\frac{q_a}{C_a}\right)^{\beta}\right) \tag{4.1}$$

Where for motorways, α is 0.15 and β equals 4 (Transportation Research Board, 1985). As the original values for α and β from the Bureau of Public Roads are meant for motorways, Mtoi & Moses (2014) calibrated these parameters for different situations. For urban roads with a speed limit of 30 mph (48 km/h), they fitted a value for α of 0.24, and for β of 7.50.

Table 4.1: Scenarios

Scenario	Optimisation goal	Effective compliance	Split unguided
Base	N.A.	0	UE
1	Travel time	0.1	UE
2	Travel time	0.4	UE
3	Travel time	0.7	UE
4	Travel time	1	N.A.
5	Air quality	0.1	UE
6	Air quality	0.4	UE
7	Air quality	0.7	UE
8	Air quality	1	N.A.
9	Noise	0.1	UE
10	Noise	0.4	UE
11	Noise	0.7	UE
12	Noise	1	N.A.
13	Accident risk	0.1	UE
14	Accident risk	0.4	UE
15	Accident risk	0.7	UE
16	Accident risk	1	N.A.
17	Residents	0.4	0.5
18	Residents	0.4	0.8
19	Residents	0.4	1
20	Road users	0.4	0.5
21	Road users	0.4	0.8
22	Road users	0.4	1
23	All equal	0.4	0.4

5

Results

In this chapter the results of the different optimisations are described. In the sections below the results of the optimisations are discussed per case. First, the individual objectives travel time, air quality, noise, and accident risk are discussed. Then, the objectives combining all effects are described as well.

For each case, first, the split fractions and resulting effects for all assessed compliance rates are shown for the objective travel time, to give an idea of how different compliance rates affect the results. Then, for the objectives air quality, noise, and accident risk, only the graphs for the split fraction advice and resulting effects at a compliance rate of 0.4 are shown, as this is assumed to be the most realistic. Afterwards, the effects resulting from the four different objectives are compared.

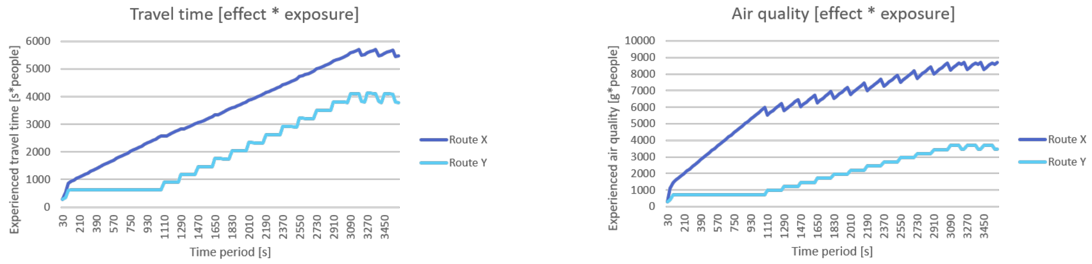
For each case, the split fraction advice for all combined objectives are shown. The results for the combined objective with equal weights are shown in detail over the assessed time period, then the maxima of all combined objectives are compared.

Finally, per case, the maximum experienced effects for all tested scenarios are compared with the base scenario, and the main takeaways for each case are discussed.

5.1. School route

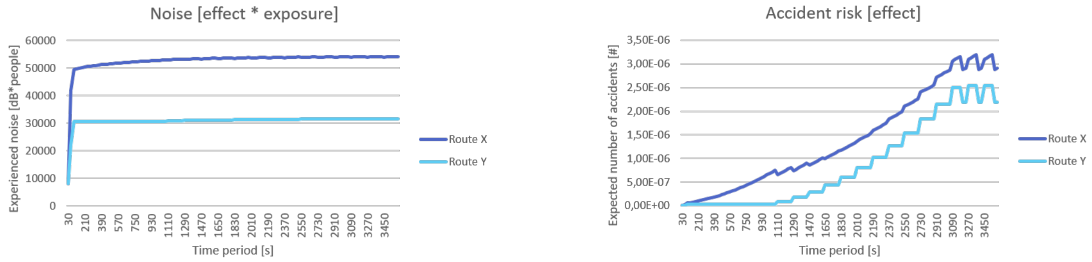
The school route case considers a situation where traffic can continue on the 60 km/h road, which has less local residents, but takes longer, or take the 30 km/h short-cut that passes a school.

In the base scenario, all vehicles are unguided and it is assumed that 90% of traffic uses the fastest route. However, as this is more than the capacity of link j, this causes congestion on this link. Over time, this congestion reaches link i as well, which is part of both routes. However, this congestion reduces the inflow on link j, alleviating the congestion and decreasing the travel time on this link. The effects of this can be seen in Figure 5.1. All experienced effects increase over time, but somewhat level out in the last few time periods, as the total travel time decreases slightly again.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

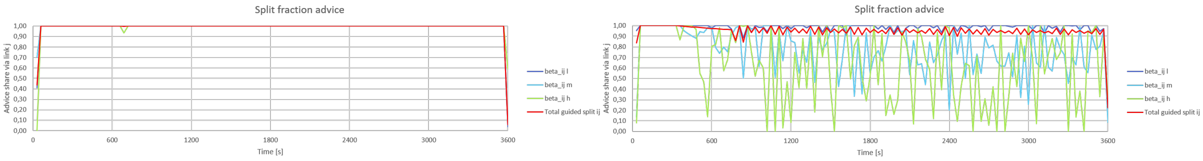
Figure 5.1: Effects in the school route case, in the base scenario

5.1.1. Optimisation individual objectives

In the sections below, the results of the four individual objectives, travel time, air quality, noise, and accident risk, are discussed.

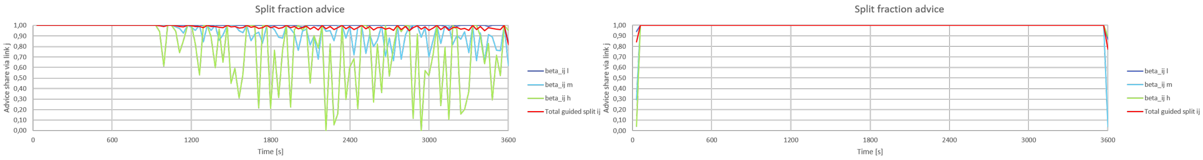
Travel time

Figure 5.2 shows the share of guided vehicles that is sent via link j for different compliance rates. The blue line represents the advice given to light vehicles, the light blue line shows the advice for medium heavy vehicles, and the green line is for heavy vehicles. The red line shows the weighted average advice, so this represents the total split fraction advice for all guided vehicles. The route via link j is the fastest alternative. It is therefore logical that when optimising for travel time, the advice is in favour of route X, which is represented in Figure 5.2 by the red line being at (almost) 1. The capacity of link j is however not sufficient for the full demand. This causes some congestion build-up. For 70% and 40% compliance, the advice switches to sending some vehicles via link k every few time steps, to reduce congestion, for 100% compliance this switching is very small. It can be observed that the switching in the advice for heavy vehicles is much stronger than for light vehicles. An explanation for this is that the number of heavy vehicles in the network in each time step is very small, causing its impact on the traffic conditions and the experienced effects to be very small as well. Therefore, any variation in the advice for heavy vehicles has limited impact.



(a) Compliance rate: 1

(b) Compliance rate: 0.7

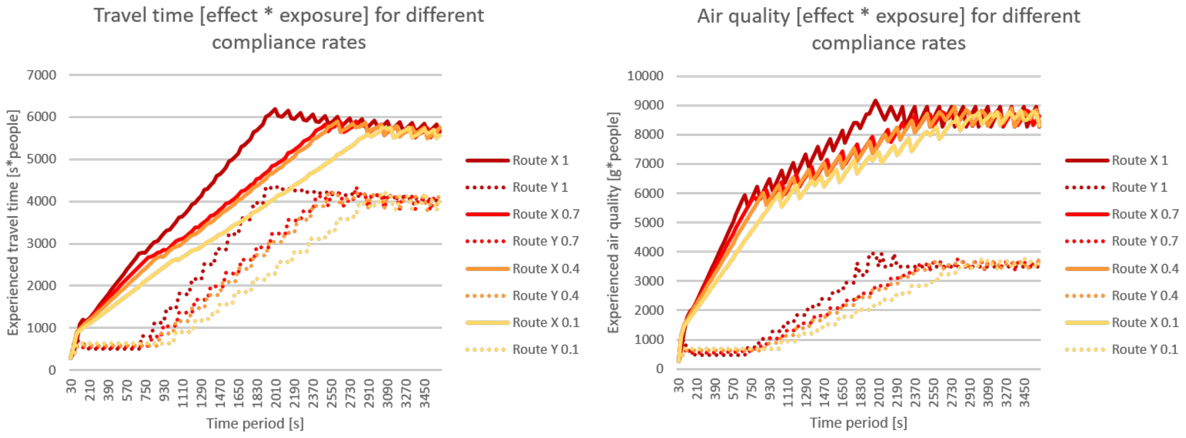


(c) Compliance rate: 0.4

(d) Compliance rate: 0.1

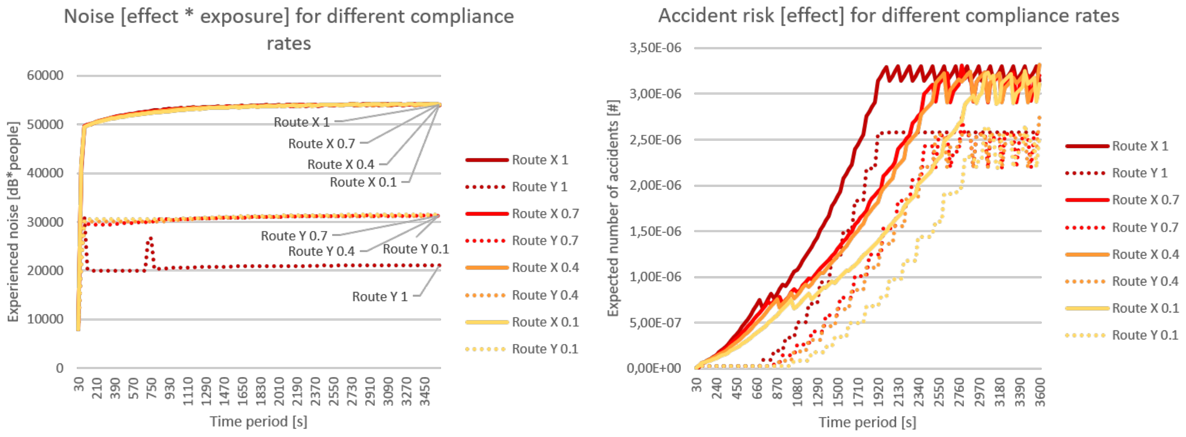
Figure 5.2: Split fraction advice towards link j when optimising travel time for different compliance rates in the school route case

In Figure 5.3, the experienced effects over the assessed time period, resulting from the split advice shown above, are displayed. Travel time, air quality and accident risk show an increase over time as congestion increases and get to a somewhat steady level. The lower the compliance behaviour in the scenario, the less steep this incline is, and the later this stability occurs. Furthermore, with lower compliance rates, less congestion occurs. This reveals an important limitation of the model set-up. The optimisation model only considers the results in the first upcoming time step. As some of the links are longer than what could be travelled in one time period, the effects occur with a delay. For some effects, the experienced effects resulting from a different split fraction advice might even worsen at first, before showing improvement. However, as the model only uses the first upcoming time step to determine the 'optimal' split fraction advice, it does not consider these improvements later in time. It therefore continues to advise the same extreme split fraction. With higher compliance, more road users follow this extreme advice, yielding adverse effects. With lower compliance, more people will use a different route from the advised one, causing a more balanced distribution and less congestion.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.3: Experienced effects on the two alternative routes over the assessed time period for different compliance rates resulting from travel time as objective in the school route case

Air quality

The route via j has a school in the surroundings and has more inhabitants, so from a social perspective, this is the more undesirable route. However, as link j is shorter than link k, when optimising for air quality, route j is still the favoured route, as is shown for a compliance rate of 0.4 in Figure 5.4. Over the assessed time period much switching of the advice can be observed, to reduce congestion. However, as can be seen in Figure 5.5, the congestion build-up still causes the experienced effects to increase over time.

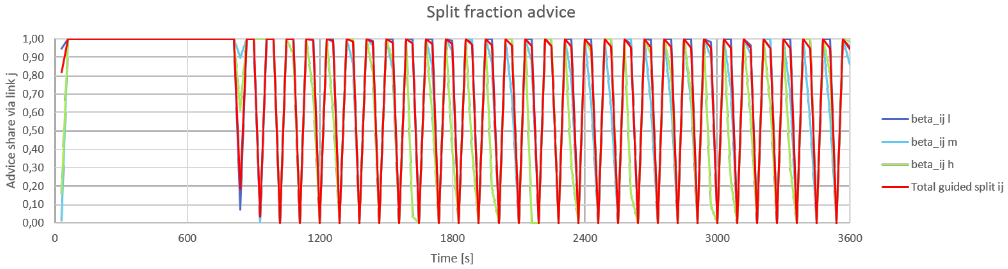
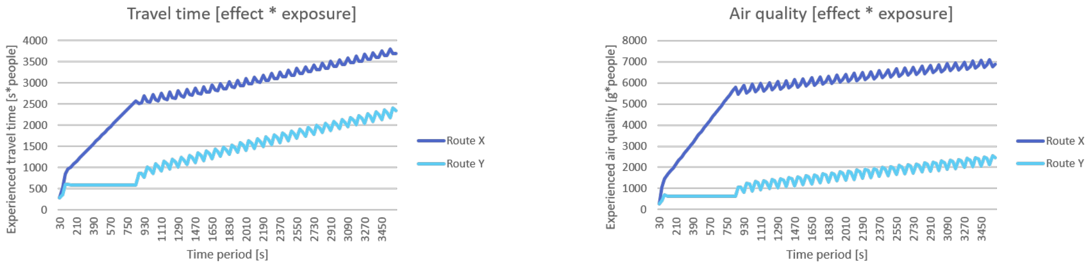
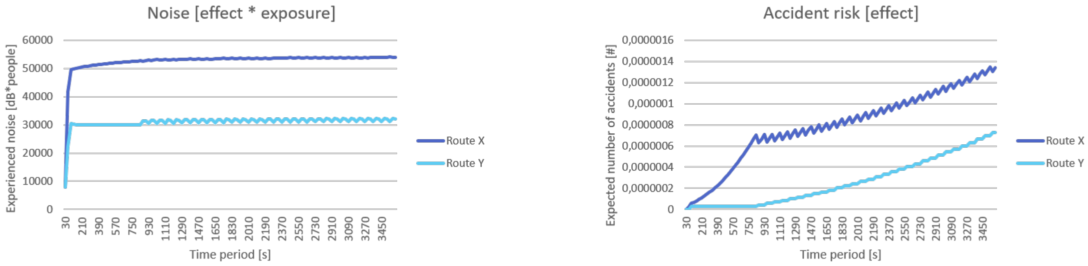


Figure 5.4: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4 in the school route case



(a) Travel time

(b) Air quality



(c) Noise

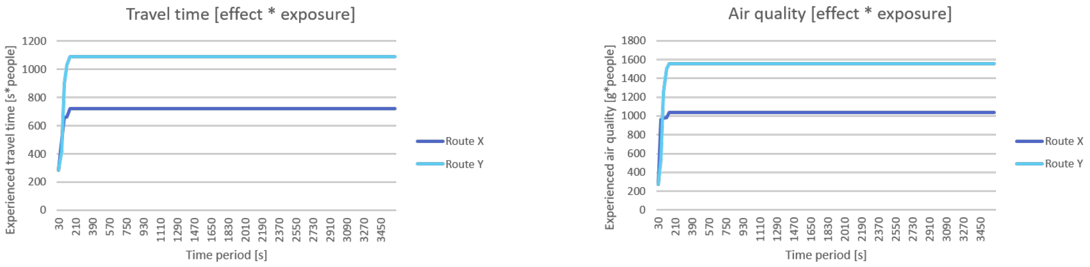
(d) Accident risk

Figure 5.5: Effects in the school route case, resulting from air quality as objective, at a compliance rate of 0.4

Noise

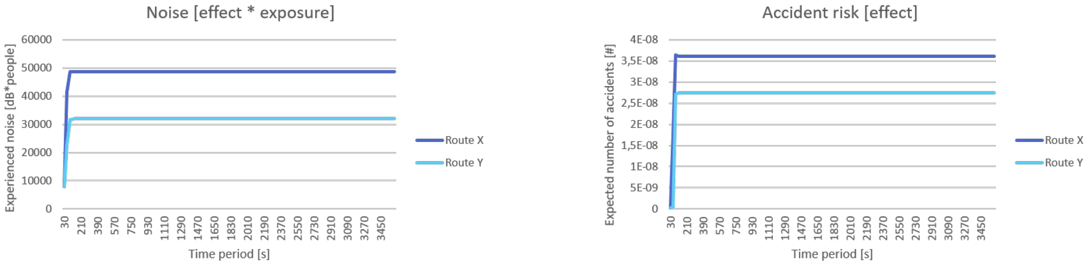
Figure 5.6: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4 in the school route case

When optimising for noise, no clear logic can be found. With full compliance, the advice keeps switching to favour a different alternative, causing the effects to vary strongly as well. However, although the effects change a lot between time steps, the overall trend is relatively stable for travel time, air quality and noise. With a compliance of 0.7, almost all guided traffic is sent via link j, the shortest route. This causes congestion on link j, leading to an increase in the experienced effects of travel time, air quality and safety. Compared to full compliance, all effects are worse. With a compliance rate of 0.4, all guided vehicles are sent via link k, as is displayed in Figure 5.6, causing more balance and less congestion, as can be seen in the steady graphs in Figure 5.7. This yields slightly better effects compared to full compliance, and strongly better effects in comparison to a compliance rate of 0.7. With only 0.1 compliance behaviour, the route advice for guided traffic is via link j. This causes the effects to develop similarly to those of 0.7 compliance, as this again causes congestion on link j.



(a) Travel time

(b) Air quality



(c) Noise

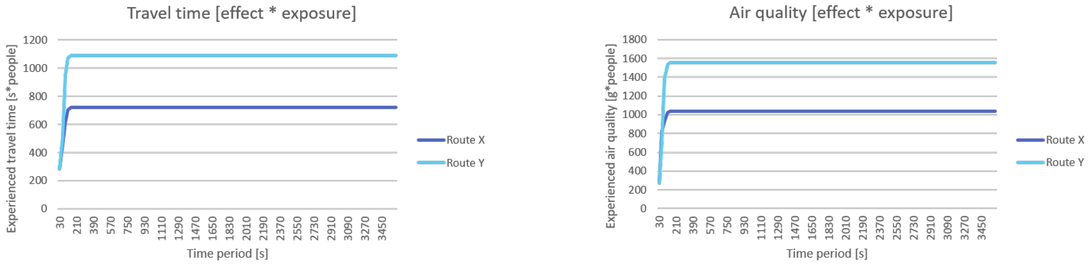
(d) Accident risk

Figure 5.7: Effects in the school route case, resulting from noise as objective, at a compliance rate of 0.4

Accident risk

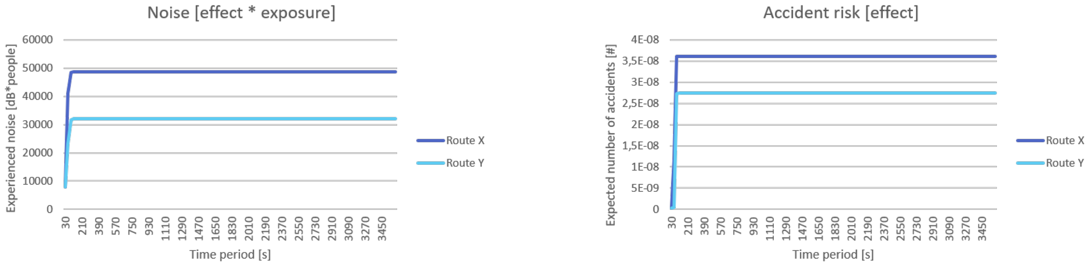
For accident risk, the favoured route is via link k, as shown in Figure 5.8. The factors of influence on the calculated accident risk are the link length, traffic flow, and road type. Although link k is longer, the parameters for this road type yield a lower accident risk. The effect patterns are similar throughout the different compliance rates 1, 0.7, and 0.4, although the values differ. Compared to a compliance rate of 1, a rate of 0.7 yields better experienced travel time and air quality, but worse noise and accident risk. The same is true for a compliance of 0.4, of which the effects are presented in Figure 5.9. In the scenario with 0.1 as a compliance rate however, congestion occurs on link j, causing all effects to be worse. Travel time, air quality and accident risk even show an increase over time.

Figure 5.8: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4 in the school route case



(a) Travel time

(b) Air quality



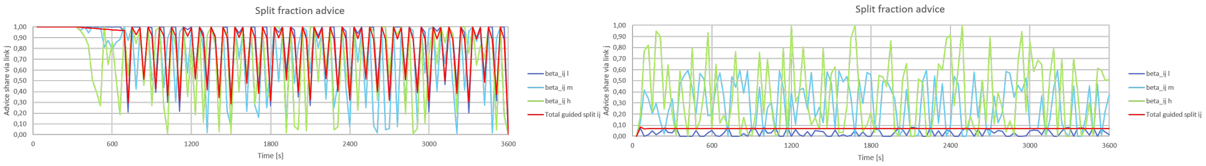
(c) Noise

(d) Accident risk

Figure 5.9: Effects in the school route case, resulting from accident risk as objective, at a compliance rate of 0.4

Sensitivity analysis

To assess the impact of the valuation of the surroundings on the given advice, a sensitivity analysis is performed for the optimisation of air quality. Here, the 300 schoolchildren are given an extra weight. This shows a completely different pattern, as is displayed for a compliance rate of 0.7 in Figure 5.10. Here, the route favoured in the advice is route Y via link k, with less inhabitants surrounding. Compared to the normal weighting, this split advice also works better at preventing congestion. This shows that the policy decision of what value to attach to inhabitants is of large influence on the 'optimal' split fraction.

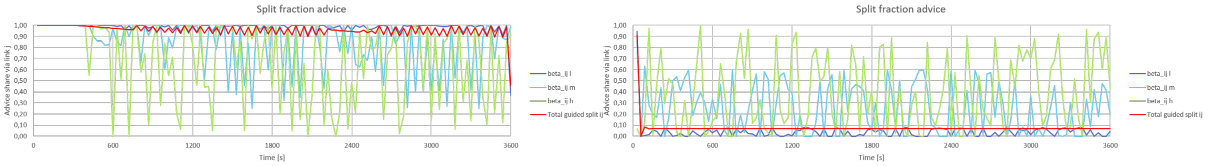


(a) Original

(b) Sensitivity analysis

Figure 5.10: Split fraction advice towards link j when optimising air quality at a compliance rate of 0.7 in the school route case, original and with extra weight attached to schoolchildren

The same sensitivity analysis as for air quality is performed when optimising for noise. For full compliance, the given advice and the resulting effects still vary greatly. In contrast to the original scenario, when doubling the weight attached to the schoolchildren the advice favours the route via link k with 0.7 compliance, as is presented in Figure 5.11. All experienced effects except for the objective noise are better with a compliance of 0.7. A compliance rate of 0.4 shows a similar pattern: all guided traffic is sent via link k, yielding even better experienced effects for travel time, air quality, and safety, but compared to higher compliance worse experienced noise. With a compliance rate of 0.1, all guided vehicles are advised to use route X via j. This causes congestion on link j, bringing about increasing experienced effects.



(a) Original

(b) Sensitivity analysis

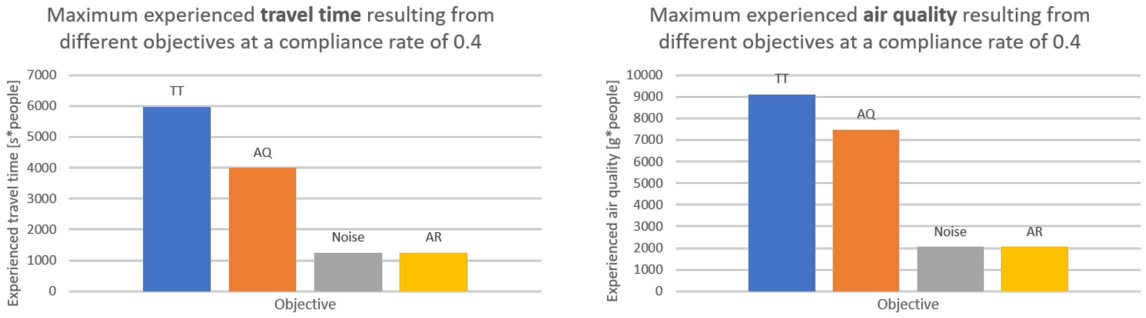
Figure 5.11: Split fraction advice towards link j when optimising noise at a compliance rate of 0.7 in the school route case, original and with extra weight attached to schoolchildren

Comparison

When comparing the experienced effects resulting from the four different objectives with a compliance rate of 1, the objective accident risk yields the best results for all effects. The objective noise also scores well for the effects travel time, air quality, and accident risk. While travel time and air quality both favour the shorter but socially less desirable link j, accident risk favours the longer route with less local residents link k. Regarding noise, although from time-step to time-step the advice varies strongly, overall, the route advice favours link k relatively more than the objectives travel time and air quality.

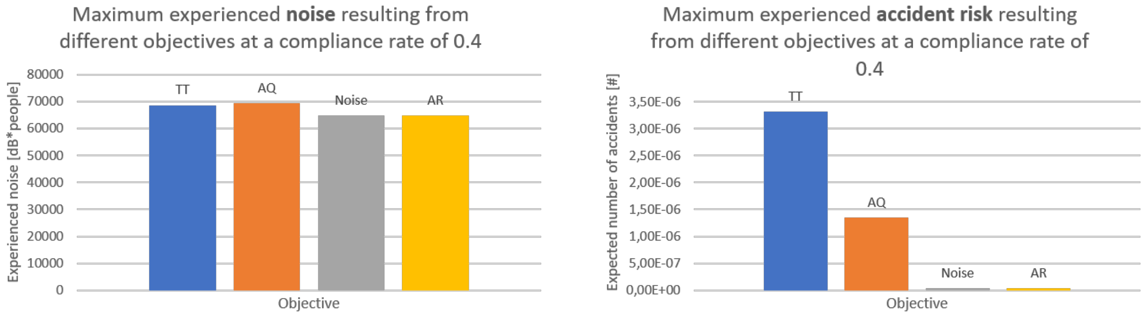
With a compliance rate of 0.7, the objective accident risk yields much better results for the effects travel time, air quality, and accident risk, and slightly better effects for noise. The objective air quality shows slightly better results than travel time and noise for the experienced effects on travel time, air quality, and accident risk. Where the objectives travel time and noise strongly favour link j, the objective air quality sends some more traffic via link k over time, and the objective accident risk sends almost all guided traffic via link k.

With a compliance rate of 0.4, it can be seen in Figure 5.12 that the objectives noise and accident risk yield better results for all effects than the objectives travel time and air quality. The first two favour link k, the longer but more social route, while the latter two favour the shorter route with more local residents.



(a) Travel time

(b) Air quality



(c) Noise

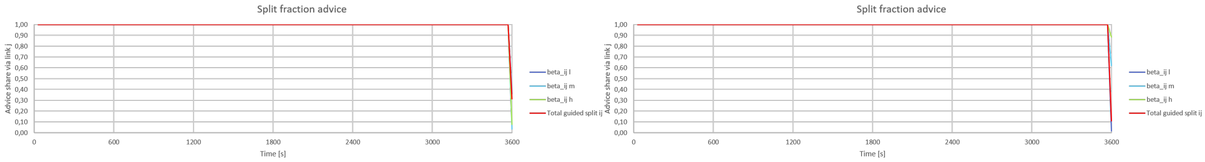
(d) Accident risk

Figure 5.12: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the school route case

For a compliance rate of 0.1, again, accident risk as objective yields relatively good effects, in this case for the experienced travel time, air quality, and accident risk. This is the only objective that favours link k, while the other favour link j.

5.1.2. Combination optimisation

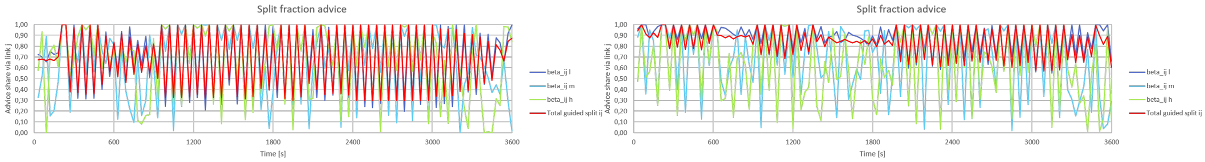
Below, the scenarios with the objectives combining all effects are discussed. In the Figures 5.13, 5.14, 5.15 the advised split fractions towards link j are shown if either more weight is attached to effects affecting road users, namely the travel time and accident risk, or to those affecting residents, namely air quality and noise. This is done for different split fractions of the unguided traffic. All objectives seem to favour the faster but socially less desirable link j, albeit more strongly for both objectives if 50% of unguided traffic travels via link j, and for residents as objective if 80% of unguided traffic uses link j. Figure 5.16 shows the given advice if unguided traffic is distributed according to a UE, and all effects are weighted equally. Here, the average advice varies more strongly in the first half of the simulation and becomes more balanced in the second half.



(a) Road users

(b) Residents

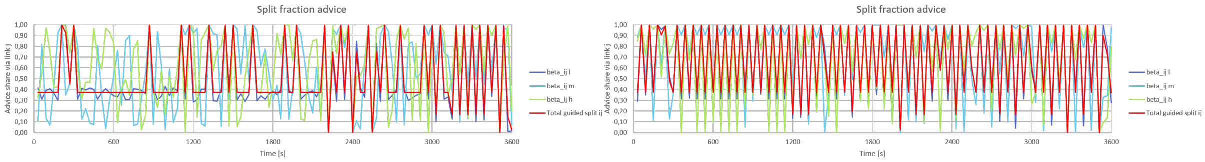
Figure 5.13: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 50% of unguided traffic uses link j, at a compliance rate of 0.4 in the school route case



(a) Road users

(b) Residents

Figure 5.14: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 80% of unguided traffic uses link j, at a compliance rate of 0.4 in the school route case



(a) Road users

(b) Residents

Figure 5.15: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 100% of unguided traffic uses link j, at a compliance rate of 0.4 in the school route case

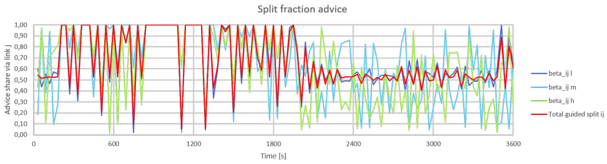
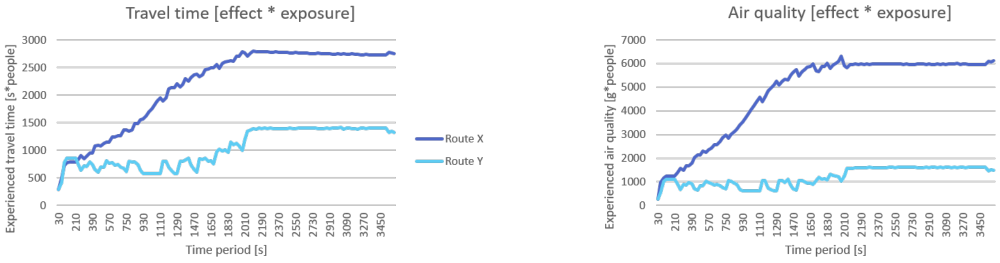


Figure 5.16: Split fraction advice towards link j when optimising all effects equally, if unguided traffic is UE distributed, at a compliance rate of 0.4 in the school route case

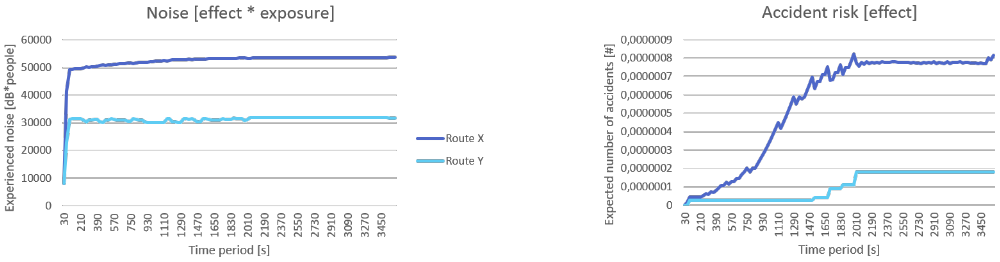
Figure 5.17 shows the experienced effects over time resulting from the objective combining all effects at an equal weight. At first, the delay increases, causing all effects to increase over time. Then, as the delay slowly decreases again, the experienced effects more or less stabilise.

Figure 5.18 shows the results of the different combined objectives. In the scenarios 'Road users 1' and 'Residents 1' all unguided traffic uses link j, however, if the objective is focused on road users, better results



(a) Travel time

(b) Air quality

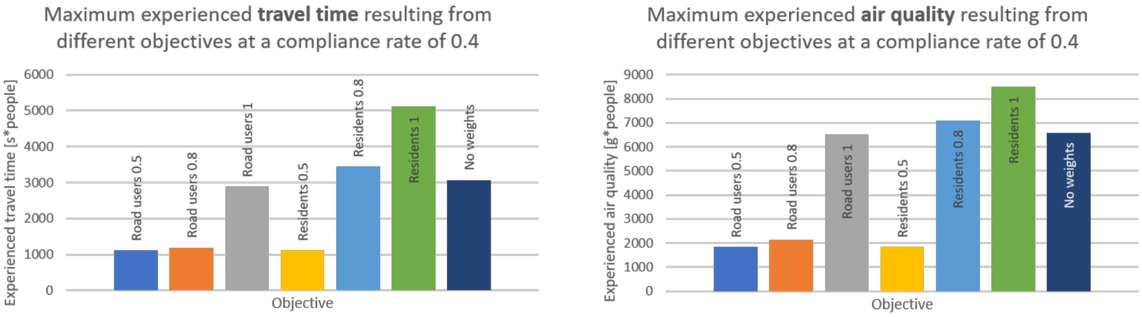


(c) Noise

(d) Accident risk

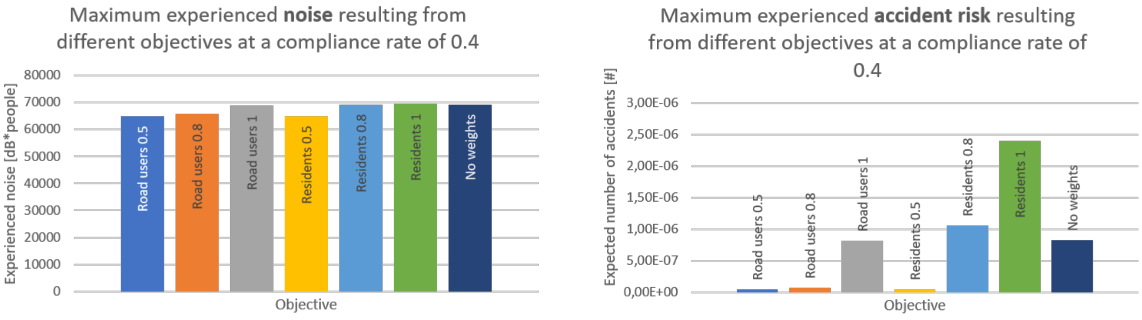
Figure 5.17: Effects in the school route case, resulting from the combined effective with equal weights, at a compliance rate of 0.4

are achieved for all experienced effects. The same is true if 80% of unguided traffic uses link j. With 50%, there is no difference between the objectives.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.18: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the school route case

5.1.3. Comparison school route case

Table 5.1 shows the maximum experienced effects of the different tested scenarios in the case with the school route, in comparison with the base case. The experienced effects in the base case are coloured yellow, more red cells indicate the effect is worse in that scenario, more green cells indicate better effects.

Table 5.1: Maximum experienced effects for the different tested scenarios in comparison to the base case, in the case with the school route

Scenario	Optimisation goal	Effective compliance	Split unguided	Travel time	Air quality	Noise	Accident risk
Base	N.A.	0	0.9	5824.26	8925.10	68866.27	3.19E-06
1	Travel time	1	N.A.	6187.41	9170.39	65156.85	3.30E-06
2	Travel time	0.7	0.9	5969.96	9040.03	68606.59	3.31E-06
3	Travel time	0.4	0.9	5975.89	9109.12	68614.10	3.32E-06
4	Travel time	0.1	0.9	5860.99	9010.34	68768.64	3.25E-06
5	Air quality	1	N.A.	4661.27	8026.92	69483.38	1.96E-06
6	Air quality	0.7	0.9	4535.26	7931.42	69491.57	1.80E-06
7	Air quality	0.4	0.9	3995.23	7469.19	69348.38	1.34E-06
8	Air quality	0.1	0.9	5731.27	9023.88	69135.47	3.06E-06
9	Noise	1	N.A.	1765.19	2784.56	66028.52	8.09E-08
10	Noise	0.7	0.9	5988.20	9061.77	68592.62	3.44E-06
11	Noise	0.4	0.9	1245.14	2047.18	64737.77	3.66E-08
12	Noise	0.1	0.9	5878.49	9064.01	68785.55	3.34E-06
13	Accident risk	1	N.A.	1707.55	2740.45	50059.36	3.12E-08
14	Accident risk	0.7	0.9	1455.67	2345.30	64069.33	3.28E-08
15	Accident risk	0.4	0.9	1245.14	2047.18	64737.77	3.66E-08
16	Accident risk	0.1	0.9	3121.14	6824.16	68905.96	8.85E-07
17	Road users	0.4	0.5	1108.69	1842.19	64873.67	4.18E-08
18	Road users	0.4	0.8	1190.33	2144.78	65662.97	6.36E-08
19	Road users	0.4	1	2891.64	6510.21	68824.77	8.14E-07
20	Residents	0.4	0.5	1108.69	1842.19	64873.67	4.18E-08
21	Residents	0.4	0.8	3439.51	7098.15	69069.89	1.05E-06
22	Residents	0.4	1	5111.73	8486.38	69288.76	2.41E-06
23	All equal	0.4	0.9	3069.25	6590.38	69032.46	8.23E-07

5.1.4. Conclusions school route case

Below, the main takeaways for the school route case are mentioned.

- Congestion negatively affects not only travel time, but also air quality, noise, and accident risk.
- Due to the nature of the model, when optimising for travel time, better effects for travel time are achieved with lower compliance, while for noise higher compliance yields better results.
- In the original situation, **link length** is of the greatest influence on what is deemed the best route for air quality. Attaching more weight to local resident drastically changes this
- When optimising for noise, the advice either prefers the shortest route, or **route with less local residents**, but the first yields worse effects in comparison to the base case, and the latter causes much better effects.
- The 'optimal' route advice for both air quality and noise strongly dependent on value attached to local residents, **attaching more weight reduces congestion and improves all effects**.
- For accident risk in this case, the road type characteristics are dominant and the **longest route** is preferred. Of the individual objectives, **accident risk causes the best results**, especially for noise, except for the lowest compliance, because there too many unguided traffic uses link j again, causing congestion.

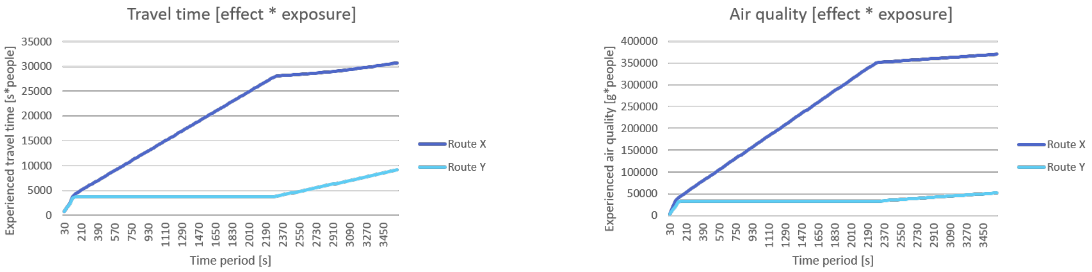
- Especially focusing on **travel time can have adverse effects on travel time, air quality, and accident risk**, optimising **air quality can have adverse effects on noise**.

- For the combined objectives, **focusing on road users yields better effects**. However, the combined objectives consider different distributions of unguided traffic compared to the base case. Nevertheless, in the worst situation where all unguided traffic uses one route, optimising for road users still yields better effects than the base case.

5.2. Parallel road

This case considers a motorway, where the shorter alternative route uses a parallel road, that has more local residents and has a lower speed and a lower capacity.

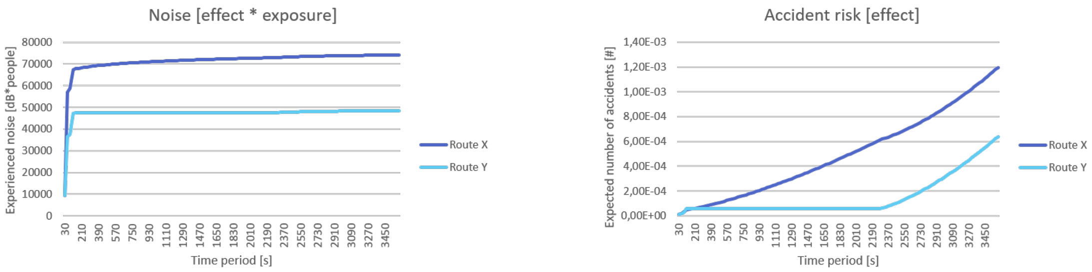
In the base scenario, all traffic is unguided and it is assumed that 62% of the road users uses the fastest route via link j. As this is more than the capacity of this link, congestion occurs here instantly. Over time, this congestion spills back to the first link in the assessed network, link i. As this reduces the inflow to link j, the travel time on this link slowly decreases again. Figures 5.19 and 5.20 show that this congestion build-up causes all liveability effects to increase over time.



(a) Travel time

(b) Air quality

Figure 5.19: Effects in the parallel road case, in the base scenario



(a) Noise

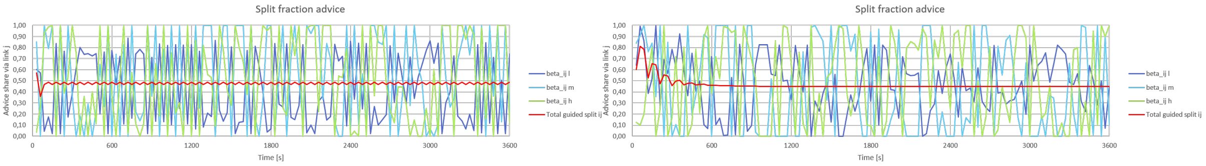
(b) Accident risk

Figure 5.20: Effects in the parallel road case, in the base scenario

5.2.1. Optimisation individual objectives

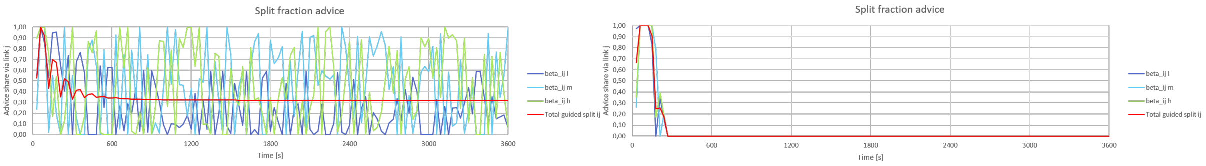
Travel time

In the case with the parallel road, link j is faster, but has a lower capacity. When optimising for travel time, the advised split fraction is almost equal for 100% compliance, and favours link k, the longer route, more with lower compliance, as is displayed in Figure 5.21. With lower compliance, the advice begins more in favour of the shorter route via link j, but over time sends more vehicles via link k, as there is more unguided traffic using link j.



(a) Compliance rate: 1

(b) Compliance rate: 0.7

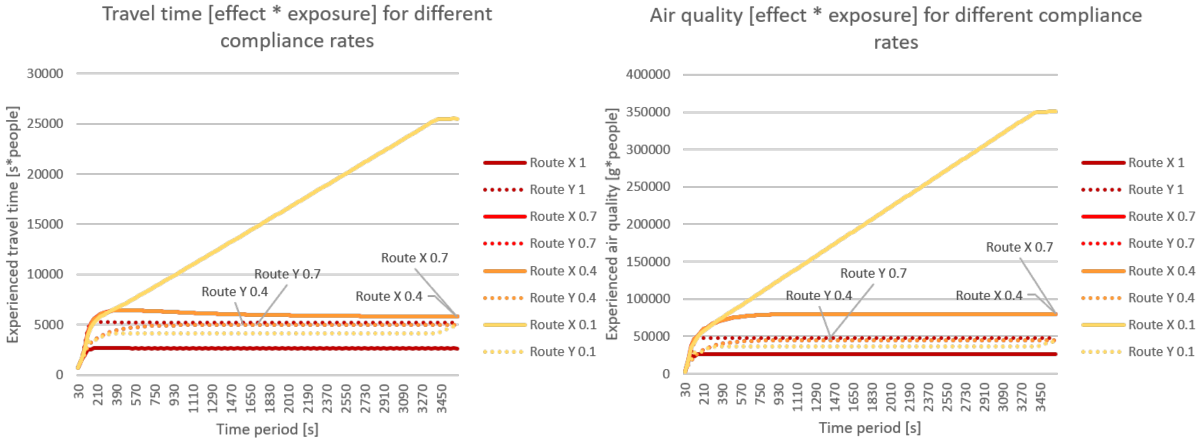


(c) Compliance rate: 0.4

(d) Compliance rate: 0.1

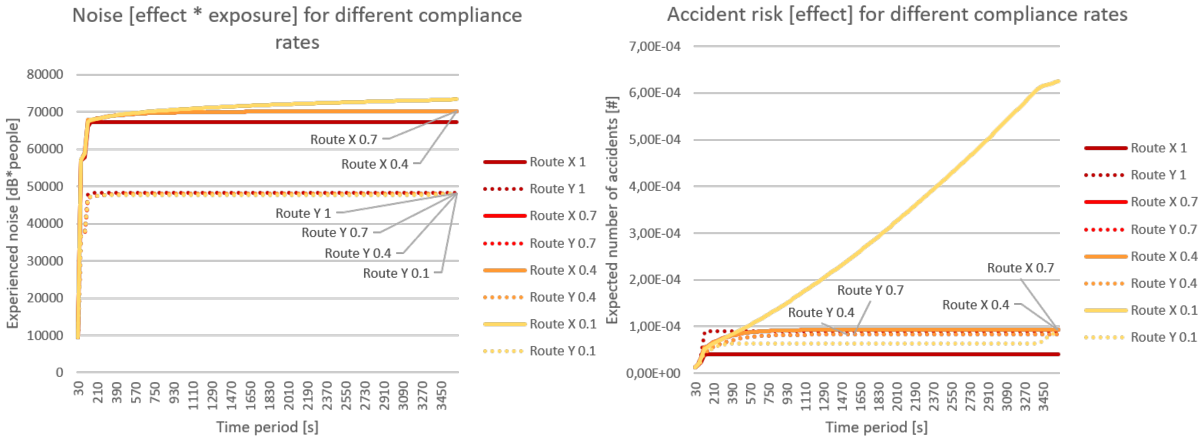
Figure 5.21: Split fraction advice towards link j when optimising travel time for different compliance rates in the parallel road case

As is displayed in Figure 5.22, with full compliance the total experienced travel time, air quality, and safety are larger for route Y via link k, but with lower compliance and the advice favouring link k, these experienced effects are higher on route X via link j. This can be explained as this is the faster route, so this is the route most of the unguided traffic takes, increasing the negative effects experienced on that route.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.22: Experienced effects on the two alternative routes over the assessed time period for different compliance rates resulting from travel time as objective in the parallel road case

Air quality

When optimising for air quality, the advice slightly favours the route via k, which is the route with less people surrounding. The advice changes with different compliance rates. With full compliance, around 33% is sent via link j, for a compliance rate of 0.7 this is is around 45%, for 0.4 32%, as shown in Figure 5.23, and for 0.1 all guided traffic is sent via link k.

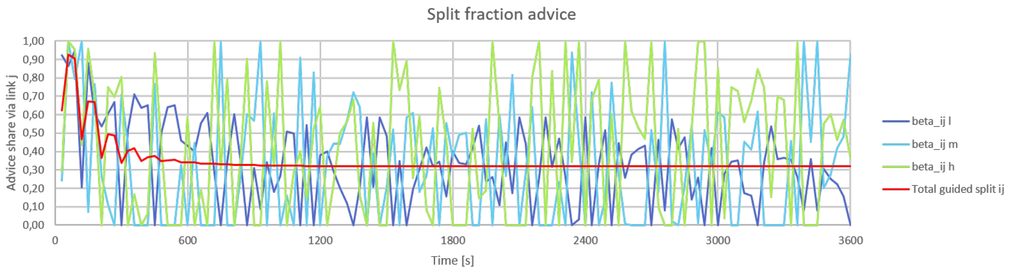
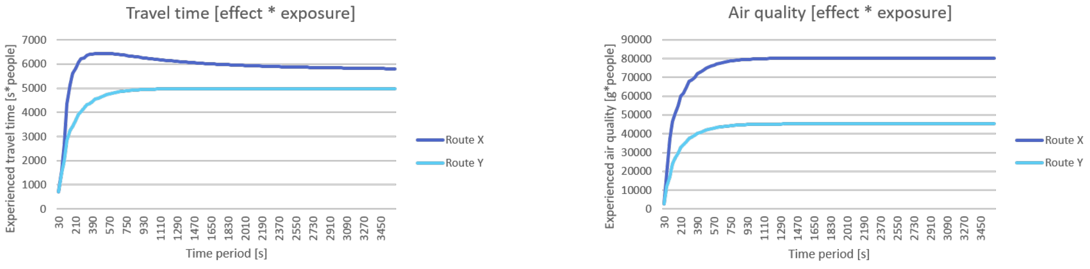


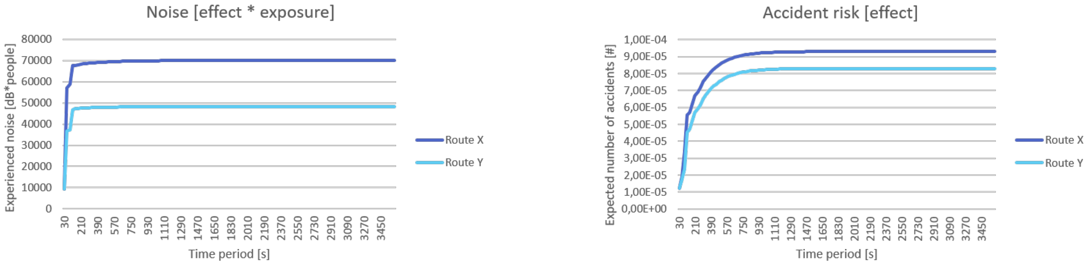
Figure 5.23: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4 in the parallel road case

How the effects are distributed over the two routes also differs with the compliance. At a compliance of 1 more traffic is sent via the link with less local residents, link k, which causes delays on this link. This yields an increasing experienced travel time, while the experienced travel time on link j remains constant. The same pattern is observed for the effects on air quality and the accident risk. This is the result of the model limitation described in Section 5.1.1. In the scenarios with a compliance of 0.7 and 0.4, the advice is slightly more equal, and congestion occurs on both routes. This yields similar effect patterns for both routes, as can be seen in Figure 5.24. Route X via link j however has more people surrounding, causing the experienced air quality and noise on this route to be higher. Furthermore, link j has a lower capacity and experiences more delay, yielding more people on this road section and therefore causing a larger experienced travel time and accident risk. Due to the large amount of unguided traffic with a compliance rate of 0.1, the delays on link j are even larger and increase over time, causing experienced travel time, air quality, and accident risk of route X to increase over the assessed time period.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.24: Effects in the parallel route case, resulting from air quality as objective, at a compliance rate of 0.4

Noise

When optimising for noise, similar average split fraction advice as for air quality can be observed for compliance rates of 0.7, 0.4, and 0.1, with 0.4 shown in Figure 5.25. This also yields similar effect patterns. Compared to full compliance, the experienced effects shown in Figure 5.26 on travel time, air quality, and accident risk in the scenarios with 0.7 and 0.4 compliance are better, while the effects on the objective noise are worse. Interestingly, the vehicle splits over the two alternative routes are very similar for 0.7 and 0.4 compliance, yielding almost identical experienced effects as well. With a compliance rate of 0.1, more traffic uses link j, causing increasing delays over time. This causes the experienced travel time, air quality and accident risk on route X to worsen over time.

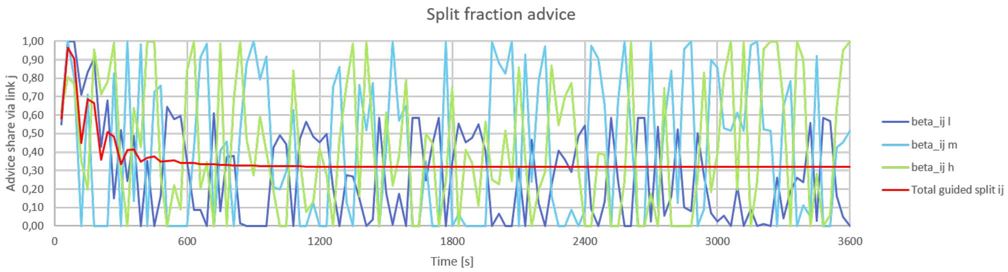
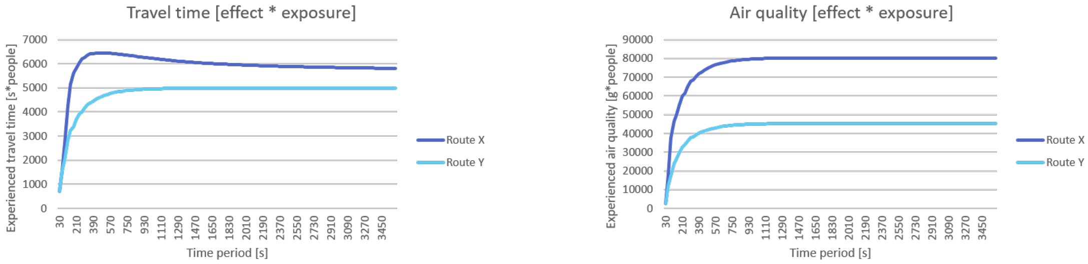
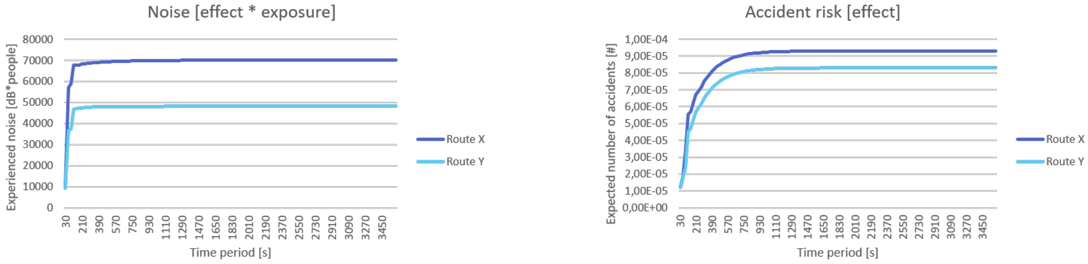


Figure 5.25: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4 in the parallel road case



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.26: Effects in the parallel route case, resulting from noise as objective, at a compliance rate of 0.4

Accident risk

When minimising the accident risk, the advised split fraction is almost fifty-fifty with full compliance, with a small preference for route Y via link k, which yields a slightly lower accident risk due to the road type. Link j is the faster alternative, so as compliance reduces, more unguided traffic will use link j. The split advice for guided traffic therefore favours link k more with decreasing compliance, as is shown for 0.4 compliance in Figure 5.27.

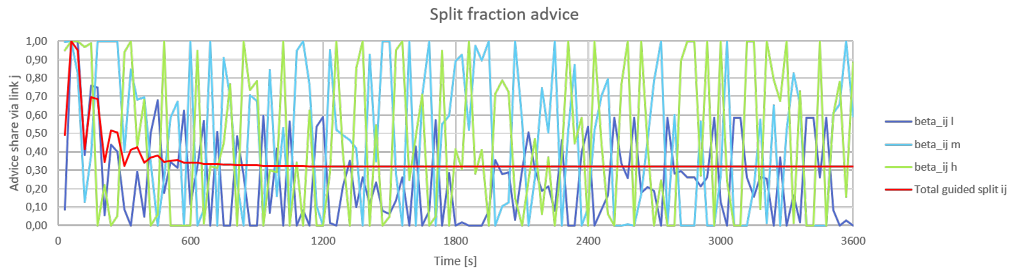
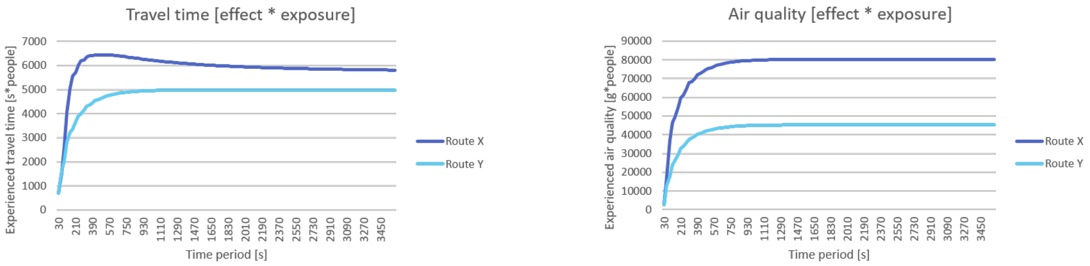


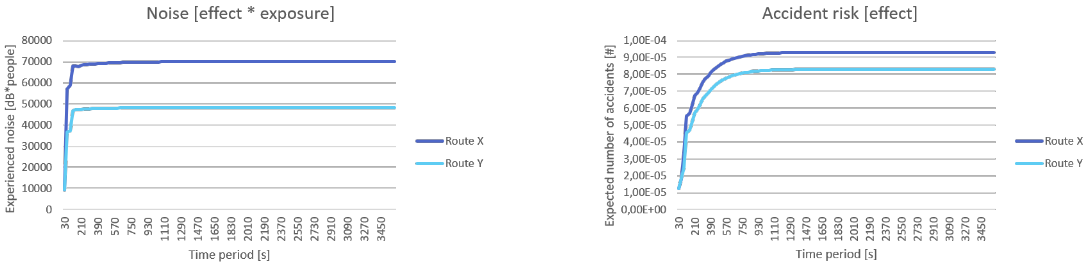
Figure 5.27: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4 in the parallel road case

With lower compliance, as the unguided split fraction is fixed, the delay on link j increases over time. Where the experienced travel time, air quality and accident risk are largest for route Y at full compliance, all experienced effects are largest on route X for all other compliance rates. For 0.1 compliance, a steep increase in experienced travel time, air quality, and accident risk can be observed. For the other compliance levels the effects become steady after a few time steps, as can be observed in Figure 5.28.



(a) Travel time

(b) Air quality



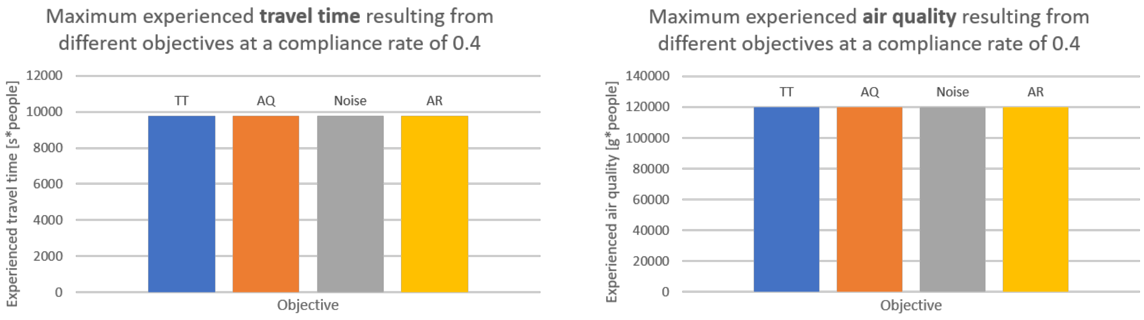
(c) Noise

(d) Accident risk

Figure 5.28: Effects in the parallel route case, resulting from accident risk as objective, at a compliance rate of 0.4

Comparison

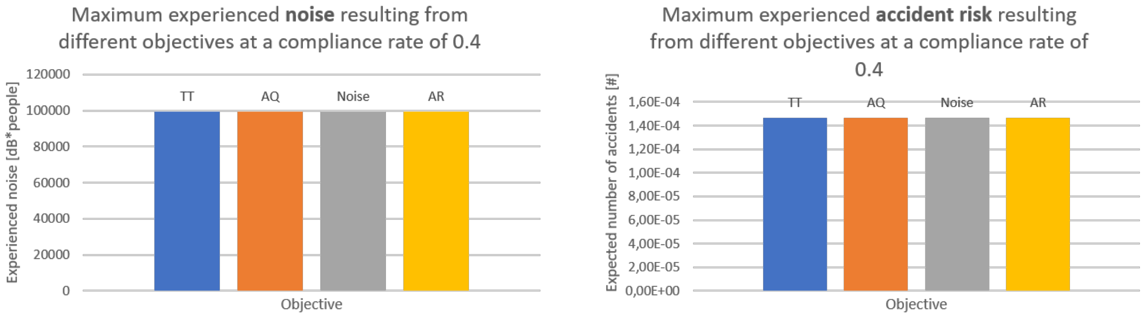
When comparing the experienced effects resulting from the four different objectives at a compliance rate of 1, the objectives for travel time and accident risk show the best results on the effects of experienced travel time, air quality, and accident risk. Air quality as objective yields the worst results for these three effects, while noise as objective yields about half the size of effects. The experienced noise is similar in size for all objectives. The objectives travel time and accident risk divide the traffic about fifty-fifty over the two alternative routes. The advice for noise as objective varies more and sends more traffic via link k over time. The split fraction advice when the objective is air quality sends about a third via link j. For the compliance rates of 0.7, 0.4, and 0.1, all objectives cause similar sized effects, as the advised split fraction is similar as well. The results for a compliance rate of 0.4 are shown in Figures 5.29 and 5.30.



(a) Travel time

(b) Air quality

Figure 5.29: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the parallel road case



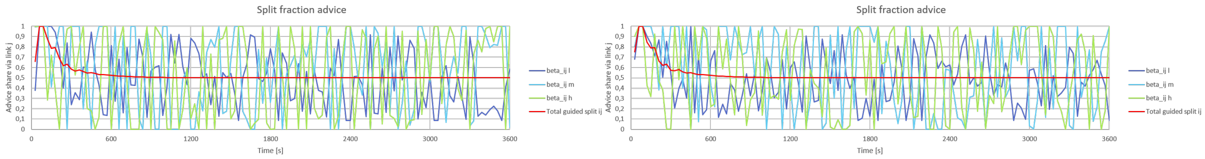
(a) Noise

(b) Accident risk

Figure 5.30: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the parallel road case

5.2.2. Combination optimisation

Figures 5.31, 5.32, and 5.33 show the split fraction advice towards links j for the different combined objectives with different distributions of unguided traffic. The given advice is similar for both the objectives focusing on road users and those focusing on residents. The more unguided traffic uses link j, the more of the guided traffic is sent via the alternative link k. Figure 5.34 shows the split fraction advice if unguided traffic is UE distributed, and all effects are weighted equally. This advice slightly favours link k, as more unguided traffic uses link j.



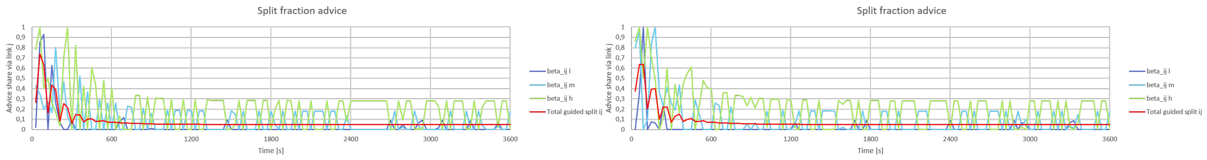
(a) Road users

(b) Residents

Figure 5.31: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 50% of unguided traffic uses link j, at a compliance rate of 0.4 in the parallel road case

In Figure 5.35 the effects resulting from the objective weighting all effects equally are displayed. As traffic is distributed fairly equally, with slightly more traffic using link k, the experienced effects are relatively similar as well. However, even though less traffic uses link j, this link has a lower capacity and more local residents, causing the experienced effects on route X to be larger than those on route Y.

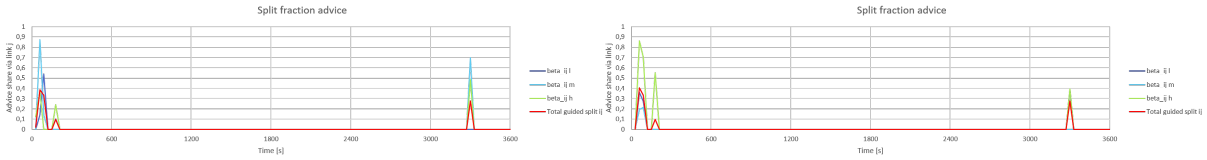
In Figure 5.36, the experienced effects resulting from the combined objectives in the case with the parallel road are shown. If all unguided traffic uses link j, the effects on travel time, air quality, and accident risk



(a) Road users

(b) Residents

Figure 5.32: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 80% of unguided traffic uses link j, at a compliance rate of 0.4 in the parallel road case



(a) Road users

(b) Residents

Figure 5.33: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 100% of unguided traffic uses link j, at a compliance rate of 0.4 in the parallel road case

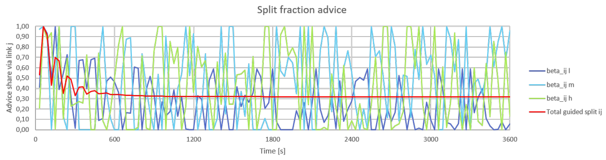
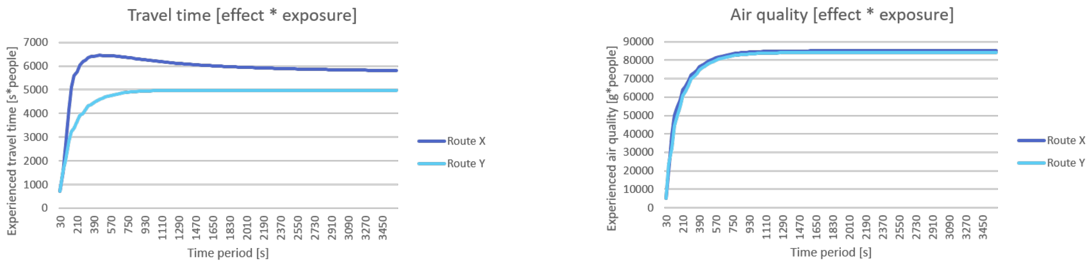
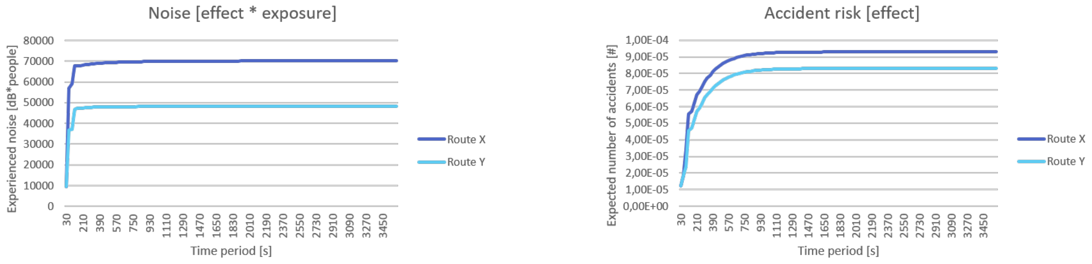


Figure 5.34: Split fraction advice towards link j when optimising all effects equally, if unguided traffic is UE distributed, at a compliance rate of 0.4 in the parallel road case



(a) Travel time

(b) Air quality

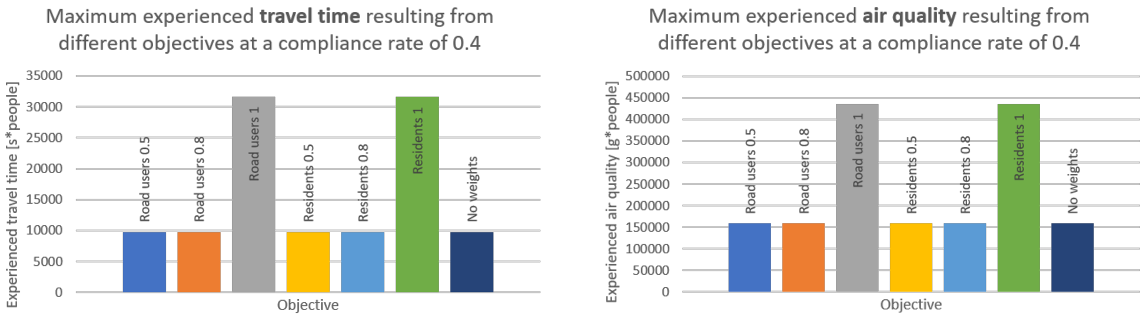


(c) Noise

(d) Accident risk

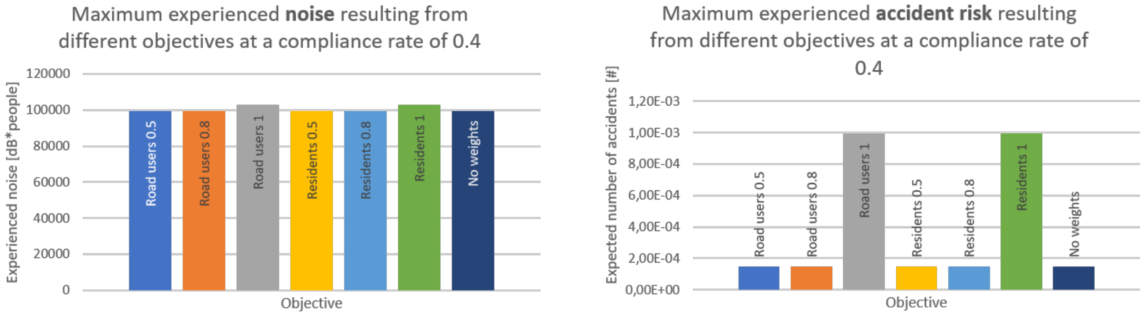
Figure 5.35: Effects in the parallel road case, resulting from the combined effective with equal weights, at a compliance rate of 0.4

become much larger for both road users and residents as objectives compared to the other scenarios. This can easily be explained, as the amount of unguided traffic is larger than the capacity of link j, causing issues irrespective of the given advice.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.36: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the parallel road case

5.2.3. Comparison parallel road case

Table 5.2: Maximum experienced effects for the different tested scenarios in comparison to the base case, in the case with the parallel road

Scenario	Optimisation goal	Effective compliance	Split unguided	Travel time	Air quality	Noise	Accident risk
Base	N.A.	0	0.62	33160.03	398506.50	102800.64	1.23E-03
1	Travel time	1	N.A.	6478.02	69380.03	96545.56	1.02E-04
2	Travel time	0.7	0.62	9782.12	119911.89	99364.65	1.46E-04
3	Travel time	0.4	0.62	9781.71	119911.90	99364.65	1.46E-04
4	Travel time	0.1	0.62	28707.38	387080.14	102433.81	6.72E-04
5	Air quality	1	N.A.	48195.03	422439.94	97890.22	2.36E-03
6	Air quality	0.7	0.62	9782.10	119911.89	99364.65	1.46E-04
7	Air quality	0.4	0.62	9782.16	119911.90	99364.65	1.46E-04
8	Air quality	0.1	0.62	28702.07	387060.52	102431.43	6.71E-04
9	Noise	1	N.A.	23610.59	231039.58	98473.26	8.50E-04
10	Noise	0.7	0.62	9782.11	119911.90	99364.65	1.46E-04
11	Noise	0.4	0.62	9782.10	119911.89	99364.65	1.46E-04
12	Noise	0.1	0.62	28707.61	387080.99	102433.91	6.72E-04
13	Accident risk	1	N.A.	6559.35	69750.65	96548.17	1.03E-04
14	Accident risk	0.7	0.62	9726.69	119911.89	99364.48	1.46E-04
15	Accident risk	0.4	0.62	9781.11	119911.90	99364.65	1.46E-04
16	Accident risk	0.1	0.62	28707.86	387081.90	102434.02	6.72E-04
17	Road users	0.4	0.5	9761.66	158803.06	99364.65	1.46E-04
18	Road users	0.4	0.8	9781.97	158803.06	99364.65	1.46E-04
19	Road users	0.4	1	31575.05	436028.07	102795.12	9.93E-04
20	Residents	0.4	0.5	9767.14	158803.06	99364.65	1.46E-04
21	Residents	0.4	0.8	9782.17	158803.06	99364.65	1.46E-04
22	Residents	0.4	1	31575.10	436028.39	102795.12	9.93E-04
23	All equal	0.4	0.62	9781.79	158803.06	99364.65	1.46E-04

In Table 5.2, the maximum experienced effects resulting from the various tested scenarios are presented, in comparison with the base case. Green cells indicate better effects compared to the base scenario, more red cells indicate the experienced effect is worse compared to the base scenario. For noise, the base situation is indicated with red, as all other scenarios yield better effects.

5.2.4. Conclusions parallel road case

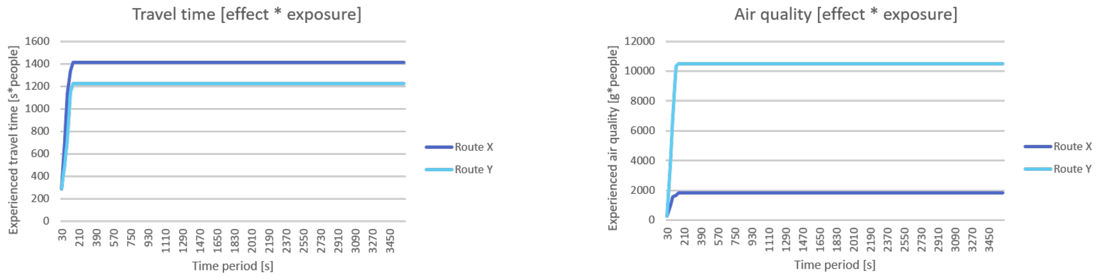
Below, the main conclusions for the case with the parallel road are described.

- In comparison to the school route case, this case has a smaller difference between travel times of both routes, and a more even distribution of unguided traffic. When optimising for travel time, advice aims at a **balanced distribution of traffic**. Higher compliance yields better results, but all show an improvement compared to the base scenario.
- The route with **less local residents is preferred when optimising air quality**, but a too strong advice causes congestion there, worsening travel time, air quality, and accident risk. A more **balanced distribution** of traffic shows improvement for all effects in comparison to base case.
- When optimising for noise, a **higher compliance yields better results for noise**, but worse for other effects. However, all compliance rates still show improvement for all effects in comparison with base case.
- In this case, the **traffic flow is most determining for the optimal split for minimising the accident risk**: the distribution is almost 50/50, with a slight preference for route with lower accident risk due to road characteristics.
- For all individual objectives, very **small differences in the effects between 0.7 and 0.4 compliance** can be observed.
- For the combined objectives in this case, the **context seems more important than the objective**, as the split advice and resulting effects are similar for both road users and residents as objectives for the same distribution of unguided traffic. If no weights are attached to the effects, improvement compared to base scenario can be seen as well.
- For the combined objectives, the **distribution of unguided traffic only shows strong impact if it instantly poses a problem for the capacity**.
- **For the experienced noise, any advice is an improvement**.
- A more **balanced distribution yields better results**, even though the given advice is not as extreme as in school case. The **situation is a bit more 'sensitive' to advice**, which might be because the two alternatives are closer together in their characteristics, for example in free flow travel time.
- The **experienced effects are similar for similar compliance rates 0.7, 0.4, and 0.1, independent of the objective**. More differences for full compliance, **travel time shows best results**, closely followed by accident risk.

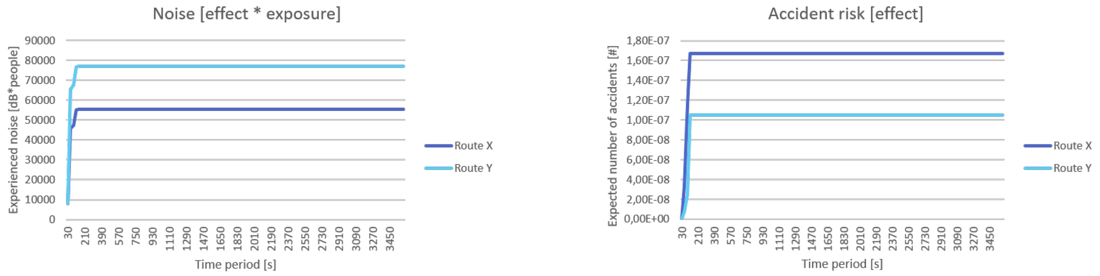
5.3. Restricted for heavy traffic

This case considers two alternative routes in the build-up area, of which one is restricted for heavy traffic. All medium heavy and heavy traffic uses the longer route via link k, with more local residents. It is assumed that 82% of the unguided light vehicles uses the restricted shorter route via link j.

In the base case, if no traffic uses route guidance, the distribution of vehicles is such that no congestion occurs. The effects, shown in Figure 5.37, increase in the first time steps as the network fills, and remain at the same level for the rest of the assessed time period.



(a) Travel time (b) Air quality



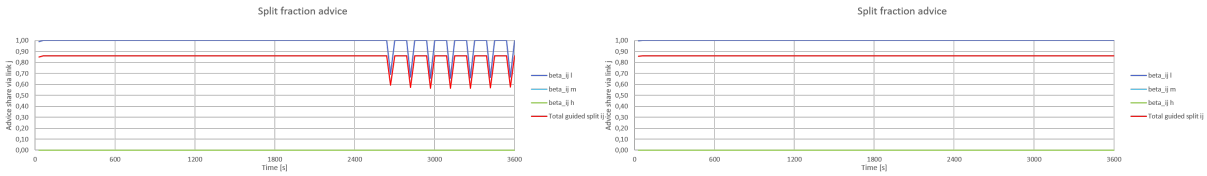
(c) Noise (d) Accident risk

Figure 5.37: Effects in the road restricted for heavy traffic case, in the base scenario

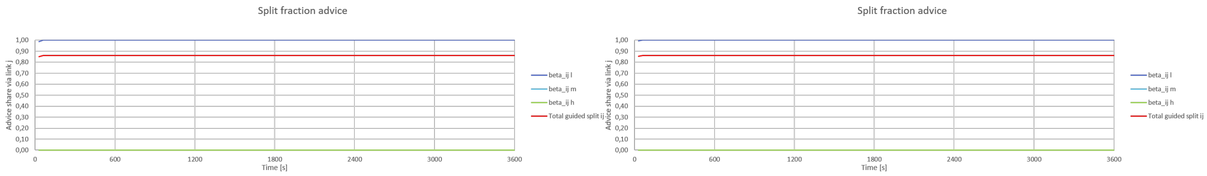
5.3.1. Optimisation individual objectives

Travel time

The fastest route is via link j. This is also the link that is restricted for medium heavy and heavy traffic. When optimising for travel time, all light vehicles are sent via this fastest route, as is displayed in Figure 5.38. However, as the capacity of link j is insufficient for the complete demand, delay on route X increases over time, causing the experienced effects on travel time, air quality and safety to increase over time as well, which can be seen in Figure 5.39. This is caused by the model assumption that only the effects in the first upcoming time step are considered, which is discussed in detail in Section 5.1.1. With full compliance, some traffic is sent via link k towards the end of the optimisation, to reduce congestion, see Figure 5.38a. This levels the experienced effects. With a lower compliance rate, traffic is split over the network more evenly, reducing congestion and other negative effects.

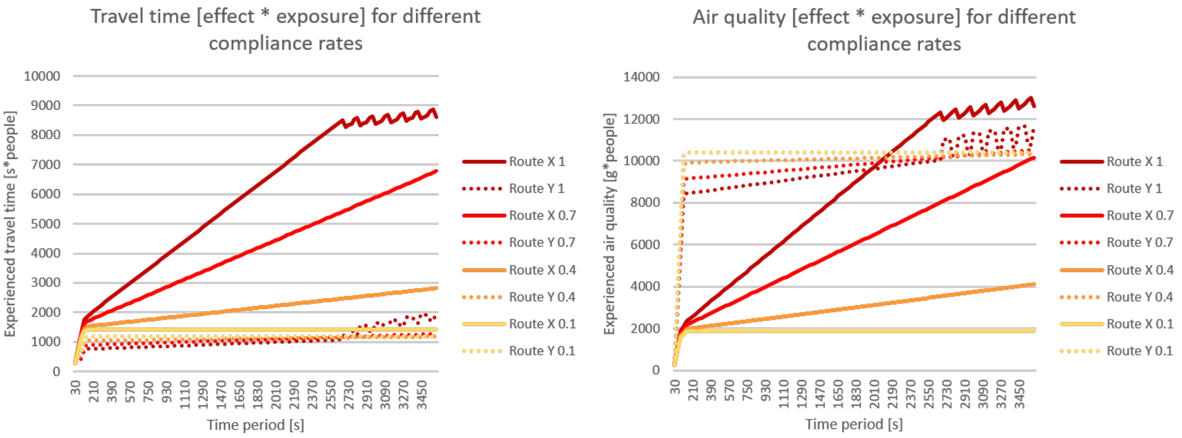


(a) Compliance rate: 1 (b) Compliance rate: 0.7



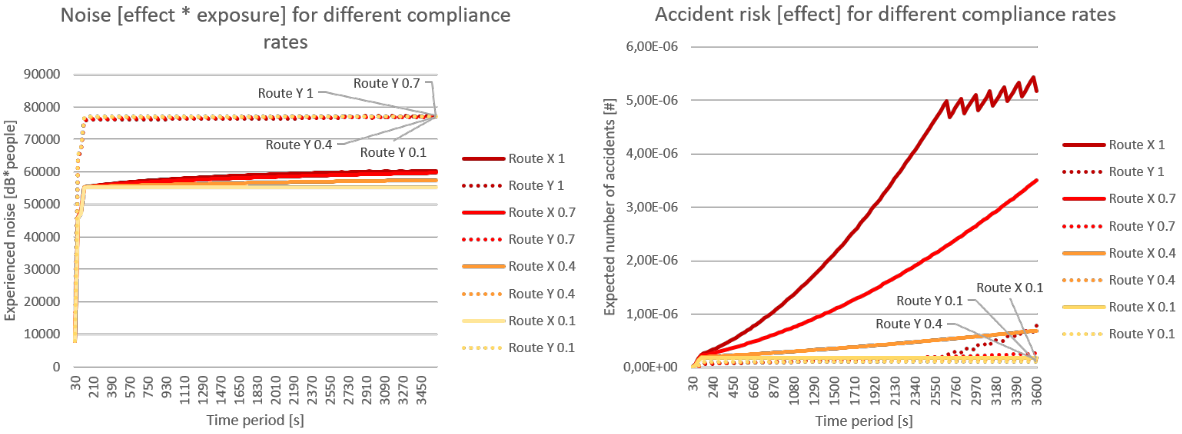
(c) Compliance rate: 0.4 (d) Compliance rate: 0.1

Figure 5.38: Split fraction advice towards link j when optimising travel time for different compliance rates in the road restricted for heavy traffic case



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.39: Experienced effects on the two alternative routes over the assessed time period for different compliance rates resulting from travel time as objective in the road restricted for heavy traffic case

Air quality
Route j is also the route with the least people surrounding. It therefore makes sense that all guided traffic is sent via this route, as can be seen for a compliance rate of 0.4 in Figure 5.40. This, however, causes delay on link j to increase over time, affecting not only the experienced travel time, but also the air quality and accident risk, as is displayed in Figure 5.41. A lower compliance rate causes more vehicles to use link k, reducing the delay on link j. This not only benefits the experienced travel time, but all other effects as well.

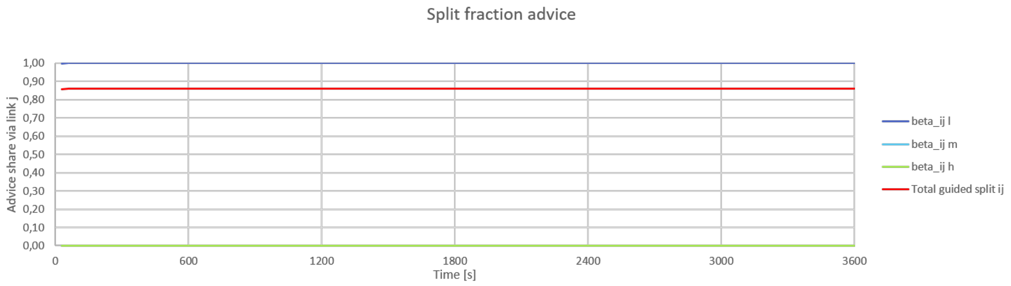
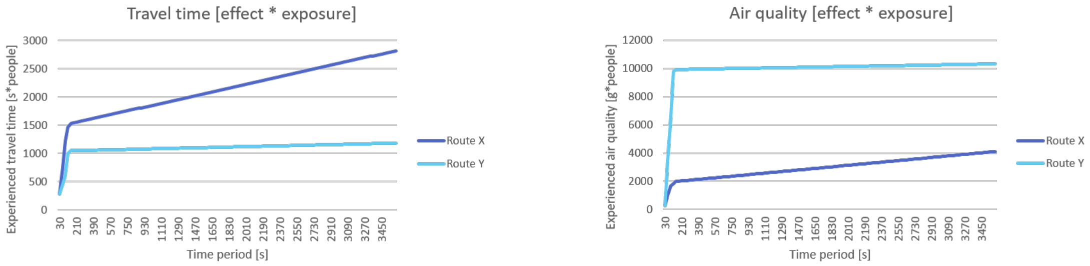


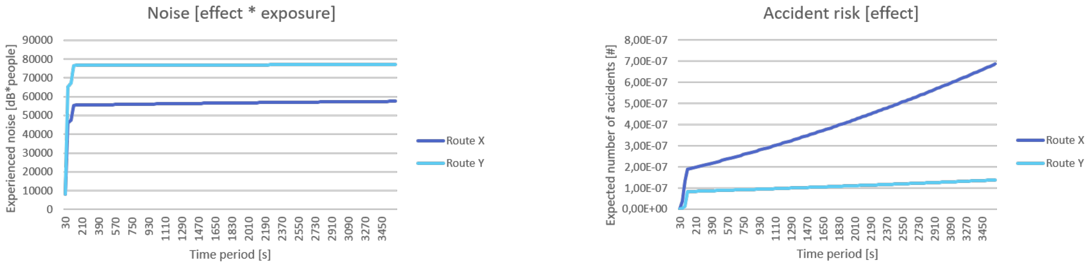
Figure 5.40: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4 in the road restricted for heavy traffic case

As can be seen in Figure 5.41, route X experiences more travel time and a higher accident risk. These factors are strongly dependent on the number of vehicles on the road, and link j in route X is assigned all complying guided light vehicles. Route Y on the other hand experiences the worst air quality and noise. This is the route that all medium heavy and heavy traffic uses. These vehicles are more polluting and noisier than the lighter vehicles, bringing about these large effects.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.41: Effects in the road restricted for heavy traffic case, resulting from air quality as objective, at a compliance rate of 0.4

Noise

When optimising for noise, the advised split fraction seems counter-intuitive, as most traffic is sent via the route with most people surrounding it, as can be seen in Figure 5.42. However, as additional noise is counted logarithmically, extra vehicles absolutely do not add much dB, even though the experienced noise may be much higher. Therefore, as link k already experiences noise, it might be beneficial to send the additional vehicles via that link as well.

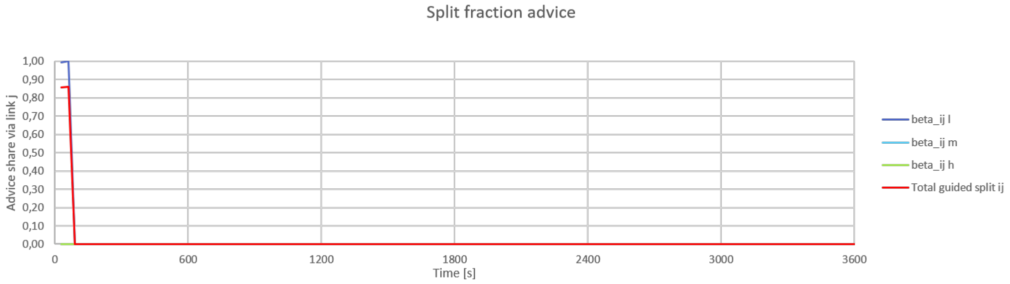
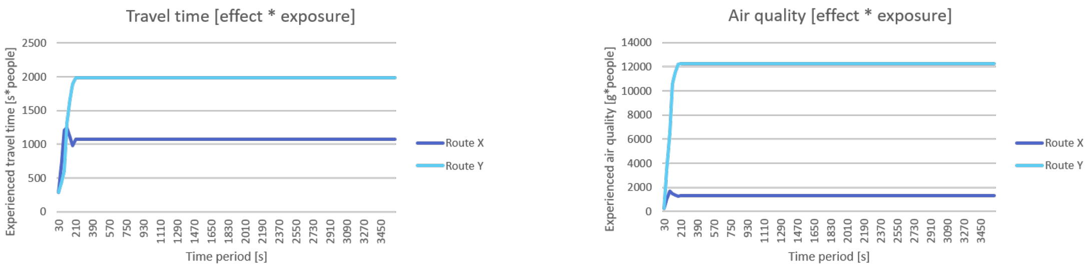


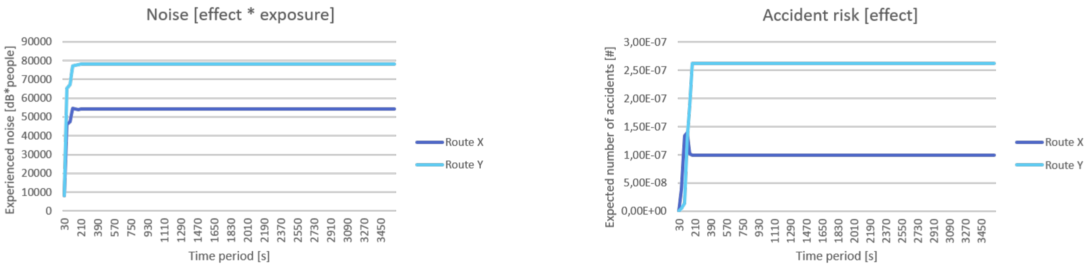
Figure 5.42: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4 in the road restricted for heavy traffic case

With a compliance rate of 0.4, many unguided vehicles will use the faster route X. With most guided vehicles being sent via route Y, this causes a more balanced traffic split, causing relatively stable effects, as can be seen in Figure 5.43.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.43: Effects in the road restricted for heavy traffic case, resulting from noise as objective, at a compliance rate of 0.4

Accident risk

When minimising the accident risk, with full compliance, about 80% of light vehicles are sent via link j, the shorter route. The accident risk on this route is lower, but as traffic flow also influences the accident risk, not all traffic should be sent via the same route. With lower compliance the share of guided vehicles sent via route j decreases, displayed for 0.4 in Figure 5.44. After the first few time steps, the total transition flow to both alternative links is equal throughout the different compliance rates. Therefore, the size of the experienced effects is almost identical for the different compliance rates, but lower compliance yields slightly better effects. The effects resulting from a compliance rate of 0.4 are presented in Figure 5.45.

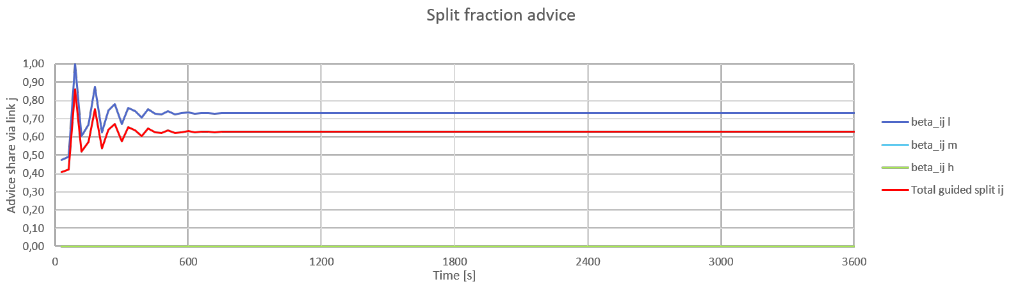
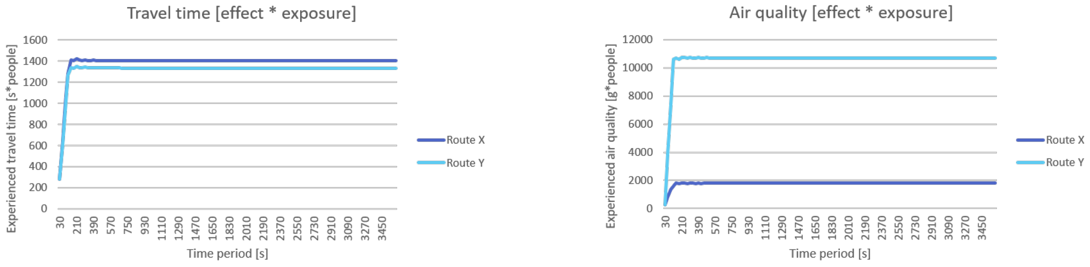
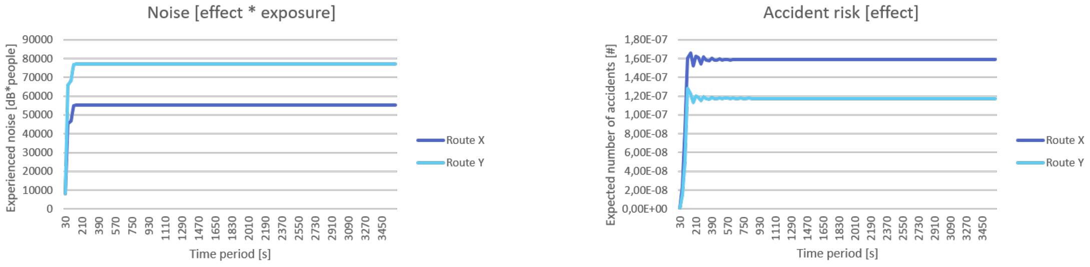


Figure 5.44: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4 in the road restricted for heavy traffic case



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

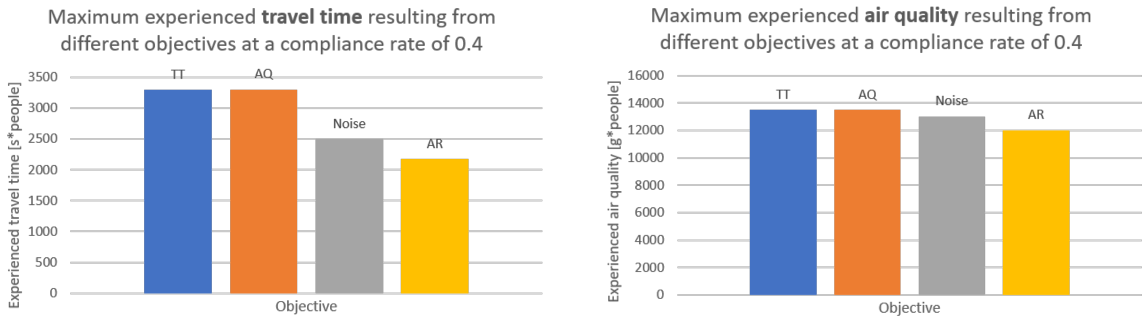
Figure 5.45: Effects in the road restricted for heavy traffic case, resulting from accident risk as objective, at a compliance rate of 0.4

Comparison

Comparing the experienced effects resulting from the four different objectives at a compliance rate of 1 shows that the objective accident risk yields the best results for all effects. Noise as an objective causes good effects as well on experienced travel time and accident risk. The objectives travel time and air quality strongly favour link j, the road that is restricted for heavy traffic. With noise as an objective, about 30% of the light vehicles is sent via link j. With accident risk as objective, the advice lies somewhere in between, at 78%.

At a compliance rate of 0.7, accident risk as objective yields the best results for all effects as well. Noise as objective again causes good effects for experienced travel time and accident risk. The objectives travel time and air quality again send all guided traffic via link j, while noise as objective strongly favours link k. Accident risk as objective gives a similar advice as with full compliance.

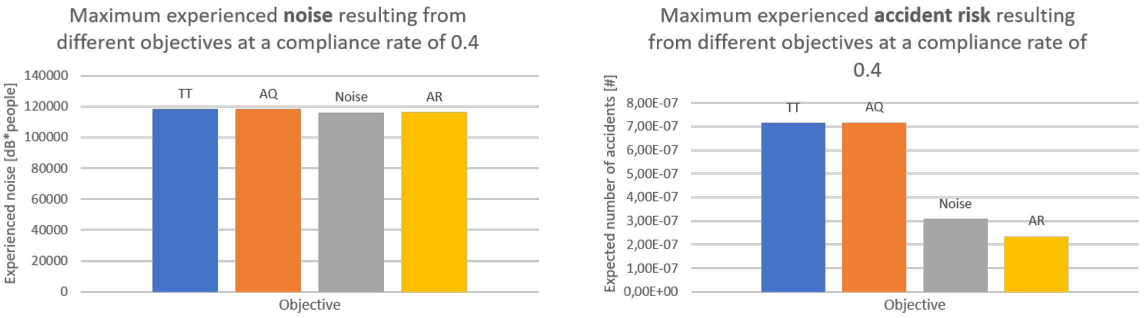
With 0.4 compliance, of which the results are shown in Figures 5.46 and 5.47, accident risk and noise again yield the better results, especially on experienced travel time and accident risk. Travel time and air quality favour link j, while noise favours link k, and accident risk sends three quarters of light traffic via link j.



(a) Travel time

(b) Air quality

Figure 5.46: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the road restricted for heavy traffic case



(a) Noise

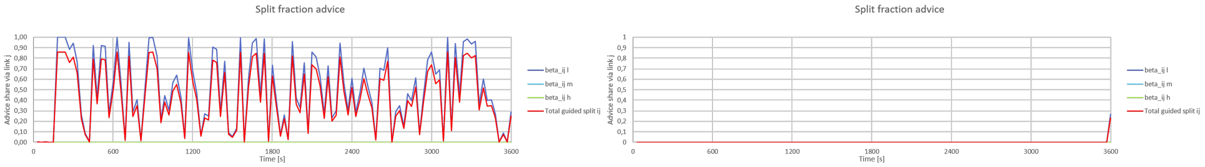
(b) Accident risk

Figure 5.47: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the road restricted for heavy traffic case

With a compliance rate of 0.1, there is no objective that yields clearly better results.

5.3.2. Combination optimisation

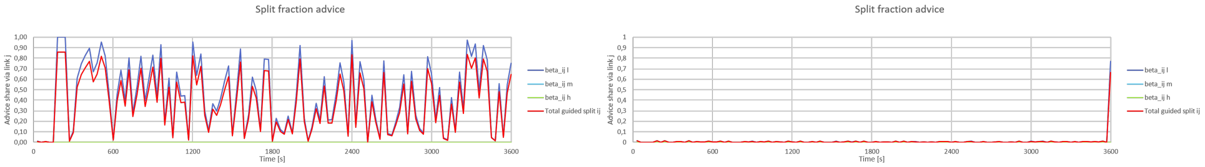
The Figures 5.48, 5.49, and 5.50 show the route advice given to guided traffic if more importance is attached to either road users or residents for different distributions of unguided traffic. The advice focusing on road users is much more irregular than the advice if residents are given a higher weight. With more unguided traffic using link j, the advice for road users favours link k more.



(a) Road users

(b) Residents

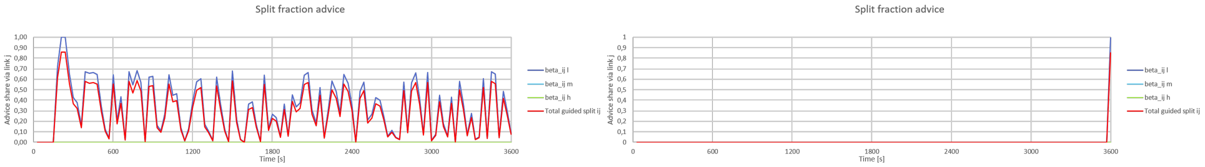
Figure 5.48: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 50% of unguided traffic uses link j, at a compliance rate of 0.4 in the road restricted for heavy traffic case



(a) Road users

(b) Residents

Figure 5.49: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 80% of unguided traffic uses link j, at a compliance rate of 0.4 in the road restricted for heavy traffic case



(a) Road users

(b) Residents

Figure 5.50: Split fraction advice towards link j when optimising the effects experienced by road users and residents respectively, if 100% of unguided traffic uses link j, at a compliance rate of 0.4 in the road restricted for heavy traffic case

Figure 5.51 shows a similar irregular pattern for the combined objective with equal weights as for the objectives focusing on road users. The advice slightly favours link k.

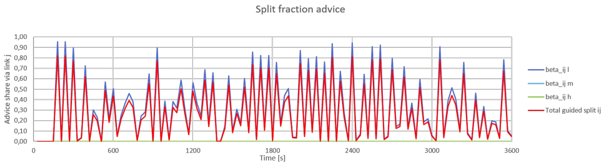
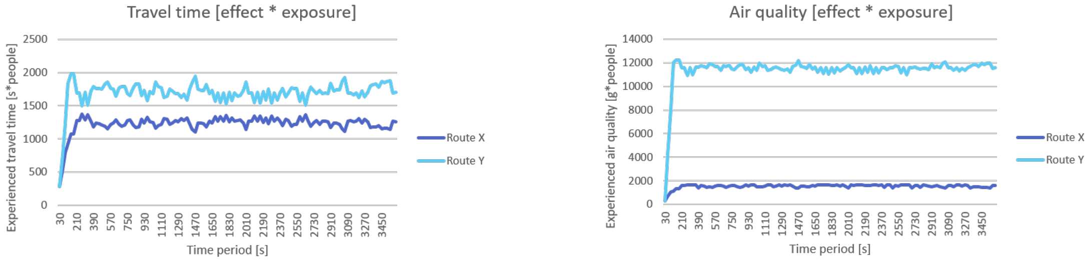


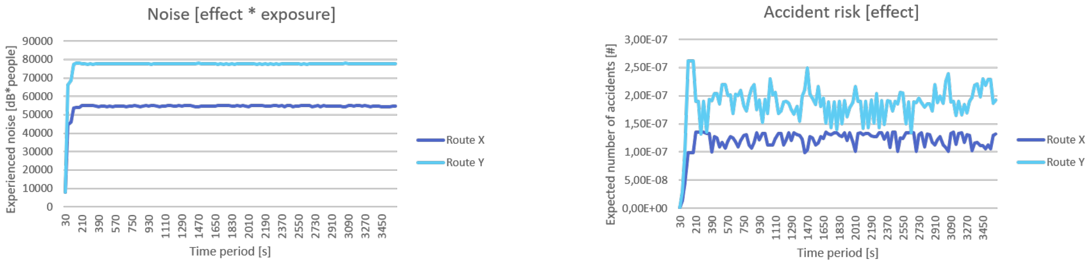
Figure 5.51: Split fraction advice towards link j when optimising all effects equally, if unguided traffic is UE distributed, at a compliance rate of 0.4 in the road restricted for heavy traffic case

In Figure 5.52 the experienced effects resulting from the combined objective with equal weights are displayed. The switching in the advice can be found in the effects as well, with irregularities from time step to time step. Over time, however, the effects remain around the same level.



(a) Travel time

(b) Air quality



(c) Noise

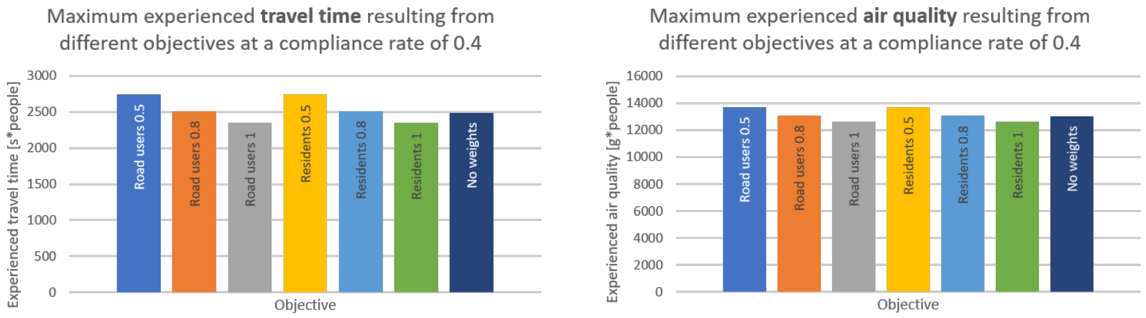
(d) Accident risk

Figure 5.52: Effects in the road restricted for heavy traffic case, resulting from the combined effective with equal weights, at a compliance rate of 0.4

In Figure 5.53 the experienced effects resulting from the different combined objectives in the case with the road restricted for heavy traffic are displayed. If all unguided traffic uses link j, more guided traffic is sent via link k and the experienced effects are lower. When comparing the objectives favouring either road users or residents, no strong difference in experienced effects is observed, even though the split fraction advice patterns were so different.

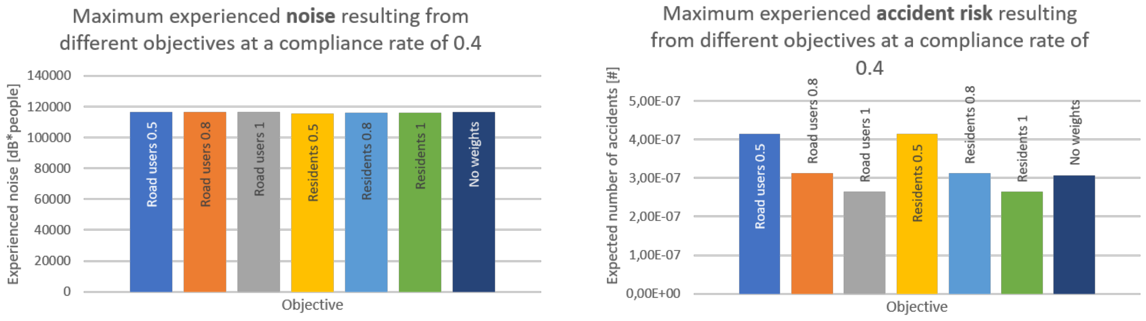
5.3.3. Comparison road restricted for heavy traffic case

Table 5.3 shows the maximum experienced effects for the different tested scenarios, in comparison with the base case. Cells that are greener than the base scenario comprise better experienced effects, cells that are more red indicate the experienced effect is worse in comparison to the base scenario. It can be seen that most scenarios yield worse effects in comparison to the base scenario. Only when optimising for travel time or air quality at a compliance rate of 0.1, an improvement for all effects is found with the used model set-up.



(a) Travel time

(b) Air quality



(c) Noise

(d) Accident risk

Figure 5.53: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the road restricted for heavy traffic case

Table 5.3: Maximum experienced effects for the different tested scenarios in comparison to the base case, in the case with the road restricted for heavy traffic

Scenario	Optimisation goal	Effective compliance	Split unguided	Travel time	Air quality	Noise	Accident risk
Base	N.A	0	0.82	2070.24	11791.72	116360.87	2.19E-07
1	Travel time	1	N.A.	9127.56	21563.47	120767.45	5.43E-06
2	Travel time	0.7	0.82	7112.18	18735.97	120072.62	3.52E-06
3	Travel time	0.4	0.82	3296.54	13478.67	118269.21	7.15E-07
4	Travel time	0.1	0.82	2047.25	11725.03	116353.28	2.18E-07
5	Air quality	1	N.A.	9626.26	21436.88	120468.84	6.09E-06
6	Air quality	0.7	0.82	7112.52	18736.47	120072.73	3.52E-06
7	Air quality	0.4	0.82	3298.92	13482.45	118271.61	7.17E-07
8	Air quality	0.1	0.82	2047.40	11725.12	116353.43	2.18E-07
9	Noise	1	N.A.	4183.70	21481.12	116919.35	9.52E-07
10	Noise	0.7	0.82	3975.63	21103.11	116851.91	8.85E-07
11	Noise	0.4	0.82	2495.59	13015.91	116106.63	3.08E-07
12	Noise	0.1	0.82	2189.53	12106.21	116369.2	2.30E-07
13	Accident risk	1	N.A.	2198.02	12084.79	116512.8	2.39E-07
14	Accident risk	0.7	0.82	2195.95	12081.51	116509.65	2.38E-07
15	Accident risk	0.4	0.82	2177.25	12007.7	116473.4	2.35E-07
16	Accident risk	0.1	0.82	2145.16	11977.47	116429.13	2.28E-07
17	Road users	0.4	0.5	2740.19	13721.36	116718.34	4.14E-07
18	Road users	0.4	0.8	2506.89	13050.31	116731.75	3.12E-07
19	Road users	0.4	1	2353.78	12608.34	116650.45	2.65E-07
20	Residents	0.4	0.5	2740.42	13721.9	115407.92	4.14E-07
21	Residents	0.4	0.8	2508.44	13054.16	116082.08	3.13E-07
22	Residents	0.4	1	2353.78	12608.34	116280.58	2.65E-07
23	All equal	0.4	0.82	2492.97	13009.22	116535.87	3.07E-07

5.3.4. Conclusions road restricted for heavy traffic case

The main takeaways for the case with the road restricted for heavy traffic are discussed below.

- When optimising for travel time, naturally, the fastest route is suggested, but this causes congestion over time due to the model set-up.
- In this case, the fastest route is also the route with the least local residents. This route is advised when optimising air quality as well.
- This case shows a clear distinction between the factors influencing the effects. Although the number of **medium heavy and heavy vehicles** is quite small, their **impact on air quality and noise is very strong**.
- **Travel time and accident risk are strongly dependent on the number of vehicles on a link**.
- When optimising for noise, advice aims to send traffic via the link already in use and experiencing noise, which is relatively beneficial for travel time, noise, and accident risk.
- Minimising the accident risk, which **aims at a more balanced distribution, yields the least worse effects** in comparison to the base situation across all tested compliance rates.
- For the combined objectives, the **context is more important for travel time, air quality, and accident risk**. However, **noise slightly benefits from focusing on the residents**.
- In this case, almost no improvements of effects were achieved. This might suggests that the original congestion could be a good indicator of the potential of improvement on liveability as well.

5.4. Comparison of the three cases

Comparing the three cases with each other, some differences in the results can be observed. First of all, in the school route case, the given advice across the tested scenarios is quite extreme; almost all guided traffic on average is sent via either one route or the other. This might be the result of the large differences between the two alternative routes, in comparison to the other two cases. For example, the ratio between the free flow travel times of the two alternatives is relatively large, yielding an extreme distribution of unguided traffic as well. This large difference between the two routes might be an explanation for the fact that not only for travel time, but also for air quality and some compliance rates of noise, the shortest route is advised, as this impact is stronger than that of the amount of local residents.

In the case with the parallel road, there are no large differences between different individual objectives with the same compliance rate, or between combined objectives with the same distribution of unguided traffic. This might be explained by the fact that, in comparison with the school case, the differences between the characteristics of the two alternative routes are smaller. The ratio between the two free flow travel times is smaller, yielding a more even distribution of unguided traffic. This might be an explanation for the fact that the given advice is also much less extreme than in the school route case. However, the fact that the two alternative routes are close together in their characteristics, could also cause the case to be more sensitive to ’too extreme’ route advice.

Finally, in the case where one of the roads is restricted for heavy traffic, almost no improvement is observed across the tested scenarios. The small improvements that can be found, are small in comparison with the deteriorations that result from some scenarios. As in the base case no delay occurs, this might suggest that congestion could be a good indicator of the potential improvement that could be achieved on the effects on liveability.

5.5. Conclusion

When optimising for travel time, in the cases school and restricted for heavy traffic, the fastest route is favoured. If after some time this causes congestion to increase, some traffic is sent via the other link to reduce the experienced travel time again. In the case with the parallel road the fastest route is initially favoured in the advice as well. However, as this quickly causes a large increase in travel time, more traffic is sent via the other route to reduce congestion.

When minimising the experienced negative effects on air quality, the advice is less straightforward. A shorter link reduces the amount of pollution produced, while congestion and lower speeds increases the emissions. The value attached to the local residents can influence the advised split fraction as well, as was seen in the sensitivity analysis in the school case.

When minimising experienced noise, in general, the route with less local residents is favoured, although this can differ depending on the weight attached to the residents. As dB are counted logarithmically, additional vehicles have very limited impact on the amount of dB, even though the noise experienced might be much larger. This makes the determination of the best split advice more complicated.

The advised split fraction when minimising the accident risk depends on the road types, the length of the road section and the traffic flow. In the case with the school route, the road type is the most dominant aspect, causing the longer, but with smaller parameters, to be favoured. In the case of the parallel road, there is a difference in road type as well, however, here the traffic flows seems to be the dominant aspect, and traffic is split more evenly over the two routes. In the case with the restricted road, the road types of the two alternatives are the same. Here, the shorter route is favoured, but still a large share is sent via the other link, to prevent the traffic flow from getting to large.

As described above, in some situations, increasing compliance yields worse effects. This can be explained by the length of the links. When a link is longer than one travel time period, the travel time resulting from a certain split fraction experience a delay of the multitude of the travel time period. The controller only considers the effects in the next time step when deciding on the optimal split advice. Due to the delay, some effects may remain the same in the first upcoming time step independent of the split fraction, or may even get worse before showing an improvement some time steps later. This causes the controller in some situations to keep advising the same split fraction, even though this increases congestion and worsens the effects, or to only give different advice when a link is completely congested. A lower compliance rate means less people follow this advice with adverse effects, causing a more balanced split of traffic and less congestion.

When combining all effects normalised in one objective, in the school route case better results are obtained if more weight is attached to the effects impacting road users, in comparison to the same situation with residents valued stronger. In the cases with the parallel road and the road restricted for heavy traffic however, the weights have less of an influence, and the experienced results are more affected by the distribution of unguided traffic. For all cases, if more unguided traffic takes the fastest route, more of the guided traffic is sent via the other route.

6

Evaluation

In this chapter the effects found are evaluated individually by attaching a monetary value to them. Additionally, the experienced effects are compared with each other.

6.1. Individual evaluation of effects

To evaluate the effects resulting from different objectives, they are monetised. First, the values used for this monetisation are described, then the effects from the different cases are discussed.

6.1.1. Monetary values

In this section, the values that are used for the monetisation of the effects are described.

Travel time

One of the most well-known monetisation methods is the Value of Time (VOT). This can be used to attach a value to the resulting travel time. Different values of time are established for freight traffic, commute, business, and other travel purposes. Additionally, both low and high values are formulated (Steunpunt Economische Expertise, n.d.). The average of the low and high value for freight traffic can be used for the medium and heavy traffic. This is 46.93 €/h. A combination of the values of the other three purposes is used for light vehicles. Taking the amount of kilometres travelled per purpose into account, the VOT for light traffic is 9.22 €/h (CBS StatLine, 2018). To be able to evaluate the total effects, these two VOTs are subsequently averaged in alignment with the vehicle shares of different road types and considering an average occupation of passenger cars of 1.4 (Bleijenberg, van Essen, & van Wee, 2017). This finally yields a value of 17.70 €/h for traffic within the built-up area, 28.35 €/h for motorways, and 21.18 €/h for other roads outside the built-up area.

Air quality

The other effects might seem less straightforward to monetise. To be able to calculate and compare societal effects, CE Delft has established environmental prices for various effects on the environment (de Bruyn et al., 2017). For PM_{10} a value of 44.60 $€_{2015}$/kg was found. For NO_x, this value is 34.79 $€_{2015}$/kg. Converted to the consumer price index of February 2020, these values are 47.56 €/kg and 37.00 €/kg respectively (CBS StatLine, 2020). Of the combined emissions about 95% is NO_x and 5% PM_{10}, the used average monetary value for air quality is 37.53 €/kg.

Noise

For noise environmental prices are set up as well (de Bruyn et al., 2017). These prices increase with higher noise levels, as can be seen in Table 6.1. As described in Section 3.2.2, only the noise production is considered and correction factors are not included. This causes the calculated noise to be higher than what would be actually experienced. The cases and scenarios that are analysed are not expected to exceed the limit of 50 dB. Therefore, a value of 26 $€_{2015}$/dB per person per year is used. As the assessed time period in the research is only an hour, this is converted to 8,79E-07 $€_{2020}$/dB per person per s.

Table 6.1: Prices attached to noise levels

Noise level	€2015 / dB (Lden) per person per year
50-54 dB(A)	26
55-59 dB(A)	48
60-64 dB(A)	52
65-69 dB(A)	97
70-74 dB(A)	103
75-79 dB(A)	108
>= 80 dB(A)	111

Safety

Accidents can bring about non-material damage such as pain and grief. To be able to develop and compare policies and solutions, these human experiences need to be translated into monetary values. For this, the Value of a Statistical Life (VOSL) is developed. This value can vary strongly, depending on for example the method of research or the form of the survey. The recommended value to use for cost-benefit analyses is 2.2 million € (Wesemann, de Blaeij, & Rietveld, 2005).

6.1.2. School route

In Table 6.2 the maxima of all effects resulting from different individual objectives are shown. The corresponding monetary value is presented in each row below.

Within the same effect between objectives, the largest impact on experienced travel time is almost five times as large as the smallest maximum. For air quality, this ratio is more than four, while the largest maximum of noise is less than 10% larger. The largest relative difference can be observed for accident risk, where the largest maximum is more than 90 times the size of the smallest maximum.

Within the same objective between effects, strong differences are observed. Especially the monetary value of experienced air quality is large compared to the other effects, particularly if travel time is the used objective.

Table 6.2: Monetisation of effects resulting from four different individual objectives, in the school route case at a compliance rate of 0.4

Objective	Effect >	Travel time	Air quality	Noise	Accident risk
Travel time	Maximum value	5975.89	9109.12	68614.10	3.32E-06
	€	29.38	341.87	1.81	7.30
Air quality	Maximum value	3995.23	7469.19	69348.38	1.34E-06
	€	19.64	280.32	1.83	2.96
Noise	Maximum value	1245.14	2047.18	64737.77	3.66E-08
	€	6.12	76.83	1.71	0.08
Accident risk	Maximum value	1245.14	2047.18	64737.77	3.66E-08
	€	6.12	76.83	1.71	0.08

In Table 6.3 the maximum effects and their monetary equivalent of the combination objectives are presented. Here again, large differences can be observed, both within and between objectives.

Table 6.3: Monetisation of effects resulting from seven different combined objectives, in the school route case at a compliance rate of 0.4

Objective	Effect	Travel time	Air quality	Noise	Accident risk
Road users 0.5	Maximum value	1108.69	1842.19	64873.67	4.18E-08
	€	5.45	69.14	1.71	0.09
Road users 0.8	Maximum value	1190.33	2144.78	65662.97	6.36E-08
	€	5.85	80.49	1.73	0.14
Road users 1	Maximum value	2891.64	6510.21	68824.77	8.14E-07
	€	14.22	244.33	1.82	1.79
Residents 0.5	Maximum value	1108.69	1842.19	64873.67	4.18E-08
	€	5.45	69.14	1.71	0.09
Residents 0.8	Maximum value	3439.51	7098.15	69069.89	1.05E-06
	€	16.91	266.39	1.82	2.31
Residents 1	Maximum value	5111.73	8486.38	69288.76	2.41E-06
	€	25.13	318.49	1.83	5.29
No weights	Maximum value	3069.25	6590.38	69032.46	8.23E-07
	€	15.09	247.34	1.82	1.81

Conclusions school route case

The main conclusions that can be drawn from this evaluation are:

- Air quality is the most dominant effect, followed by travel time, while noise and accident risk differ per scenario.
- Accident risk relatively varies strongly, but is limited in absolute size.
- Noise does not vary much across scenarios: the experienced effects are relatively close together, but the monetary value is also low
- As discussed in the Results chapter, from individual objectives, accident risk and noise yield overall the best results, of the combined objectives, focusing on road users shows better results.

6.1.3. Parallel road

Table 6.4 captures the maxima and the monetisation of the effects resulting from different individual objectives in the case with the parallel road. Here, the size of the experienced air quality is even larger than in the school route case. The accident risk is much larger as well, which is in part caused by the larger demand in this case compared to the school route case. Furthermore, in this case, more freight traffic is present, which has a higher VOT, and therefore causes the monetary value of the experienced travel time to be larger compared to the previous case.

Table 6.4: Monetisation of effects resulting from four different individual objectives, in the parallel road case at a compliance rate of 0.4

Objective	Effect >	Travel time	Air quality	Noise	Accident risk
Travel time	Maximum value	9781.71	119911.90	99364.65	1.46E-04
	€	77.03	4500.29	2.62	322.23
Air quality	Maximum value	9782.16	119911.90	99364.65	1.46E-04
	€	77.03	4500.29	2.62	322.23
Noise	Maximum value	9782.10	119911.89	99364.65	1.46E-04
	€	77.03	4500.29	2.62	322.23
Accident risk	Maximum value	9781.11	119911.90	99364.65	1.46E-04
	€	77.03	4500.29	2.62	322.23

The effects resulting from the different combined objectives and their respective monetisation are shown in Table 6.5. As discussed in Section 5.2.2, the effects resulting from the scenarios where all unguided traffic uses link j are much larger than in the other scenarios, because the unguided traffic alone causes congestion already. This can also be seen in Table 6.5, where the effects for 'Road users 1' and 'Residents 1' are particularly large.

Comparing the effects resulting from the objectives focusing on one individual effect and those combining all effects, it can be seen that air quality yields better results from the individual objectives. The values for travel time, noise and accident risk are the same, except for 'Road users 1' and 'Residents 1'.

Table 6.5: Monetisation of effects resulting from seven different combined objectives, in the parallel road case at a compliance rate of 0.4

Objective	Effect >	Travel time	Air quality	Noise	Accident risk
Road users 0.5	Maximum value	9761.66	158803.06	99364.65	1.46E-04
	€	76.87	5959.88	2.62	322.23
Road users 0.8	Maximum value	9781.97	158803.06	99364.65	1.46E-04
	€	77.03	5959.88	2.62	322.23
Road users 1	Maximum value	31575.05	436028.07	102795.12	9.93E-04
	€	248.75	16364.13	2.71	2184.96
Residents 0.5	Maximum value	9767.14	158803.06	99364.65	1.46E-04
	€	76.92	5959.88	2.62	322.23
Residents 0.8	Maximum value	9782.17	158803.06	99364.65	1.46E-04
	€	77.03	5959.88	2.62	322.23
Residents 1	Maximum value	31575.10	436028.39	102795.12	9.93E-04
	€	248.65	16364.15	2.71	2184.96
No weights	Maximum value	9781.79	158803.06	99364.65	1.46E-04
	€	77.03	5959.88	2.62	322.23

Conclusions parallel road case

The main takeaways of the monetary evaluation of the effects in the case with the parallel road are:

- The effect on air quality is extremely dominant, even stronger than in the school case.
- After air quality, accident risk has the largest value, while this was shared last in the school case, followed by travel time, and finally noise.
- The size of the effects is almost identical within the individual objectives. This is also the case within combined objectives, except for situations where all unguided traffic uses the same route)
- The individual objectives are more beneficial for air quality compared to combined objectives, the rest of the effects are comparable.

6.1.4. Road restricted for heavy traffic

In Table 6.6 the maximum effects and their monetary values are displayed for the case with the road restricted for heavy traffic, at a compliance rate of 0.4. Compared to the previous case, experienced travel time, air quality and accident risk are lower, but experienced noise is larger than both two cases. This can partially be explained by the fact that all the louder medium heavy and heavy vehicles use the route with the most local residents. This also causes the experienced air quality to be worse compared to the case with the school route.

Table 6.6: Monetisation of effects resulting from four different individual objectives, in the road restricted for heavy traffic case at a compliance rate of 0.4

Objective	Effect >	Travel time	Air quality	Noise	Accident risk
Travel time	Maximum value	3296.54	13478.67	118269.21	7.15E-07
	€	16.21	505.85	3.12	1.57
Air quality	Maximum value	3298.92	13482.45	118271.61	7.17E-07
	€	16.22	506.00	3.12	1.58
Noise	Maximum value	2495.59	13015.91	116106.63	3.08E-07
	€	12.27	488.49	3.06	0.68
Accident risk	Maximum value	2177.25	12007.70	116473.40	2.35E-07
	€	10.70	450.65	3.07	0.52

Table 6.7: Monetisation of effects resulting from seven different combined objectives, in the road restricted for heavy traffic case at a compliance rate of 0.4

Objective	Effect	Travel time	Air quality	Noise	Accident risk
Road users 0.5	Maximum value	2740.42	13721.90	115407.92	4.14E-07
	€	13.47	514.98	3.04	0.91
Road users 0.8	Maximum value	2506.89	13050.31	116731.75	3.12E-07
	€	12.33	489.78	3.08	0.69
Road users 1	Maximum value	2353.78	12608.34	116650.45	2.65E-07
	€	11.57	473.19	3.08	0.58
Residents 0.5	Maximum value	2740.42	13721.90	115407.92	4.14E-07
	€	13.47	514.98	3.04	0.91
Residents 0.8	Maximum value	2508.44	13054.16	116082.08	3.13E-07
	€	12.33	489.92	3.06	0.69
Residents 1	Maximum value	2353.78	12608.34	116280.58	2.65E-07
	€	11.57	473.19	3.07	0.58
No weights	Maximum value	2492.97	13009.22	116535.87	3.07E-07
	€	12.26	488.24	3.07	0.68

Table 6.7 shows the experienced effects and their monetary equivalent resulting from the different combined objectives. The values are relatively similar in size to those resulting from the individual objectives.

Conclusions road restricted for heavy traffic

The main takeaways from the evaluation of the case with the road restricted for heavy traffic are the following:

- Here again air quality is most dominant, followed by travel time, noise, and then accident risk.
- Noise does not vary much across scenarios.
- Accident risk as objective overall yields the best effects.
- There is no strong difference between the individual and combined objectives.

6.1.5. Conclusion

Regarding the monetisation, two important disclaimers have to be made. First, as discussed before, the effects of air quality and noise calculated in the model only consider production, and omit reduction of the experienced effect due to for example dispersion. Therefore, the size of the effects calculated in the model is larger than what would actually be experienced. This also causes the size of the effect in euros discussed above to be larger.

Second, even though the used values for the monetisation are the values recommended by authoritative agencies, depending on the situation or the method of research, these values can still vary.

Across all tested scenarios, the cost of air quality is highest. Furthermore, especially for accident risk, the values can vary strongly across the different cases and scenarios. The number of vehicles in the network and the distribution of vehicle types influences the variation of the value of the experienced travel time across scenarios. The evaluation of noise is relatively similar throughout the different cases.

6.2. Trade-offs

In this section, the trade-offs between the different effects are discussed per case. In every graph, two effects are compared. The effects are the result from the four different objectives travel time (TT), air quality (AQ), noise, and accident risk (AR). The different data points represent the 120 time steps simulated. Some data points are labelled with the corresponding total split fraction advice in that time step. As an example, the results corresponding with a compliance rate of 0.4 are used.

6.2.1. School route

When comparing two different effects with each other, the data points in the lower left corner represent the best experienced effects for both. However, the best points that can be noticed correspond with the first few time-steps, when the network is not completely filled yet. A further overall remark that must be made, is that the overall increase in effects, especially for the objectives travel time and air quality, is not directly the result from a different split fraction, but more from the congestion build-up over time.

When comparing travel time with air quality, see Figure 6.1, it can be seen that an increase in travel time corresponds with an increase in negative effects on air quality as well. However, the steepness of this increase decreases after some time, so where first pollution increased faster than travel time, now this is the other way around. The small waves in the blue data points of the travel time objective result from the changes in advised split fraction and can be found in Figure 5.3a as well.

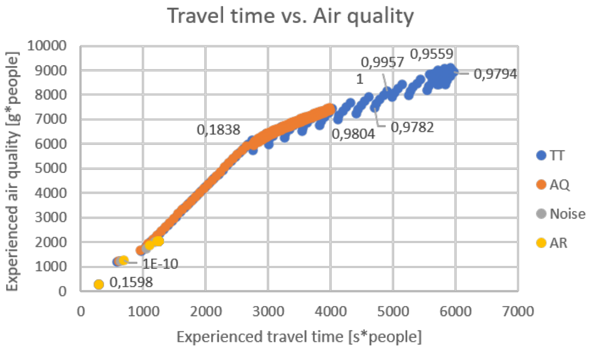
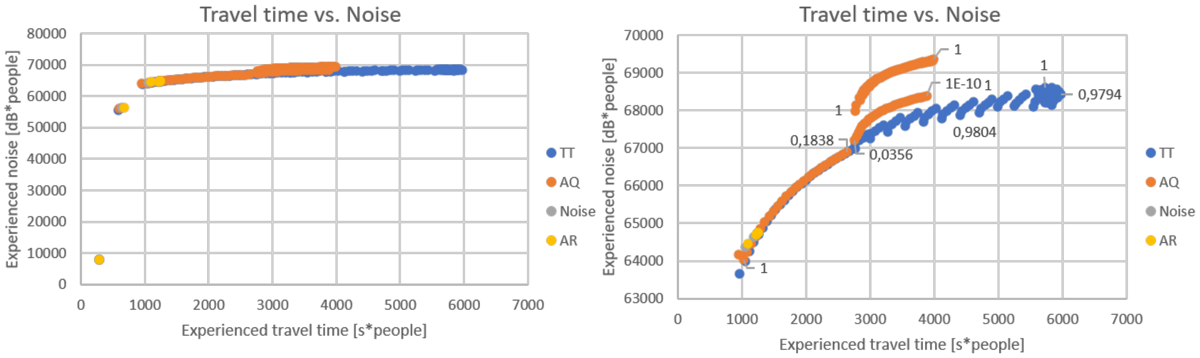


Figure 6.1: Trade-off between travel time and air quality for a compliance rate of 0.4 in the school route case

In the comparison between travel time and noise in Figure 6.2, the first few time steps, when the network is filled, show a very strong increase in experienced noise. After the third time period, the increase in in noise seems minor compared to the increase in experienced air quality. When zooming in on the section of the data points after the third time step, as is done in Figure 6.2b, more information can be distinguished. The increase in travel time corresponds with an increasingly smaller increment of noise. Of the two orange curves in the air quality graph, the lower one with better results on noise are all data points favouring link k, while the upper curve favours link j.



(a) Normal

(b) Zoomed in

Figure 6.2: Trade-off between travel time and noise for a compliance rate of 0.4 in the school route case

Comparing travel time with accident risk, see Figure 6.3, shows that these effects increase in a somewhat similar fashion, with at first a stronger increase in travel time, and then a relatively stronger increase in accident risk.

When comparing air quality with noise in Figure 6.4, a similar pattern as between travel time and noise can be distinguished. The first few time steps show a very large increase in the experienced noise, while the increase in experienced negative effects on air quality remain relatively small. Zooming in, in Figure 6.4b, the same two orange curves of air quality as objective can be observed, with the lower curve favouring link k, and the upper one link j.

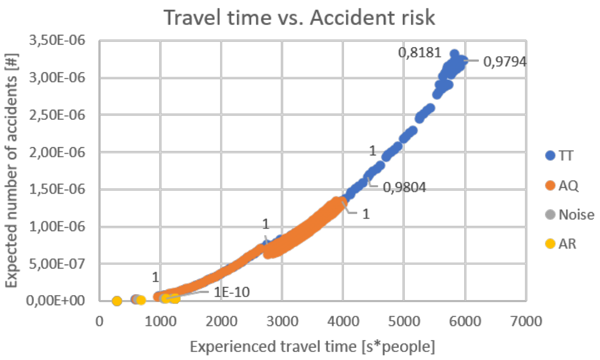
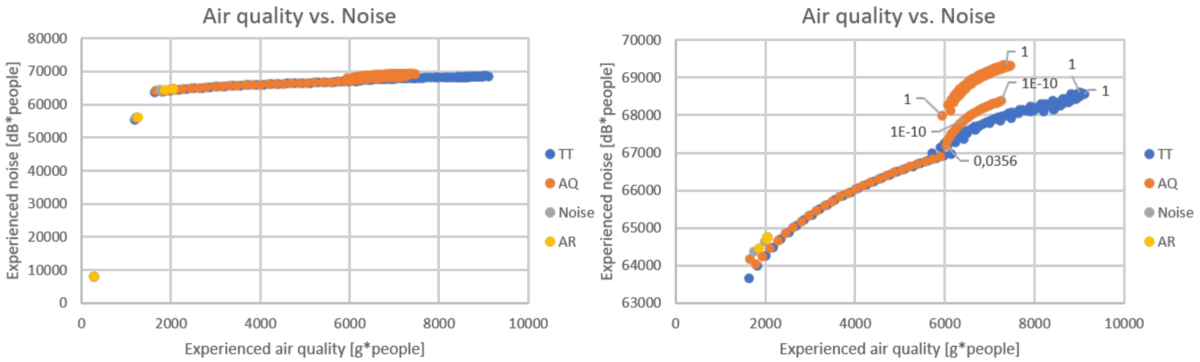


Figure 6.3: Trade-off between travel time and accident risk for a compliance rate of 0.4 in the school route case



(a) Normal

(b) Zoomed in

Figure 6.4: Trade-off between air quality and noise for a compliance rate of 0.4 in the school route case

If air quality and accident risk are compared in Figure 6.5, first, a large increase in experienced negative effects on air quality shows a small increase in accident risk, while after about the first 30 time periods, this relationship is reversed.

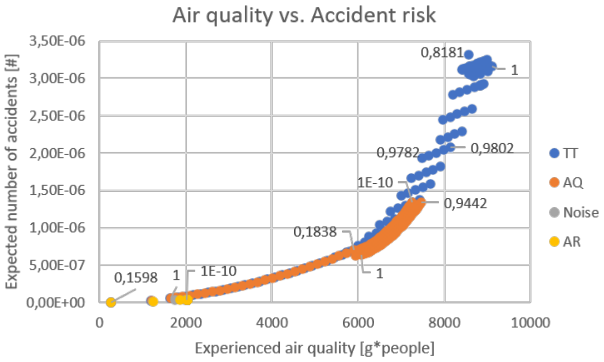
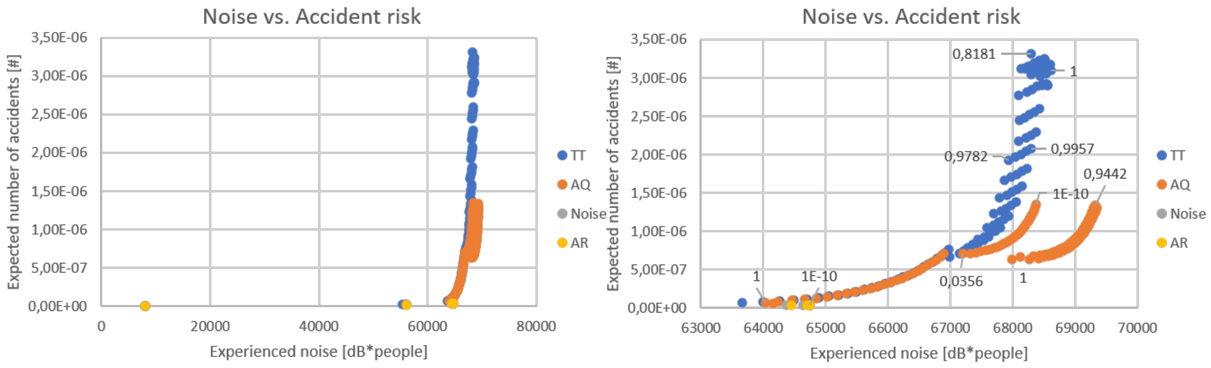


Figure 6.5: Trade-off between air quality and accident risk for a compliance rate of 0.4 in the school route case

Finally, in the comparison between noise and accident risk in Figure 6.6, for the first few time periods, a large increase in experienced noise corresponds with a relatively small increase in accident risk, while after that, with a large increase in accident risk, experienced noise shows almost no increase. When zooming in again in Figure 6.6b, the increment in accident risk becomes stronger after about 30 time steps.



(a) Normal

(b) Zoomed in

Figure 6.6: Trade-off between noise and accident risk for a compliance rate of 0.4 in the school route case

Besides the trade-offs existing between effects for different split fraction advice discussed above, there can also be trade-offs observed for different levels of compliance, as was shown in Table 5.1 in the Results chapter. When optimising for travel time, a higher compliance was beneficial for noise, while full compliance was worse for the experienced travel time and air quality. When minimising the accident risk, for the compliance rates 1, 0.7, and 0.4, noise and accident risk benefit from a higher compliance, while the experienced travel time and air quality are better at a lower compliance. This means that if the compliance can be influenced, a trade-off has to be made what effect is preferred to be improved.

Conclusions school route case

The main observations from the trade-off analysis in the school route case are:

- In this case, there are no dilemmas as a result of the split fraction advice: an increase for one effect corresponds with an increase for other effects as well.
- Most of the increase in the effects is the result of congestion build-up, not directly the split fraction advice.
- There exists a trade-off as a result of the compliance rate: a higher compliance when minimising travel time is beneficial for noise, but this yields the worst results for travel time and air quality.
- Noise and accident risk benefit from a higher compliance when minimising accident risk, while a lower compliance is more beneficial for travel time and air quality.

6.2.2. Parallel road

When comparing travel time with air quality, as shown in Figure 6.7, at first, the effects increase at a similar rate. However, after 23 time steps, the experienced travel time decreases, while the experienced negative effects on air quality increase, revealing a dilemma. In absolute numbers, the increase in experienced air quality effects is however very small.

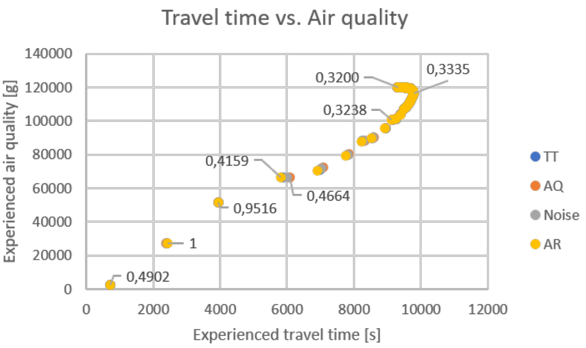
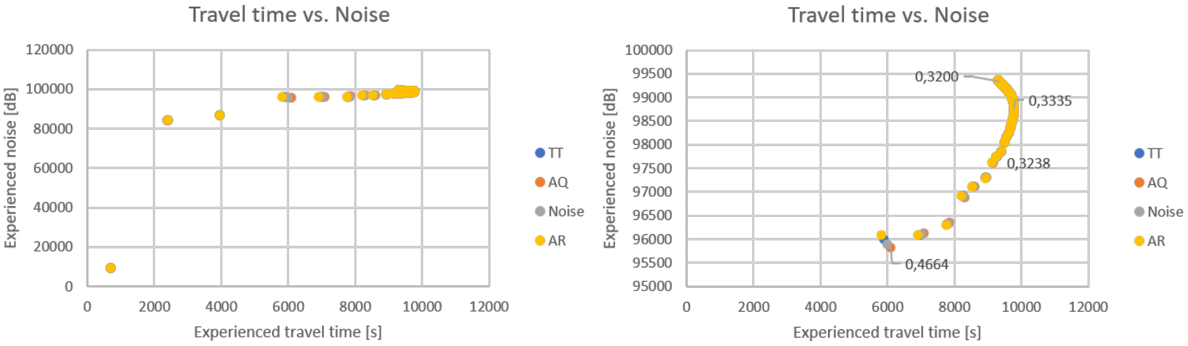


Figure 6.7: Trade-off between travel time and air quality for a compliance rate of 0.4 in the parallel road case

Comparing travel time with noise in Figure 6.8a shows, similar to the case with the school route, at first a large increase in noise, compared to a small change in experienced travel time, with the opposite true for the results after the first three time steps. Zooming in on the results in Figure 6.8b, a similar dilemma as between travel time and air quality can be observed. Noise keeps increasing over time, while the experienced travel time reduces ever so slightly after the first 23 time periods.



(a) Normal

(b) Zoomed in

Figure 6.8: Trade-off between travel time and noise for a compliance rate of 0.4 in the parallel road case

The graph comparing travel time and accident risk, Figure 6.9, shows a similar pattern to that of travel time compared with air quality. After 23 time steps, when the experienced travel time decreases, the accident risk keeps growing, albeit at a very slow rate.

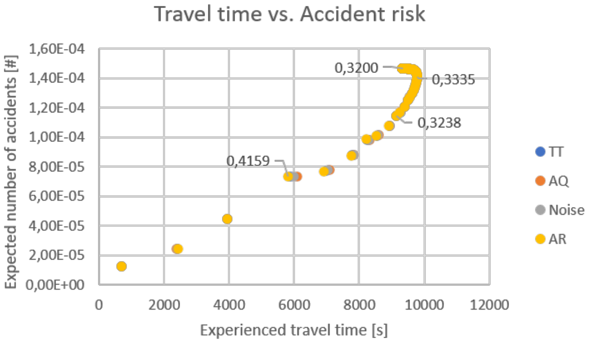
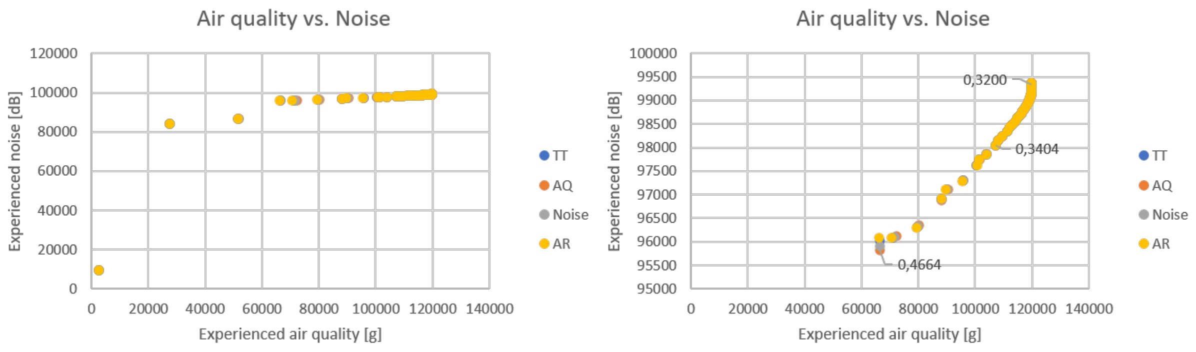


Figure 6.9: Trade-off between travel time and accident risk for a compliance rate of 0.4 in the parallel road case

If air quality and noise are compared in Figure 6.10, no trade-off is present. The experienced noise increases strongly in the first few time steps, with limited increase in negative effects on air quality, while after the full network is filled, with increased experienced air quality comes a relatively small incline in experienced noise.



(a) Normal

(b) Zoomed in

Figure 6.10: Trade-off between air quality and noise for a compliance rate of 0.4 in the parallel road case

When comparing air quality with accident risk in Figure 6.11, these effects increase at a similar rate, with the same incline over time.

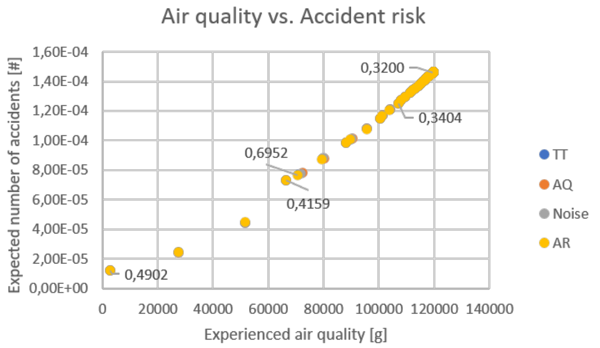
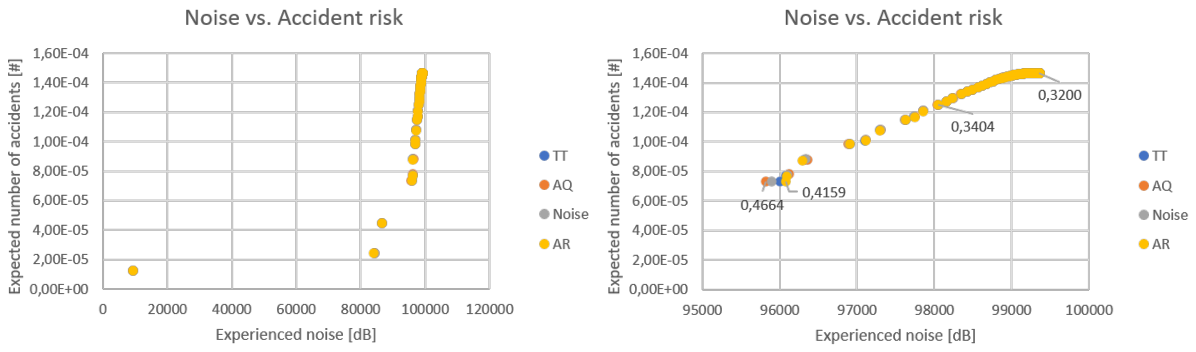


Figure 6.11: Trade-off between air quality and accident risk for a compliance rate of 0.4 in the parallel road case

Finally, if noise and accident risk are compared in Figure 6.12, the first few time periods show a large increase in experienced noise, while the incline of the accident risk is limited. As is the case for all effects compared to noise, after these initial time steps where the network is filled, a large increase in the accident risk corresponds with a relatively small increase in experienced noise.



(a) Normal

(b) Zoomed in

Figure 6.12: Trade-off between noise and accident risk for a compliance rate of 0.4 in the parallel road case

Considering the trade-offs that occur between effects resulting from different compliance rates in Table 5.2, a few dilemmas can be observed. When optimising air quality, the worst results for travel time, air quality, and accident risk are occurring at a compliance rate of 1, while this corresponds with the best results for noise. The same is true when minimising noise, although less extreme than for air quality as objective.

Conclusions parallel road case
The takeaways from the trade-offs in the case with the parallel road are:

- In general, an increase in one effect coincides with an increase in other effects.
- A dilemma between travel time and the other three effects, air quality, noise, and accident risk exists. However, their increase in effects is very small.
- The effects on air quality and accident risk are nicely aligned.
- A dilemma resulting from compliance rates occurs when optimising air quality: at full compliance, the best results for noise are achieved, while this corresponds with the worst results for travel time, air quality, and accident risk. Although less extreme, the same occurs when optimising noise.

6.2.3. Restricted for heavy traffic

When comparing travel time and air quality in Figure 6.13, the first few time steps show large increases in both the effects, with the incline on air quality being slightly stronger. After the first four time steps, for the objectives travel time and air quality, the increase on the travel time axis becomes relatively larger than that on the air quality axis.

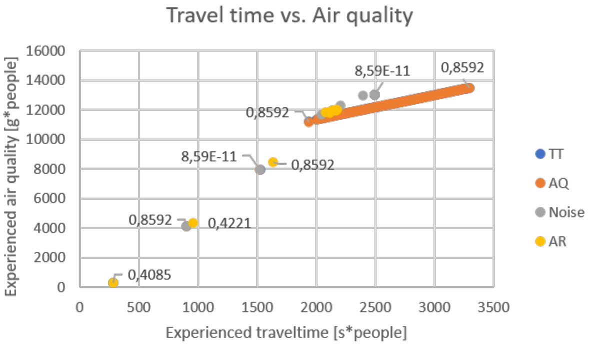
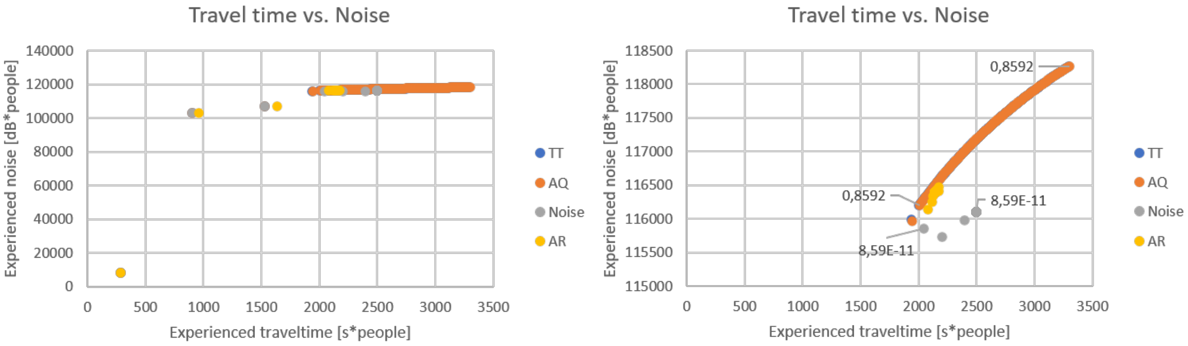


Figure 6.13: Trade-off between travel time and air quality for a compliance rate of 0.4 in the road restricted for heavy traffic case

In the comparison between travel time and noise in Figure 6.14, as discussed in the other two cases, the first few time periods show a strong increase in experienced noise, with relatively small increase in experienced travel time. After these initial time steps, an increase in travel time corresponds with a limited incline in experienced noise.



(a) Normal (b) Zoomed in

Figure 6.14: Trade-off between travel time and noise for a compliance rate of 0.4 in the road restricted for heavy traffic case

When comparing travel time and accident risk in Figure 6.15, they are relatively aligned, but for the first few time steps, a larger increase in experienced travel time corresponds with a relatively smaller increase in accident risk. After the first four time periods, this relationship reverses.

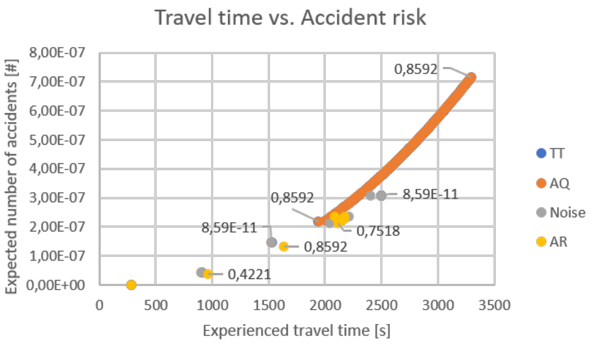
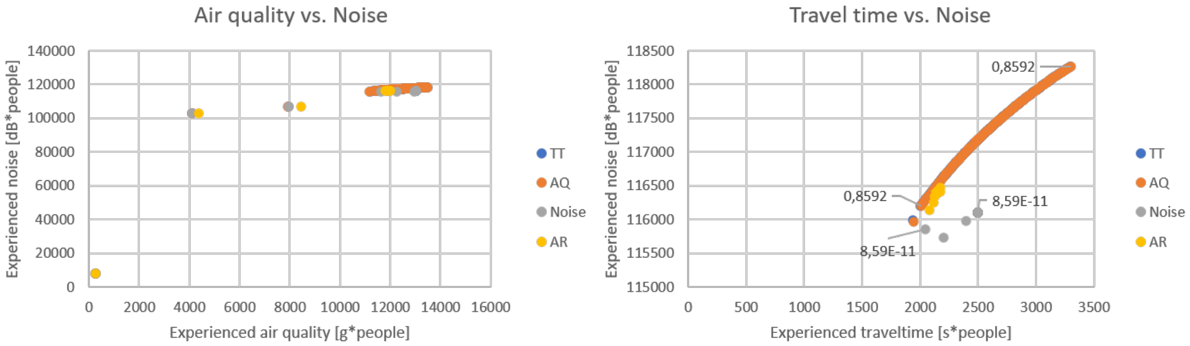


Figure 6.15: Trade-off between travel time and accident risk for a compliance rate of 0.4 in the road restricted for heavy traffic case

In the comparison between air quality and noise in Figure 6.16 a pattern similar to that of travel time compared to noise can be observed: a strong increase in experienced noise corresponds with a relatively small change in experienced air quality, while this relationship reverses after the first time steps.



(a) Normal

(b) Zoomed in

Figure 6.16: Trade-off between air quality and noise for a compliance rate of 0.4 in the road restricted for heavy traffic case

If the experienced air quality and accident risk are compared, as shown in Figure 6.17, a strong rise in experienced negative effects on air quality compared to a limited increase in accident risk can be observed. After the first four time steps, the reverse of this ratio is true: an increment in experienced air quality corresponds with a stronger incline in accident risk.

Finally, when comparing the effects on noise and accident risk in Figure 6.18, at first, a large increase in experienced noise coincides with a limited incline in accident risk. Then, a relatively very small change in experienced noise corresponds with a strong increase in accident risk.

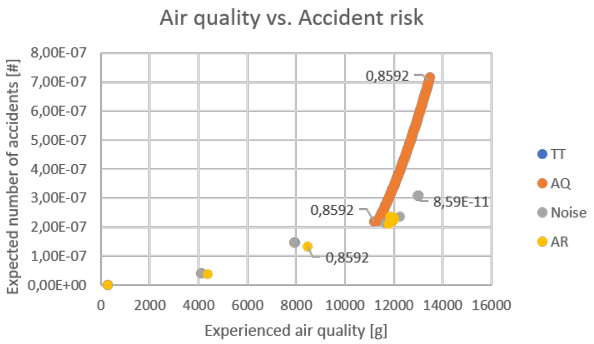
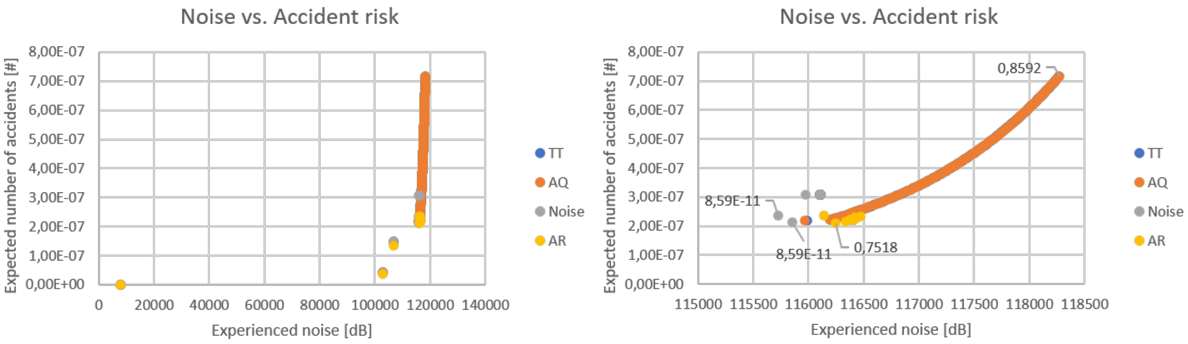


Figure 6.17: Trade-off between air quality and accident risk for a compliance rate of 0.4 in the road restricted for heavy traffic case



(a) Normal

(b) Zoomed in

Figure 6.18: Trade-off between noise and accident risk for a compliance rate of 0.4 in the road restricted for heavy traffic case

In contrast to the previous two cases, Table 5.3 reveals no trade-offs between effects as a result of different compliance rates.

Conclusions road restricted for heavy traffic case

Regarding the trade-offs in the case where one road is restricted for heavy traffic, only the following observations can be made:

- No dilemmas resulting from the split fraction advice exist.
- No dilemmas as a result from compliance rate exist.

6.2.4. Conclusion

Due to congestion build-up, the same split fraction advice can have different effects over time. An overall observation that can further be made, is that in most of the scenarios assessed, there are no situations where a decrease of one effect corresponds with an increase in another effect. This indicates that a good division of traffic can benefit all effects. The ratio between the effects can however change over the simulated time period.

Only in the case with the parallel route, when comparing travel time with the other effects, after 23 time periods, a decrease of travel time, is associated with an increase of the other effects.

Across the cases, travel time and accident risk seem to align the best. In the case with the parallel road, air quality and accident risk show a steady incline over time as well. In all cases, and in comparison with all other effects, noise shows a strong increase in the first few time steps, while afterwards, limited change is observed.

In some situations, dilemmas resulting from compliance rates exist. This shows that if it is possible to influence compliance, it is necessary to consider which effects are preferred to be improved.

6.3. Comparison of the three cases

When comparing the three cases, the case with the parallel road has relatively more heavy traffic, which is more polluting, causing the experienced air quality to be larger than the other two cases. Furthermore, freight traffic has a higher VOT, explaining the higher monetary value of travel time in this case. The fact that accident risk is much larger in this case, is influenced by the link length and larger traffic flow in comparison to the two other cases.

In the case with one road restricted for heavy traffic, air quality and noise are larger than in the case with school route, even though both are inside the built-up area. This can be explained because of the amount of local residents that is larger in the case with the restricted road.

Regarding the trade-offs, the case with the parallel road is the only one with an actual dilemma, albeit for very small values. This seems to be caused by a strong initial increase in travel time, which decreases quickly afterwards, as the resulting delay on link i reduces the inflow to the congested link j.

7

Discussion and Recommendations

This research has several limitations, which are discussed below. During this study, several interesting directions for research were found, these are considered in this chapter as well.

7.1. Discussion

The limitations of this research can be divided into a few categories and are discussed below.

7.1.1. Network assumptions

One limitation of this study is that the basic network structure that was adapted in the three different cases is very simple. It only considers traffic that enters the first link and travels further through the two alternative routes. There are no other inflow or outflow possibilities, that would be present in a real-life network and could impact the effects on liveability. Furthermore, the effects produced were assigned to only one link. However, for example noise or pollution could spread and thus affect residents on another link as well. Another aspect not considered is the distance from the road to the houses, which could affect the air quality and noise experienced.

7.1.2. Model assumptions

Due to the considered time steps, multiples of 30 km/h had to be used. This meant that instead of 50 km/h, a speed of 60 km/h had to be used, bringing about different effects on for example the accident risk on that road section.

For the unguided traffic, the split fraction was determined in advance of the simulation. This meant that the division of the sending flow of unguided traffic remained the same of the assessed time period, irrespective of occurring congestion. Even though this might resemble some users unwillingness to switch from their preferred route, it can be expected that congestion also affects the decisions of unguided road users.

In the calculation of the effects, for air quality and noise only the produced effects are considered. This causes the effects to be larger than what would actually be experienced. This meant that the legal limits for these effects were not applicable. Furthermore, the monetary evaluation and comparison of all effects was less realistic. Additionally, as noise is calculated logarithmically in dB, the comparison with other effects is complicated. Regarding safety, only road traffic is considered. The safety of pedestrians, cyclists, or local residents is very important as well. However, currently, there are two effects influenced by the number of vehicles on the road, namely travel time and accident risk, and two influenced by the surroundings, namely air quality and noise. Considering the safety of local residents as well changes this ratio and might affect the suggested route, so precautions are required. Additionally, the used parameters, although being the most recent publicly available at the time of this research, were relatively old. Furthermore, no distinction was made between the accident risk of different vehicle classes.

7.1.3. Optimisation

A very important limitation in the optimisation model is caused by the fact that only the upcoming time step is considered when determining the split fraction advice to be given. As some link lengths are longer than what can be travelled in one time step, some effects show delayed impact of the given route advice, while others even become worse before showing improvement. If no improvement is shown in the next time step, the model continues giving the same advice, which can even have negative impact on the effect that is aimed to be minimised. Considering the effects of multiple upcoming time steps can prevent this issue.

A distinction was made between light, medium heavy, and heavy traffic. The route advice of the latter two however differed strongly, which can be explained by the absolute limited number of vehicles in these categories, causing their respective impacts on the effects to be limited as well. Therefore, in the scenarios tested in this research, no conclusions could be made on the optimal distribution per vehicle type.

7.2. Recommendations for future research

Based on the limitations described above, several improvements of the model for future research could be distinguished.

7.2.1. Network assumptions

The first category of possible improvements considers the network. Future research could assess a larger network where additional inflow and outflow traffic uses the network as well. This is another category of unguided traffic, that does not use the complete assessed network, but is of influence on the traffic flow on a section of it. It is also relevant to take the distance between the road and the houses into account.

7.2.2. Model assumptions

Instead of discrete time steps of 30 seconds as was developed in Excel, a continuous model, for example built in Python, could improve the accuracy and prevent the issues caused by the delay in effects. This could allow to consider all speed limits, instead of only multiples of 30 km/h.

For future research, it could be more realistic to allow the unguided split fraction to vary over time, to incorporate variations due to congestion.

Regarding the calculation of the effects, the relationships between the traffic conditions and the effects could be improved. For air quality and noise, this would mean considering the reduction factors of these effects. The safety of pedestrians and cyclists could be incorporated as well. A distinction in accident risk could also be made between the different vehicle classes. Additionally, it might be useful to consider the spread of the effects over the network or an assessed area, instead of attaching it to one link only.

7.2.3. Optimisation

The most important improvement of the model for future research is to include more time steps in the evaluation of the optimal route advice. This will most likely improve the advice and thus the effects, and give a more accurate insight in the effects of traffic advice over time.

Additionally, prediction of the traffic conditions and effects could improve the given advice, and consequently increase the compliance as well.

7.2.4. Additional research directions

New directions or additions for research can be distinguished as well. Future research could for example also consider the impact of electric vehicles. As they produce much less local emissions and at low speeds their noise is limited as well, this could invoke different distribution advice. It could also be relevant to distinguish multiple groups of road users, each with different evaluations of the effects. Furthermore, it could be beneficial to gain more insight in the variations of factors influencing compliance between road users. This way, the route guidance could be more personalised, which yields a higher compliance. Other influences on compliance, such as the traveller's familiarity with the network, could be incorporated as well. Additionally, it might be interesting to further research what methods are useful in convincing travellers to use the longer route, for example creating social pressure by informing what choices other people made, stating the impact of a decision on the liveability, or rewarding points for certain routes.

Finally, it could be useful to test more cases and scenarios, to be able to eventually quantify the relationships between the different network characteristics, traffic conditions, and circumstances, and the optimal split fraction and resulting liveability effects. After analysing the optimisation model in various situations, a real-life case study could be insightful.

8

Conclusions

Although research on the possibilities of traffic management on reducing emissions is growing, studies focusing on reducing noise and accident risk are limited. A study combining these multiple negative externalities of traffic exists, but Variable Message Signs were studied as a means to communicate advice, only allowing to give the same route advice to all road users. At the time of this research, no studies considered the impact of individual traffic management on not only the travel time, but also the liveability effects air quality, noise, and accident risk. The aim of this research was therefore to obtain an insight in the factors impacting liveability, caused by road traffic, and how individual traffic management could reduce these negative externalities. The main research question was: *How can negative effects on liveability be improved using individual traffic management, considering users willingness to comply with the given advice?* This question comprises two parts: the impact of individual traffic management on liveability, and compliance of road users.

8.1. Compliance

By improving compliance of road users with the given advice, the impact of individual traffic management can be increased. An important factor for increasing compliance is the credibility of the given advice. This is improved by a high quality of the advice, comprising for example correct travel time estimations. Furthermore, exclusion of shortcuts is quickly noticed by road users, reducing their likelihood to follow advice. This is important to take into account when giving the route advice. Credibility of the advice can also be strengthened by confirmation, for example by other travellers using the same route. A high familiarity with the network brings about a lower compliance rate. Although this is not something that can be influenced when giving advice, it is relevant to know that some situations, for example commute where road users are highly familiar with the network, have less potential for improvement.

As advice aimed at alleviating congestion is complied with more than advice with environmental or safety objectives, this can be considered in the communication of the route guidance. Because several personal factors such as age, gender, and driving experience influence both the compliance and the willingness to trade-off effects, personalised route advice that takes these factors into account can yield a greater improvement in the liveability.

8.2. Individual traffic management

To analyse how different factors are of influence on the liveability an optimisation model was developed comprising traffic propagation, individual route guidance and effect estimation. This model was then optimised for scenarios varying in compliance rate, objective, and distribution of unguided traffic, across three different cases. These cases were variations of a simple network with two alternative routes. In the first case one of the routes passes a school. The second case considers a motorway with a parallel road. In the third case one of the two routes is restricted for heavy traffic. The details of these cases have been discussed in Chapter 4.

8.2.1. Results

In the school route case the differences between the characteristics of the two routes, such as link length and speed, are relatively large, causing the distribution of unguided traffic to strongly favour the fastest route. Across the tested scenarios in this case, the given advice is quite extreme: either one route or the other is suggested to guided traffic. If the objective is to minimise the experienced travel time, logically, the fastest route is advised. This route is suggested when aiming to optimise the experienced air quality as well. This reveals that in the set-up of this case the link length is of greater influence on the experienced air quality then the number of local residents. However, as this advised route is also the road that most unguided traffic uses, this causes congestion over time, and effects can even be worse than if no advice was given. The preferred route to minimise the experienced noise varies with compliance, but if the advice sends most travellers via the route with less local residents, better results are obtained for all four effects. In the school route case, the best results for all effects are achieved if minimising accident risk is the objective. For that objective, guided traffic is sent via the longest route, but this route has lower accident risk due to the road characteristics, revealing the road type to be a dominant factor for this objective. A sensitivity analysis reveals that the 'optimal' advice and resulting effects strongly depend on the weight attached to local residents. If the importance attached to the schoolchildren is doubled, the advice when optimising for air quality and noise sends guided traffic via the route with less local residents, which causes the results of all effects to improve. Besides the individual objectives experienced travel time, air quality, noise, and accident risk, these effects were also combined into one normalised objective, and tested in scenarios with either no weights, more weight attached to the effects affecting road users, or more weight attached to those affecting local residents. In the school route case, the best results for all effects were achieved if the objective focused on road users. This could be explained as this comprises accident risk, which yielded the best results of the individual objectives.

The differences between the characteristics of the two alternative routes in the case with the parallel road are smaller. This causes the distribution of unguided traffic to be more even compared to the school route case, and could also be an explanation of the less extreme advice: the only situations where all guided traffic is sent via one route is at the low compliance rate of 0.1. Due to the small difference in travel time between the two routes, if the experienced travel time is minimised, the advice aims ate a more balanced distribution of traffic. If air quality is optimised, the route with less local residents is preferred, but if too much traffic is sent via this route, congestion occurs. This reveals that, compared to the other cases, the situation seems more 'sensitive' to slightly too strong advice, which might be explained by the relatively small differences in the characteristics of the two routes. Where the road type was most influential for the preferred route to reduce the accident risk in the school case, in the case with the parallel road the traffic flow seems most dominant, inducing a more balanced division of traffic. Travel time and accident risk both yield this more balanced advice, and bring about the best results for all effects at full compliance. For all the lower compliance rates, there exist very small differences between the experienced effects resulting from the different individual objectives. The same is true for the combined objectives, there is no strong difference in experienced effects between the objectives focusing on road users or local residents. This indicates that in this case where the two alternatives are more similar, the context is more important than the objective used in the optimisation.

In the base scenario of the case where one road is restricted for heavy traffic no congestion occurs. Compared to this base case, almost no scenario shows improvement in effects, suggesting that congestion is a good indicator of the potential improvement in the liveability. In this case, the fastest route is also the route with less local residents. This is the route that is advised both if travel time and air quality are the objectives. When noise is minimised, the route that is suggested is the one that already experiences noise from the heavy traffic that can only use that road. This could be explained by the fact that due to the logarithmic counting of dB, the first vehicle on a link has a much greater marginal impact than any additional vehicle after that. If the objective is to minimise the accident risk, the advice aims at a more balanced distribution of traffic, which yields the least worse results over all tested compliance rates. This case shows a clear distinction between the influences of the effects: experienced travel time and accident risk strongly depend on the number of vehicles on the road, while air quality and noise are greatly influenced by the vehicle type.

Concluding, in determining the split fraction advice, various factors revealed to be of influence. The fastest route was generally suggested to minimise experienced travel time, but yielded congestion if the advice too strongly favoured one route and many travellers followed the advice. The optimisation of air quality either favoured the fastest route, or was impacted by the speed and vehicle type and thus resulting emissions, or the number of and weight attached to local residents. The minimisation of noise is even more complex, as this is calculated logarithmically, causing the marginal increase caused by a single additional vehicle to be smaller than that of the first vehicle on a link. The optimal split fraction advice to minimise the accident risk is dependent on the link length, as well as the road type and the traffic flow. Throughout these complex split fraction determinations, the best results for all effects were caused by advice aiming at a more even distribution of traffic over the two alternative routes.

When combining the four liveability effects normalised in one objective, depending on the case characteristics, the weights attached to the effects can have different impact on the optimal advice. In the case with the school route, attaching a higher value to the effects impacting the road users, namely travel time and accident risk, yielded better results for all effects, in comparison to situations with the same distribution of unguided traffic focusing on residents. In both the cases with the parallel road and the road restricted for heavy traffic however, the weights did not have impact on the effects achievable. In those cases, the distribution of unguided traffic was of stronger influence.

8.2.2. Evaluation

The experienced effects were monetised to compare their impact. The monetary values varied strongly, both between effects and across the tested cases and scenarios. Across the tested cases and scenarios, the cost of effects on air quality was largest. This can in part be explained because for air quality and noise only the produced effects were considered, and reduction factors caused for example by dispersion were omitted, causing the effect discussed to be larger than what would actually be experienced. The size of the value of the experienced air quality was especially large in the case with the parallel road. This is partially caused by the larger share of medium heavy and heavy traffic in this case, which are more polluting. The value of noise varied little, both within and between cases. Relatively, the monetary value of accident risk varied strongest, ranging to a factor 90 within the same case. These strong variations in costs, both within and between effects, could cause more value to be attached to a certain effect if they all would be combined into one objective with their monetary value. It is therefore critical to either consider the importance of the different effects and the corresponding weights in advance, or use a different method, such as the normalisation used in this research, when defining the objective to find the optimal split fraction advice to reduce negative impact on liveability.

As was the case with the split fraction advice and the resulting effects, the trade-offs that could be observed between the effect differed depending on the case and scenario characteristics. In general, the effects worked in the same direction, showing the potential for route advice benefiting all effects. However, variations between effects and cases could be observed. Noise always shows an initial strong increase, followed by very limited change in comparison to the other effects. For the other effects, the incline sometimes varied with increasing effects. The only dilemma as a result of the split fraction advice that could be observed in the tested scenarios was in the case with the parallel road between travel time on the one hand, and the other effects on the other hand. Here, after some time, a decrease of experienced travel time corresponded with an increase of the effect compared. However, this increase was relatively small. Another type of dilemma that was observed is caused by differences in compliance rates. In the case with the school route, when minimising the experienced travel time, a higher compliance is beneficial for noise, but this corresponds with worse results for travel time and air quality. Furthermore, if minimising accident risk is the objective, noise and accident risk benefit from a higher compliance, while a lower compliance is more beneficial for travel time and air quality. In the case with the parallel road, if optimising air quality is the objective, a dilemma as a result from compliance occurs as well. If all travellers comply with the given advice, this yields the worst results for the experienced travel time, air quality, and accident risk, while this coincides with the best results for noise. The same is the case when minimising noise, although the difference in the effects is smaller.

8.2.3. Limitations

The constructed optimisation model only considers the first upcoming time step to evaluate the optimal split fraction advice. As some links in the considered cases take longer to travel than one time step, there is a delay in the resulting liveability effects. This can cause the controller to give advice that has an adverse impact on the experienced effects. An important conclusion that can be drawn from this, is that the assessment of only one period ahead is not sufficient in determining the optimal split fraction advice. Future research should therefore consider the effects over multiple time steps ahead.

8.3. Recommendations for practice

A high quality and credibility of the given advice causes higher compliance. It is therefore beneficial to ensure good travel time estimation, and to not give too large detours as advice. Personalised advice yields better compliance as well. Taking personal characteristics into account, naturally considering privacy, could therefore also be advantageous. Furthermore, as familiarity with the network decreases the compliance, situations where travellers are well acquainted with the road section might have less potential for improvement by individual traffic management. To get road users to take a longer route, research suggests it could be beneficial to aim information at reducing congestion instead of an environmental or safety objective, and to use nudging, social reinforcement or education. Additionally, older drivers are more willing to comply with advice than young road users and experienced drivers. This could both be considered in situations were a certain age group is more strongly represented in the population of road users and in the personalisation of route advice.

It was shown that the weight attached to local residents can strongly influence the advice given. Additionally, the costs of the different effects varied extremely. From a policy perspective, it is therefore important to consider what effects are deemed most important, and consequently what values should be attached to them. This causes the ’optimal’ advice to be aligned with this evaluation.

When only considering the size of the effects, advice aiming at a more balanced distribution of traffic over the two alternative routes, which in the tested cases usually corresponded with the objective to minimise the accident risk, yielded good results for all liveability effects. This could therefore be seen as a good starting point for determining social routing advice.

The case where one road was restricted for heavy traffic suggested that congestion might be a good indicator of the potential improvement that can be achieved with individual traffic management.

Finally, individual traffic management has potential in reducing the negative impact of traffic on liveability, as was shown in this research. However, this study has been simplified on some aspects to fit the scope of the research. To fully fulfil this potential, experts on the various aspects of this approach should join forces. Good navigation apps already exist, detailed models calculating resulting emissions and noise are in use, and traffic safety experts consider various factors of influence on accident risk.

All in all, this research gave an insight in the different factors influencing the liveability effects travel time, air quality, noise, and accident risk. It contributed to closing the research gap on the impact of individual traffic management on liveability, considering multiple effects at once. It showed that various aspects, both fixed, such as the road characteristics or the number of local residents, and variable, such as number of vehicles on the road, the compliance behaviour or the weight attached to the different effects, impact the optimal route advice and thus the liveability experienced. Even though the suggested split fraction did not always yield the best results, this research showed part of the complex structure of buttons that can be pressed to reduce negative externalities on liveability caused by road traffic.

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A

Paper

Impact of individual traffic management on liveability

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***Abstract*— Limited quantitative research exists on the effects of individual traffic management on four liveability aspects: travel time, air quality, noise, and accident risk. The aim of this research is to get an insight in how these effects on liveability can be improved using ITM, given road users willingness to comply with given advice. Literature research is used to provide an insight in factors influencing compliance. Furthermore, an optimisation model in Excel comprising LTM, individual route guidance, and effect estimation is built. The model is tested across three cases and multiple scenarios varying in compliance rate, objective, and distribution of unguided traffic. The achievability of effects is complex: depending on network characteristics and compliance assumed different impacts can be found. In general, the best results are obtained with advice aiming at a more balanced distribution of traffic. However, the weight attached to local residents is of strong influence on the optimal distribution. An important limitation of this research is that the optimisation model only considers effects in upcoming time step, causing extreme advice with negative effects on liveability. For future research it is therefore important to consider the effects in multiple time steps ahead.**

Keywords: Individual traffic management, Social routing, Compliance, Liveability

I. INTRODUCTION

Marchetti's constant, or in Dutch the *'BREVER-wet'*, describes that over time, people keep spending the same amount of their time on transport. However, people travelling from A to B causes several negative externalities, such as congestion, pollution, noise, and accidents. These externalities can have consequences for the liveability of the environments of roads, causing nuisance, reduced safety, or mental and physical health issues [1]–[3]. Furthermore, congestion can be seen as a loss of money [4].

One of the possible methods to reduce these externalities is individual traffic management, where road users are given individual route guidance, that may differ from vehicle to to vehicle. Research that studies the impact of aiming at a System Optimum instead of a User Equilibrium on reducing congestion is quite extensive [5]–[8]. Furthermore, studies on the possibilities of individual traffic management regarding pollution are increasing [9]–[13]. However, the amount of research considering the reduction of noise or accident risk by individual route guidance is small [14, 15], and research combining travel time, air quality, noise, and accident risk in a quantitative way are even more limited [16, 17]. [18] considers the impact of Dynamic Traffic Management (DTM) on multiple externalities of traffic such as emissions, noise, and safety. However, they consider VMS as a means to communicating the advice, which can only give the same message to all drivers currently on that section of the road. Individual traffic management allows to advise road users at any point or time, and differ this advice from vehicle to vehicle. This brings about the opportunity to give more detailed and accurate advice. However, currently, no research has considered the effects of individual traffic management on travel time as well as air quality, noise and accident risk yet. Therefore, the aim of this research is to get an insight in the effects on liveability that could be obtained if individual traffic management is used. This is captured in the main research question: *How can negative effects on liveability be improved using individual traffic management, considering users willingness to comply with the given advice?* This main research question consists of two parts: the impact of individual traffic management on liveability, and the compliance of road users with advice.

Two important terms in the research question are liveability and individual traffic management. The first, liveability, comprises experienced travel time, air quality, noise, and accident risk. Individual traffic management in this research considers in-car route advice, that can differ among travellers with the same origin, destination, and departure time.

II. METHODOLOGY

Below, the approach for answering the research question is described.

A. Literature research

First, the relationships between traffic conditions and externalities have to be determined. As some studies and national guidelines on this already exist and conducting real-life experiments would be out of scope for this research, this is done using literature research. Another aspect that can be examined using existing literature is the influences on compliance of road users. As the existing literature on this is fairly large, this serves more as context information.

B. Model building

When the relationships between traffic conditions and externalities are known, minimising these externalities serve as multiple objectives. To do this, an optimisation model has to be developed. First, this is described in a mathematical model, using the relationships between traffic conditions and externalities found earlier. A fictional network is described in terms of link lengths, speed, capacity, demand, and vehicle type distribution, as well as the number of people in the surroundings that are affected, to be able to change and test these variables. Limits on additional travel time and the externalities on air quality, noise, and accident risk will serve as constraints. Combined, this forms an optimisation model that is solved in Excel.

C. *Effect estimation*

To be able to assess the different factors that can be of influence on the impact reduction attainable, various cases and scenarios are set-up. Within these cases and scenarios, the model is optimised for multiple objectives: minimising experienced travel time, minimising negative effects on air quality, minimising noise, and minimising accident risk.

D. *Effect appraisal*

Finally, these solutions are evaluated. By attaching a monetary value to each of the individual effects, the effects can be appraised and compared in the same unit. Furthermore, trade-offs between the different objectives can be made explicit.

III. MODEL

A. *Requirements*

To be able to answer the research questions, several requirements on the model exist. First of all, the model should describe the traffic propagation. It has to determine the number of vehicles that are currently on a link, the available capacity on a following link and what the speeds on the different links are. To allow to consider variations in these variables over time, a Dynamic Traffic Assignment is required. To be able to determine the effects of the traffic through the network, the instantaneous travel time should be calculated, as should the production of NO_x, PM_{10}, dB, and the accident risk. To determine the impact on the liveability of the effects, the surroundings have to be taken into consideration as well. Furthermore, given a certain penetration and compliance rate, and a fixed split of unguided traffic, the model should determine the optimal split advice for the guided traffic, for a certain objective. Additionally, requirements exist to allow for testing of different cases and scenarios. Because different weight classes of vehicles yield different emissions and noise, the model should distinguish between light, medium heavy, and heavy traffic. Furthermore, different routes should be able to have different speeds and different lengths.'

B. *Relationships traffic conditions and liveability effects*

1) Air quality: In this research, air quality is depicted by PM_{10} and NO_x. Every year, the Dutch government publishes emission factors [19]. They distinguish between light, medium heavy, and heavy traffic, types of roads, and speeds. They describe factors in g/km for CO, PM_{10}, $PM_{2.5}$, NO_2, and NO_x, for 2014, 2017, 2018, and 2019, and include predictions up to and including 2030. The factors for PM_{10} and NO_x are used to calculate the air quality resulting from the traffic conditions.

2) Noise: For noise, the government has established rules for the calculation of noise levels [20]. This comprises the noise production and several correction and deduction factors considering for example the effect of the car pulling up or the reduction caused by the air. For this research, only the noise production is considered:

$$E = 10 * \log\left(10^{\frac{E_l}{10}} + 10^{\frac{E_m}{10}} + 10^{\frac{E_h}{10}}\right) \tag{1}$$

with:

$$E_l = 70.0+29.8*\log\left(\frac{v_l}{v_0}\right)+10*\log\left(\frac{q}{v}\right)_l+C_{roadsurface,l} \tag{2}$$

$$E_m = 73.2+19.0*\log\left(\frac{v_m}{v_0}\right)+10*\log\left(\frac{q}{v}\right)_m+C_{roadsurface,m} \tag{3}$$

$$E_h = 76.0+17.9*\log\left(\frac{v_h}{v_0}\right)+10\log\left(\frac{q}{v}\right)_{ht}+C_{roadsurface,h} \tag{4}$$

Here v_l, v_m, and v_h are the speeds of respectively light, medium heavy, and heavy traffic. v_0 is the reference speed for the different vehicle categories, respectively 80 km/h for light traffic and 70 km/h for medium and heavy traffic. q is the flow in veh/h. The correction for the road surface is calculated as follows:

$$C_{roadsurface,cat} = \sigma_{cat} + \tau_{cat}\log\left(\frac{v_{cat}}{v_{0,cat}}\right) \tag{5}$$

Here cat is the vehicle category l, m, or h, σ_m is the difference in dB(A) at reference speed v_0, and τ_m is the speed index in dB(A) per decade change in speed.

3) Accident risk: Originally, the safety of a road section is assessed by the number of accidents that has occurred in the past, and this influences safety improving measures. The expected number of accidents on a road section is for example described by [21] as:

$$\mu = \alpha * L^{\beta} * q^{\gamma} * e^{\sum_{i=1}^{n}\delta_i x_i} \tag{6}$$

Here μ is the expected number of accidents on a road section in a given period, L is the length of the road section, and q is the traffic flow per 24 hours. x_i indicates other explaining variables, such as the width of the road. α, β, γ, $\delta_1 ... \delta_n$ are parameters that are fitted to the observed number of accidents.

[21] adapted this general formula to fit data of different types of roads in the city region Haaglanden, the province of Gelderland, and the province of North-Holland. Although this study is from 2006, this is currently the best available data and is used in this research.

C. Mathematical model

Now that the relationships between traffic conditions and effects are defined, the mathematical model used to minimise the negative effects can be described. The model comprises traffic propagation, route advice, and effect determination. The Link Transmission Model is used to describe traffic propagation in the network, as this takes spillback into account [22, 23]. The LTM uses Newell's triangular fundamental diagram, comprising only two wave speeds: a positive forward one for free-flow traffic v_f, and a negative backwards one for congestion w. The values describing the traffic situation can then be used to determine the effects on travel time, air quality, noise, and accident risk. Depending on the objective, the individual route advice has to be determined. Below, this is described in a mathematical model.

1) *Sets:*

V	Set of nodes
A	Set of links
I_n	Set of incoming links into node n, $I_n \subset A$
J_n	Set of outgoing links of node n, $J_n \subset A$
O	Set of all origins in the network, $O \subset V$
T	Set of simulation time step indices
X	Total network space

2) *Indices:*

t	A certain time interval, $t \in T$
n	Node, $n \in O$
r	Origin node, $r, \in R \subset O$
a	Link, $a, \in A$
i	Incoming link, $i \in I_n$
j	Outgoing link, $j \in J_n$
x	Point in network space, $x \in X$
x_a^0	Entrance point (upstream end) of link a
x_a^L	Exit point (downstream end) of link a
p	A path between a node and the destination
r	A path between a node and the destination, other than p

3) *Decision variable:*

β_{ij}	The split fraction at a node connecting link i and j.

4) *Model variables:*

Δt	Time interval length, simulation time step
$S_{ij}(t)$	Sending flow of link i to link j during time interval $[t, t + \Delta t][veh]$
x_a^t	The total number of vehicles on link a at time interval t. This is not the flow rate, but the link vehicle count [veh]
$T_a^t(x_a^t)$	The travel time on link a at time interval t, as a function of the number of vehicles on that link on that time [s]
η	The share of vehicles arriving at a decision node that requires guidance and complies to it. This value is between 0 and 1 and represents the penetration rate multiplied by the compliance rate. This variable ensures the distinction between guided and unguided traffic and reflects the compliance behaviour of guided drivers
γ_{ij}	The fixed split fraction of unguided and non-complying guided individuals from link i to link j
EX_a^t	Emitted NO$_x$ on link a at time t
EP_a^t	Emitted PM$_{10}$ on link a at time t
EN_a^t	Emitted dB on link a at time t
EA_a^t	Accident risk on link a at time t
Y_a	Number of local residents at link a
BT	Benchmark value for experienced travel time
BX	Benchmark value for experienced NO$_x$
BP	Benchmark value for experienced PM$_{10}$
BN	Benchmark value for experienced noise
BA	Benchmark value for accident risk
WT	Weight attached to travel time in the combined objective
WX	Weight attached to NO$_x$ in the combined objective
WP	Weight attached to PM$_{10}$ in the combined objective
WN	Weight attached to noise in the combined objective
WA	Weight attached to accident risk in the combined objective
LX_a^t	Limit for the emitted NO$_x$ on link a at time t
LP_a^t	Limit for the emitted PM$_{10}$ on link a at time t
LN_a^t	Limit for the emitted dB on link a at time t
LA_a^t	Limit for the accident risk on link a at time t
HT_n	Maximum travel time difference between two paths to a destination for guided travellers passing node n. [s]
HA_n	Maximum difference in accident risk between two paths to a destination for guided travellers passing node n
HX_n	Maximum difference in NO$_x$ between two paths to a destination for guided travellers passing node n
HP_n	Maximum difference in PM$_{10}$ between two paths to a destination for guided travellers passing node n
HN_n	Maximum difference in dB between two paths to a destination for guided travellers passing node n

5) *Traffic flow propagation description:* For the traffic propagation, the Link Transmission model is used. For a detailed description of the LTM, the reader is referred to [22]. A further description of the LTM in combination with individual traffic management can be found in [23].

To consider individual traffic management, some adaptations have to be made to the LTM. In diverge nodes, one incoming link splits into two outgoing links. Therefore, the sending flow must be split. A distinction is made between guided and unguided traffic. η is the penetration rate multiplied with the compliance rate, and indicates the share of people that will follow the advice given to them. β_{ij} describes the split fraction advice from the incoming link i to one of the outgoing links j.

$$S_{ij,guided}(t) = S_i(t) * \eta * \beta_{ij}, \forall i \in I_n; j \in J_n \tag{7}$$

$$S_{ij,unguided}(t) = S_i(t) * (1-\eta) * \gamma_{ij}, \forall i \in I_n; j \in J_n \tag{8}$$

In this research, a distinction was made between different vehicle types. To determine the values of the variables in the LTM for the three different vehicle weight classes light, medium, and heavy traffic, the total values are multiplied with the respective passenger car unit (PCU) and vehicle share ratio.

6) Objective functions: Per effect an objective can be described. This considers the produced effects and weighs this by the amount of people affected, either on or surrounding the road.

The objective to minimise the effect on travel time can be described as

$$\min \sum_{a \in A} T_a^t(x_a^t) * x_a^t, \forall t \in T \tag{9}$$

The total travel time on a route is dependent on the amount of people using the links on that route. The total experienced effect is calculated by multiplying the travel time of a link with the amount of people present on that link in that time step.

Contrary to the experienced travel time, the air quality and noise are mainly perceived by people surrounding the road instead of the drivers themselves. The objective to minimise the effect on air quality is therefore described as

$$\min \sum_{a \in A} (EX_a^t + EP_a^t) * Y_a, \forall t \in T \tag{10}$$

This comprises both the emitted NO_x and PM_{10}.

The objective to minimise the effect on noise is

$$\min \sum_{a \in A} EN_a^t * Y_a, \forall t \in T \tag{11}$$

Finally, the objective to minimise the effect on accident risk is again dependent on the amount of drivers on the link, and is therefore described as

$$\min \sum_{a \in A} EA_a^t * x_a^t, \forall t \in T \tag{12}$$

These four objectives can be combined into all encompassing objective. As the effects are measured in different units, they first all have to be normalised. This can be done by expressing all effects relative to a certain value. This value is determined by sending all traffic via the route that is worst for that effect, and then taking the resulting maximum over the full hour assessed. This is not necessarily the absolute worst result of the effects, but functions merely as a benchmark.

For travel time, the worst situation is where all traffic uses the same, longest route. This is then multiplied by the resulting number of vehicles in the network.

For both air quality and noise, the benchmark situation is where all traffic uses the route with the most people surrounding. The resulting number of vehicles in the network and the number of local residents is used to determine the effect.

For safety, the comparison situation is equal to the worst travel time: every vehicle uses the same, longest route. The resulting number of vehicles in the network is used to determine the accident risk.

Additionally, weights could be attached to the different effects, as some actor might value for example travel time as more important, while others might consider safety to be the most important aspect.

This all combined yields the following objective:

$$\begin{aligned} \min \sum_{a\ \in A} & \frac{T_a^t(x_a^t) * x_a^t}{BT} * WT \\ & + \left(\frac{(EX_a^t) * Y_a}{BX} * WX + \frac{EP_a^t * Y_a}{BP} * WP \right) /2 \\ & + \frac{EN_a^t * Y_a}{BN} * WN + \frac{EA_a^t * x_a^t}{BA} * WA \end{aligned} \tag{13}$$

As NO_x and PM_{10} together form the indicator for air quality, their total impact is divided by two, so they are not counted double.

7) Constraints: Several constraints have to be formulated before the objectives can be solved. First of all, if no traffic would be on the road, no effects would occur, but the demand must be fulfilled. This can be achieved by ensuring all traffic at a diverge node is assigned to a next link

$$\sum_{j \in J_n} \beta_{ij} = 1 \forall i \in I_n; \tag{14}$$

When optimising for an effect, this might have adverse impact on the other effects. Therefore, those have to be constrained. The liveability effects caused may not be higher than set limits. For NO_x this is formulated as:

$$EX_a^t \leq LX_a^t, \forall t \in T; a \in A \tag{15}$$

For PM_{10} this limit is described in a similar fashion as:

$$EP_a^t \leq LP_a^t, \forall t \in T; a \in A \tag{16}$$

The noise limit is expressed as:

$$EN_a^t \leq LN_a^t, \forall t \in T; a \in A \tag{17}$$

For simplicity reasons, the correction factors are not considered when calculating the noise production, causing the noise level in this model to be much higher than the actual expected noise level, or than what would be calculated in a dedicated noise model. Therefore, the noise limit used as a constraint in the model is set at 110 dB, instead of the 50 dB described in the laws of environmental conservation [24].

Finally, the limit for the accident risk is formulated as:

$$EA_a^t \leq LA_a^t, \forall t \in T; a \in A \tag{18}$$

Furthermore, fairness must be ensured. The first type of fairness that should be considered is the difference between the travel time of users:

$$\left| \sum_{a \in A} T_{a,p}^t(x_a^t) - \sum_{a \in A} T_{a,r}^t(x_a^t) \right| \leq HT_n, \forall n \in V; t \in T \tag{19}$$

Here $T_{a,p}^t(x_a^t)$ and $T_{a,r}^t(x_a^t)$ describe the travel times of route p and r, respectively.

A similar constraint can be constructed for air quality, noise, and safety, by comparing the unweighted produced effects of the alternative routes for NO$_x$, PM$_{10}$, dB, and accident risk respectively:

$$\left| \sum_{a \in A} EX_{a,p}^t - \sum_{a \in A} EX_{a,r}^t \right| \leq HX_n, \forall n \in V; t \in T \tag{20}$$

$$\left| \sum_{a \in A} EP_{a,p}^t - \sum_{a \in A} EP_{a,r}^t \right| \leq HP_n, \forall n \in V; t \in T \tag{21}$$

$$\left| \sum_{a \in A} EN_{a,p}^t - \sum_{a \in A} EN_{a,r}^t \right| \leq HN_n, \forall n \in V; t \in T \tag{22}$$

$$\left| \sum_{a \in A} EA_{a,p}^t - \sum_{a \in A} EA_{a,r}^t \right| \leq HA_n, \forall n \in V; t \in T \tag{23}$$

Finally, there are some non-negativity constraints. The number of vehicles on a link a at time t must always be non-negative.

$$x_i^t \geq 0, \forall a \in A; t \in T \tag{24}$$

Due to the nature of the formulas, the advised split fractions should be larger than zero.

$$\sum_{j \in J_n} \beta_{ij} > 0 \forall i \in I_n; \tag{25}$$

D. Algorithm

The Link Transmission Model, Individual Route Guidance, and effects are combined into one model, which determines the situation in each time period of 30 seconds. The model is optimised per time step of 30 seconds, to be able to take into account variations in traffic characteristics such as speed, flow, and density over time, but also be able to operationalise the model in Excel. Figure 1 shows how the advice is determined to optimise a certain objective. The grey boxes are input, the blue boxes are model variables, the green box contains the objective, and the red box is what can be changed to achieve the objective. The 'Number of vehicles on each link' at time t is indicated in both grey and blue, as the initial number of vehicles on each link is zero, but in the next time steps this is dependent on the previous periods. The current number of vehicles on each link, the given split fraction of unguided traffic, and the demand for the next time step determine the possible sending and receiving flows of the links. The transition flows are dependent on the sending and receiving capacity of the links, the compliance and penetration rate of guided traffic, and the split advice for guided traffic. The transition flows and number vehicles on each link in the current time period in turn influence the number of vehicles on each link in the next time period. This determines the speeds and resulting travel time and liveability effects for the next period. As these effects are what need to be optimised, they iteratively determine the best split advice.

E. Scenarios

The mathematical model captures a simple network, shown in Figure 2, consisting of a link that splits into two alternative routes, and then combines into one link again.

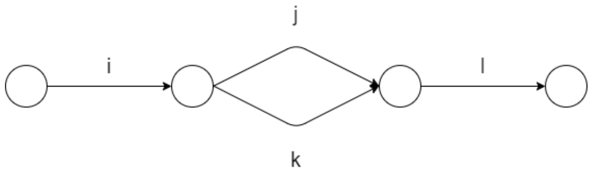


Fig. 2: Basic network

The mathematical model is translated into an optimisation model in Excel. In the optimisation, multiple factors were assessed. Network characteristics as speed, link length, capacity, average vehicle type share, and the surroundings were captured in three different cases. The first case, shown in Figure 3 considered a network were one of the two alternative routes passes a school. Due to the nature of the built-up area the school is in, speeds and capacity are low. The route passing the school has a lower speed limit but is the shortest. It has a relatively large number of people surrounding it, comprising 300 children in the school and 150 people in the rest of the street, and by nature has limited heavy traffic. The other route has a higher speed limit and has a smaller number of local residents. The second case describes a motorway with a shorter parallel road as the

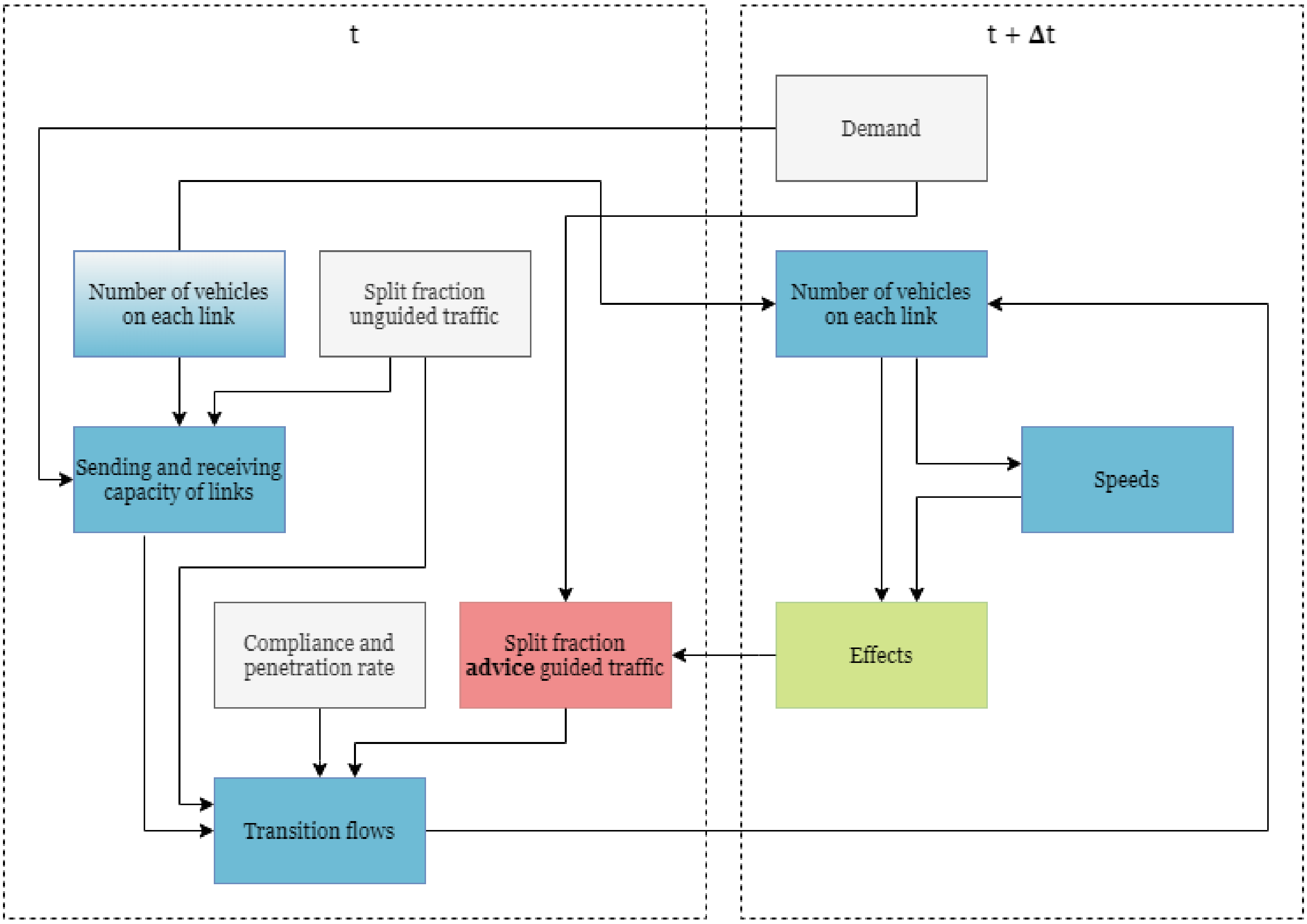


Fig. 1: Algorithm

alternative route, as is displayed in Figure 4. Speeds and capacity in this case are higher than in the previous case, and the number of people living in the surroundings of the road is smaller. In the third case, presented in Figure 5, one of the alternative routes in the built-up area is restricted for heavy traffic, as often is the case in (historical) inner cities. This means that on link j, medium heavy and heavy traffic flow is limited to zero. For all three cases, multiple scenarios were optimised. These scenarios varied in the effective compliance rate, the distribution of unguided traffic, weights of the effects, and the effect of effects to be optimised.

IV. RESULTS

A. *Compliance*

As the given advice might require additional travel time or a different route than the one preferred by the traveller, not all advice might be complied with. Therefore, the factors influencing the compliance of road users with the given advice, and the bandwidths of additional travel time, travel cost, or comfort they are willing to trade for improvements in liveability effects, are analysed using literature research. It was found that credible advice, reinforced by other travellers, the conditions on the road, or the quality of previously received guidance, is an important factor in increasing compliance [25]–[29]. Furthermore, advice aiming at congestion alleviation is found to be followed more than advice focusing on environmental effects or safety [26]. Moreover, compliance is higher if the advised route is the one the driver is currently on. Additionally, predictive and

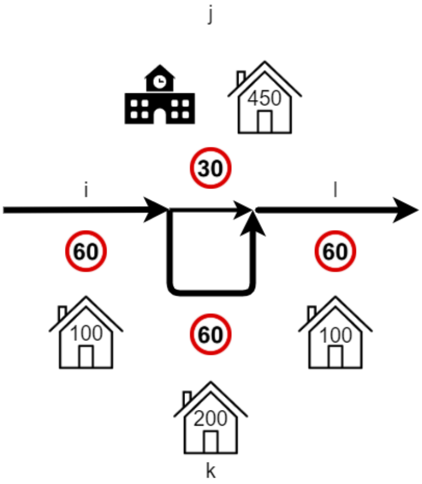


Fig. 3: School route case

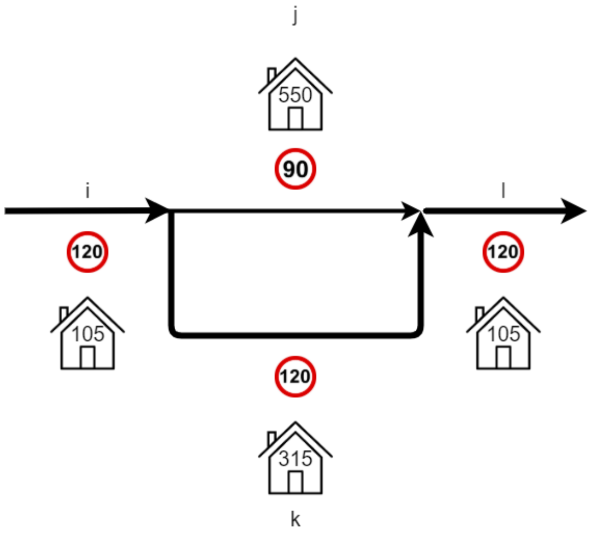


Fig. 4: Parallel road case

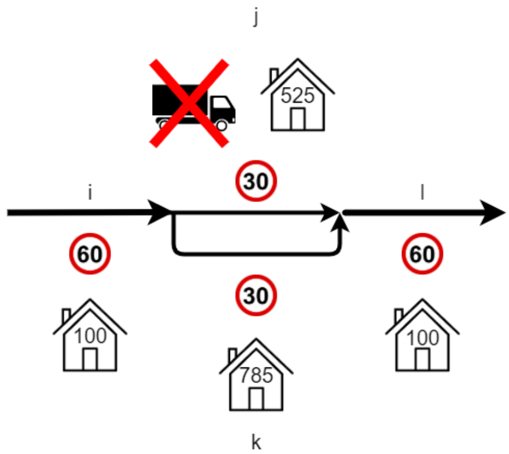


Fig. 5: Road restricted for heavy traffic case

personalised route guidance yields higher compliance as well [27, 30, 31]. Furthermore, higher familiarity of the road user with the network causes lower compliance [25, 29, 30, 32]. In addition, it was found that both young and experienced drivers are less likely to comply with the given advice [25, 28, 29]. Furthermore, different trade-offs between travel time and emissions exist between female and male, with females being willing to trade more travel time [33]. In the trade-off between travel time and safety, road users consider more travel time in the role of citizen, than as a consumer [34]. These factors are relevant context considerations when examining the achievable effect of individual traffic management.

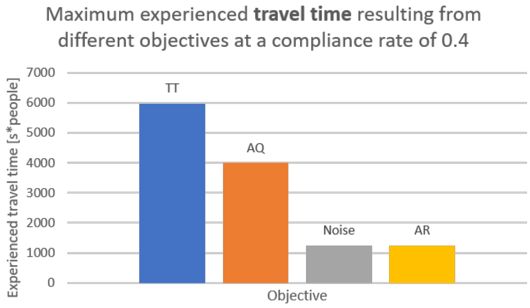
B. *Individual traffic management*

When optimising the developed model, it was found that in the school case, the fastest but socially undesirable route was favoured when optimising for both travel time and air quality. The advice for minimising travel time however is too extreme, causing congestion over time. This reveals a limitation of the developed model. The optimisation model only considers the effects in the first upcoming time step. As some of the links are longer than what could be travelled in one time period, the effects occur with a delay. For some effects, the experienced effects resulting from a different split fraction advice might even worsen at first, before showing improvement. However, as the model only uses the first upcoming time step to determine the 'optimal' split fraction advice, it does not consider these improvements later in time. It therefore continues to advise the same extreme split fraction. With higher compliance, more road users follow this extreme advice, yielding adverse effects. With lower compliance, more people will use a different route from the advised one, causing a more balanced distribution and less congestion.

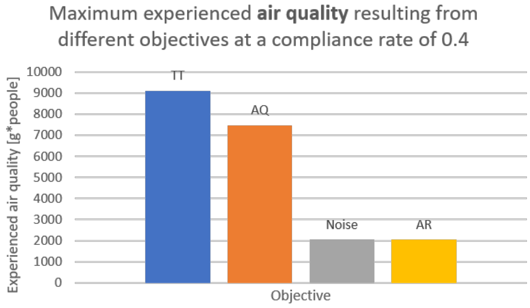
When minimising noise, the advised split fraction varied for different amounts of compliance. However, if more weight is attached to the schoolchildren, the advice for both air quality and noise favours the longer route with less local residents. This reduces congestion and improves all effects. When minimising the accident risk, the longer route is preferred, as the road type yields a lower accident risk. Across the scenarios in the case with the school route, if more traffic is sent via the longer route with less local residents, which is the case if the objective is accident risk or noise at 40% compliance, the guided traffic is better balanced with the unguided traffic using the faster route. This induces less congestion, and is beneficial for all liveability effects. Figure 6 shows the maximum effects resulting from the different objectives travel time (TT), air quality (AQ), noise, and accident risk (AR) if 40% of travellers follows the advice given. The objective accident risk yields the best results for all effects.

The case with the parallel road has a smaller ratio between the travel times of the two alternative routes. When minimising the experienced travel time, the advice is quite balanced over the two routes. When optimising air quality as well as noise, slightly more traffic is sent via the route with less local residents. However, if too much vehicles use this route, congestion occurs, deteriorating the experienced liveability effects. If the accident risk is minimised, the guided traffic is sent fifty-fifty over the two routes. With lower compliance, more unguided traffic uses the faster route, so the advice for guided traffic is more focused on the longer route, to achieve balance. As the suggested split fractions in the case with the parallel road are less extreme than in the school route case, the experienced effects across the scenarios are closer to each other, indicating the context is more important in this case than the objective. This is shown for a compliance rate of 0.4 in Figure 7.

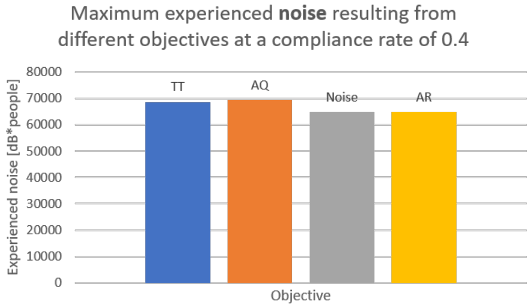
In the case with the road restricted for heavy traffic, in the base scenario were all traffic is unguided, no congestion occurs, in contrast to the other two cases. When comparing the various tested scenarios with this base case, almost no improvement is found. This suggests that congestion might be a good indicator of the potential improvement on liveability effects.



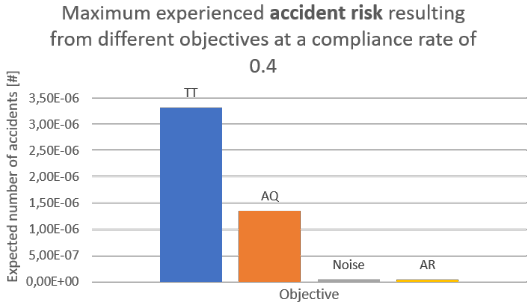
(a) Travel time



(b) Air quality

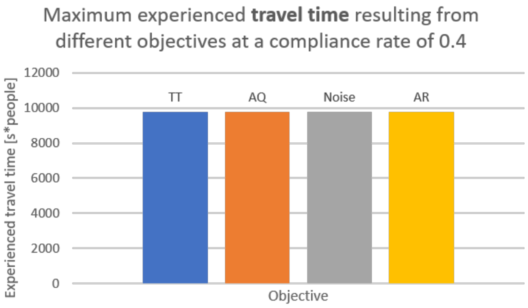


(c) Noise

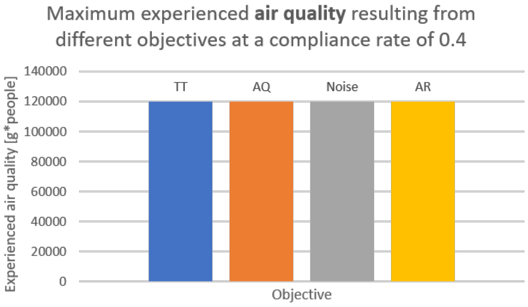


(d) Accident risk

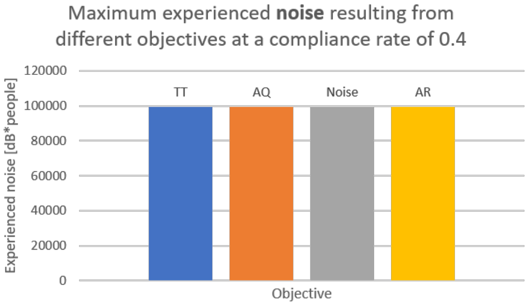
Fig. 6: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the school route case



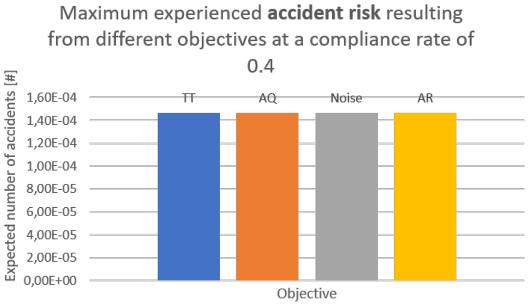
(a) Travel time



(b) Air quality



(c) Noise



(d) Accident risk

Fig. 7: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the parallel road case

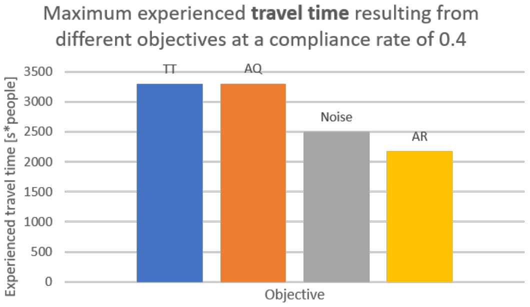
If the objective is to minimise the experienced travel time, the fastest route is suggested. However, if too many travellers follow this route, congestion occurs, worsening the experienced liveability effects. If air quality is optimised, the route with less local residents is favoured. Here, the distinction between the causes of the effects is shown: travel time and accident risk are mainly dependent on the number of vehicles on a link, while air quality and noise are also strongly influenced by the type of vehicles. Therefore, these latter two effects are higher on the route that is used by all more polluting and noisier medium heavy and heavy traffic. When minimising noise, the non-restricted route, that already experiences noise from the medium heavy and heavy vehicles, is suggested, as the marginal impact of an additional vehicle is less than the impact of the first vehicle on the other route. To minimise accident risk, the route with the safest road characteristics is favoured, but in balance with the other route, to limit traffic flows. In this case again, aiming to minimise accident risk yields the best results for all effects, as can be observed in Figure 8.

Overall, when minimising travel time, logically, the fastest route is suggested. However, less extreme advice appears to yield less congestion. The advice to optimise air quality is dependent on the number of local residents, or the weight attached to them. With more local residents or a higher weight, the less inhabited route is suggested. If the residents have a lower impact, the faster route is favoured. The optimal split fraction for noise is less clear. As noise is calculated logarithmically, any additional traffic has less impact than the first vehicle, so sending traffic via roads that already experience noise has limited impact. Furthermore, similar to air quality, the shorter road might yield lower noise production, but if the impact of local residents is strong enough, the less inhabited route is preferred. The best advice for accident risk is a balanced split, minimising traffic flow on both routes. Depending on the road characteristics, one of the two alternatives can be slightly favoured.

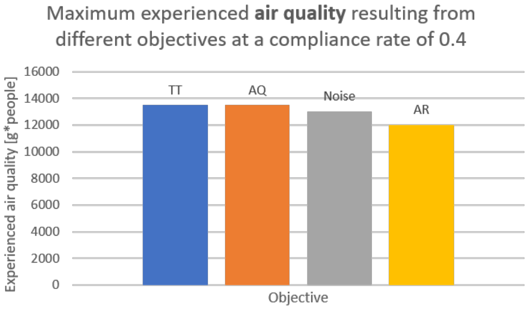
If all effects are combined in one objective, in the school case, if more weight is attached to the effects impacting road users, better effects are obtained. This can be explained as these effects are travel time and accident risk, and the latter yielded the best results in the individual optimisation.

In the parallel road case, no individual objective yielded strongly better effects. This can also be seen in the results of the combined objectives. All experienced effects are similar, irrespective of the objective, except if the amount of unguided traffic using the fastest route exceeds the capacity. For the other objectives, a less balanced split of unguided traffic yields an advice that aims to restore the balance.

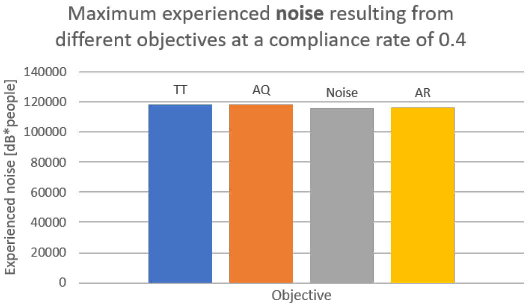
Even though the advice for the different combined objectives in the case with the road restricted for heavy traffic differs strongly between those focusing on road users and those focusing on residents, the experienced liveability effects are similar for the same unguided traffic split fraction. If more unguided traffic uses the fastest route, more guided traffic is sent via the other route.



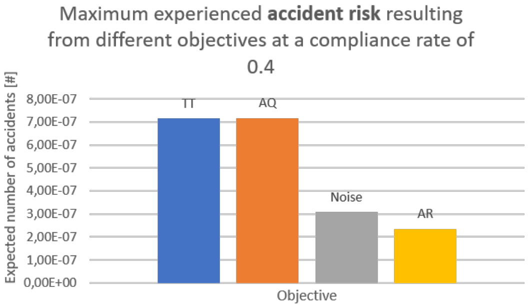
(a) Travel time



(b) Air quality



(c) Noise



(d) Accident risk

Fig. 8: Experienced effects resulting from split fractions corresponding to different objectives for a compliance rate of 0.4 in the road restricted for heavy traffic case

C. Evaluation

The results found in the optimisation were then given a monetary value. The value of experienced travel time differs both depending on the number of vehicles in the network, and on the division of vehicle types, as freight traffic has a higher Value of Time. The cost of air quality was largest in all tested scenarios. This is partially due to the fact that only the production of effects are considered. Reductions factors caused by for example dispersion are omitted, causing the calculated effects to be higher than what would actually be experienced. Air quality is especially large in the case with the parallel road, as this has relatively more medium heavy and heavy traffic, which are more polluting. Across the scenarios, the monetary value for noise was found to be relatively similar. Accident risk was found to vary the strongest between scenarios, both between and within cases. Between the effects, large differences in the monetary values exist. If all effects would be combined in one objective based on their monetary value, the impact of air quality would be extremely large. Considering the value attached to each effect, either in weight or a monetary value, is therefore of great importance when combining all effects in one objective to minimise negative externalities on liveability.

Finally, the found effects were compared. In line with existing literature, travel time and accident risk are strongly aligned, with an increase in one corresponding to a steady incline in the other. Travel time and air quality are fairly aligned as well, although in the cases with the school route and the road restricted for heavy traffic for the first time steps of the simulated period the increase in air is stronger, while later the incline in travel time is stronger. When comparing noise with any other effect, the first time periods show a very strong increase in noise, with a smaller increase in the compared effect, while after the first few time steps an increase in the compared effect corresponds with very limited change in experienced noise.

The only dilemmas resulting from split fraction advice observed in the tested cases and scenarios are in the case with the parallel road. After the first simulated minutes, a decrease in travel time corresponds with an increase in all other effects. Apart from this dilemma, an increase in one effect in general corresponds with an increase in the other effects. This indicates that a good split fraction advice can benefit all effects.

In the case with the school route, there exists a trade-off as a result of the compliance rate: a higher compliance when minimising travel time is beneficial for noise, but this yields the worst results for travel time and air quality. Furthermore, noise and accident risk benefit from a higher compliance when minimising accident risk, while a lower compliance is more beneficial for travel time and air quality. In the case with the parallel road, a dilemma resulting from compliance rates occurs when optimising air quality: at full compliance, the best results for noise are achieved, while this corresponds with the worst results for travel time, air quality, and accident risk. Although less extreme, the same occurs when optimising noise. These dilemmas show that if it is possible to influence compliance, it is necessary to consider which effects are preferred to be improved.

V. DISCUSSION

The network structure, that was adapted for the three different cases, is very simple. Only traffic that enters the network in the first link is considered, and there are no other inflow or outflow possibilities. Future research could consider a larger network were additional in- and outflow traffic uses the network as well, being another form of unguided traffic affecting the traffic flow.

In the calculation of the effects, only the production of air quality and noise are considered, causing the calculated effects to be higher than what would actually be experienced. Future research could also incorporate reduction factors on these effects. In the current research, only road traffic is considered in the accident risk. Future research could also assess the effects on cyclists and pedestrians.

Because some link lengths in the network are longer than what could be travelled in one time step, the effects experienced show some delay. This imposes another very important limitation on the optimisation model, as only the effects in the first upcoming time step are evaluated to determine the optimal split fraction advice. If due to this delay no improvement in the effects is shown, the model continues to give the same advice. This can even negatively impact the effect that is aimed to be minimised. It is therefore important to consider the effects of multiple upcoming time steps to prevent this issue in further research.

Another direction that could be interesting to assess in future research is the impact of electric vehicles. Their production of emissions and noise, especially at lower speeds, is much smaller, which could lead to a different distribution. As personalised advice seems to have high potential for increasing compliance, it could be relevant for future research to distinguish multiple groups of road users, each with different evaluations of the effects. More insight in the variations between road users of factors influencing compliance could be beneficial here.

VI. CONCLUSION

By improving compliance of road users with the given advice, the impact of individual traffic management can be increased. An important factor for increasing compliance is the credibility of the given advice. This is improved by a high quality of the advice, comprising for example correct travel time estimations. Credibility of the advice can also be strengthened by confirmation, for example by other travellers using the same route. A high familiarity with the network brings about a lower compliance rate, suggesting that situations where travellers are well acquainted with the road section might have less potential for improvement by individual traffic management. Furthermore, advice aimed at alleviating congestion is complied with more than advice with environmental or safety objectives. Personalised advice yields better compliance as well. Taking personal characteristics into account in advice, naturally considering privacy, could therefore also be advantageous.

In this research the possible impact of individual traffic management on liveability is tested in different situations. In the case with the school route, when minimising travel time, the fastest route is advised. Over time, however, this causes congestion due to the model assumption that only the effects in the first upcoming time step are considered. When optimising air quality, the link length appears to be of the greatest importance in this case, as the shortest but socially undesirable route is preferred. The advice for noise varies with different amounts of compliance, but better results are achieved if the route with less local residents is suggested. Of the individual objectives, the best results are achieved when the aim is to minimise accident risk. Here, the road type characteristics are most important, and traffic is sent via the longer route. A sensitivity analysis revealed that attaching more weight to local residents drastically changes the given advice, reduces congestion and improves all effects. If all effects are normalised combined in one objective, better results are obtained if more weight is attached to the effects impacting road users.

The characteristics of the two alternative routes in the case with the parallel road are closer together, yielding a more even distribution of unguided traffic. The given advice in this case is less extreme as well. Here, the amount of local residents influences the advice when optimising both air quality and noise. For accident risk, the dominant factor is the traffic flow, aiming at a more balanced distribution of traffic. As the advice in this case is less extreme, the experienced effects resulting from different objectives are very similar for the same amount of compliance.

In the final tested case, one route was restricted for heavy traffic. In the base scenario where no advice is given, no congestion occurred. As almost no assessed scenario showed improvements on effects, this appears to be a good indicator of the potential improvement caused by individual traffic management. The least worse results were obtained when minimising accident risk, where the advice aimed at a more balanced distribution. This case showed that travel time and accident risk are strongly influenced by the number of vehicles on a link, while air quality and noise are greatly dependent on the type of vehicle.

When attaching a monetary value to the experienced effects to be able to evaluate and compare them, air quality reveals to be the most dominant effect. This can partially be explained as only production is considered, so the effects are larger than what would actually be experienced. Air quality is especially large in the case with the parallel road, due to relatively large share of the more polluting medium heavy and heavy vehicles. Both within and between cases, accident risk varies strongly. The value is limited in size in the school case and the road restricted for heavy traffic case, but is much larger in the case with parallel road, due to larger traffic flow and longer link sections.

The only dilemma resulting from difference split fraction advice was found in the case with the parallel road, between travel time on the one hand, and the other effects air quality, noise, and accident risk on the other hand. The size of the increase was however small. Dilemmas resulting from different compliance rates exist in the school route case. A higher compliance when minimising travel time is beneficial for noise, but this yields the worst results for travel time and air quality. Noise and accident risk benefit from a higher compliance when minimising accident risk, while a lower compliance is more beneficial for travel time and air quality. In the case with the parallel road, a dilemma resulting from compliance rates occurs when optimising air quality: at full compliance, the best results for noise are achieved, while this corresponds with the worst results for travel time, air quality, and accident risk. Although less extreme, the same occurs when optimising noise. If compliance can be influenced, these trade-offs need to be taken into account to consider which effect is preferred to be improved.

Concluding, depending on the network characteristics considered and the compliance of road users assumed, different impact on the liveability effects travel time, air quality, noise, and accident risk can be achieved. Overall, the best results are obtained with advice aiming at a more balanced distribution of traffic, as this reduces congestion which benefits all effects. However, the importance attached to the local residents can strongly influence the route guidance, affecting the experienced effects. Due to the structure of the controller, both lower compliance with extreme advice and more balanced advice yield better effects. Even though the suggested split fraction did not always yield the best results, this research contributed to closing the research gap on the impact of individual traffic management on liveability, considering multiple effects at once, and revealed some of the complex relationships in reducing negative impact on liveability caused by road traffic.

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B

Acronyms

ATIS	Advanced Traveller Information Systems
DRG	Dynamic Route Guidance
DTA	Dynamic Traffic Assignment
DTM	Dynamic Traffic Management
DUE	Deterministic User Equilibrium
ITM	Individual Traffic Management
ITS	Intelligent Transport Systems
MO	Multi Objective
NDP	Network Design Problem
PCU	Passenger Car Unit
PSOI	Personalised System Optimum Traveller Information
SPI	Safety Performance Indicator
SO	System Optimum
STM	Smooth Traffic Management
UE	User Equilibrium
VOSL	Value of a Statistical Life
VOT	Value of Time

C

Parameters

C.1. Cases

Table C.1: Parameters of the school route case

	Link i	**Link j**	**Link k**	**Link l**
Speed	60	30	60	60
Capacity	1200	900	1200	1200
Critical density	20	30	20	20
Jam density	100	90	100	100
Demand	1200			
Light share	0.8592			
Medium share	0.1172			
Heavy share	0.0236			
Link length	0.5	0.25	1	0.5
Free flow travel time	30	30	60	30
Share of unguided traffic (UE)		0.9	0.1	
Local residents	100	450	200	100

Table C.2: Parameters of the parallel road case

	Link i	**Link j**	**Link k**	**Link l**
Speed	120	90	120	120
Capacity	4439	1575	4439	4439
Critical density	73.98	17.5	18.49	73.98
Jam density	665.85	122.5	166.43	665.85
Demand	3500			
Light share	0.5463			
Medium share	0.2767			
Heavy share	0.177			
Link length	1	1.5	3	1
Free flow travel time	30	60	90	30
Share of unguided traffic (UE)		0.62	0.38	
Local residents	105	550	315	105

Table C.3: Parameters of the restricted for heavy traffic case

	Link i	**Link j**	**Link k**	**Link l**
Speed	60	30	30	60
Capacity	1200	900	900	1200
Critical density	20	30	30	20
Jam density	100	90	90	100
Demand	1200			
Light share	0.8592			
Medium share	0.1172	restricted		
Heavy share	0.0236	restricted		
Link length	0.5	0.5	0.75	0.5
Free flow travel time	30	60	90	30
Share of unguided traffic (UE)		0.82	0.18	
Local residents	100	525	785	100

D
Results

D.1. School route

Figure D.1: Split fraction advice towards link j when optimising travel time with a compliance rate of 1

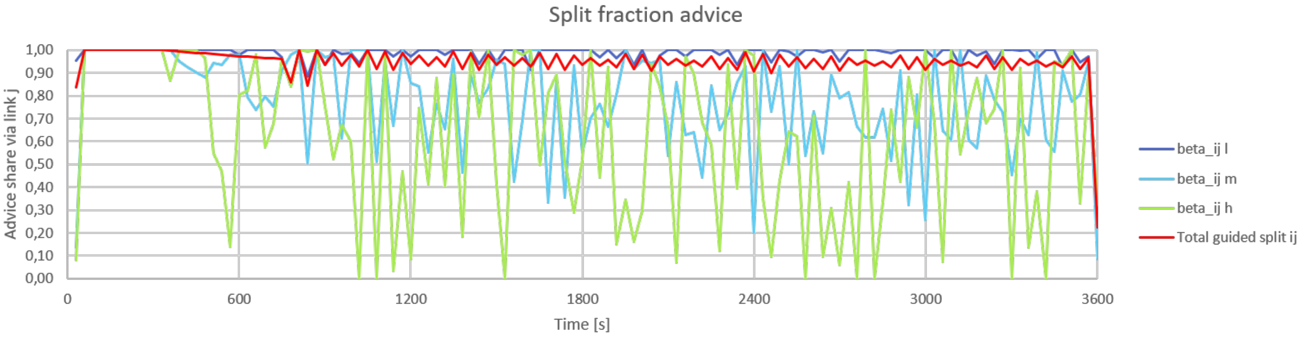

Figure D.2: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.7

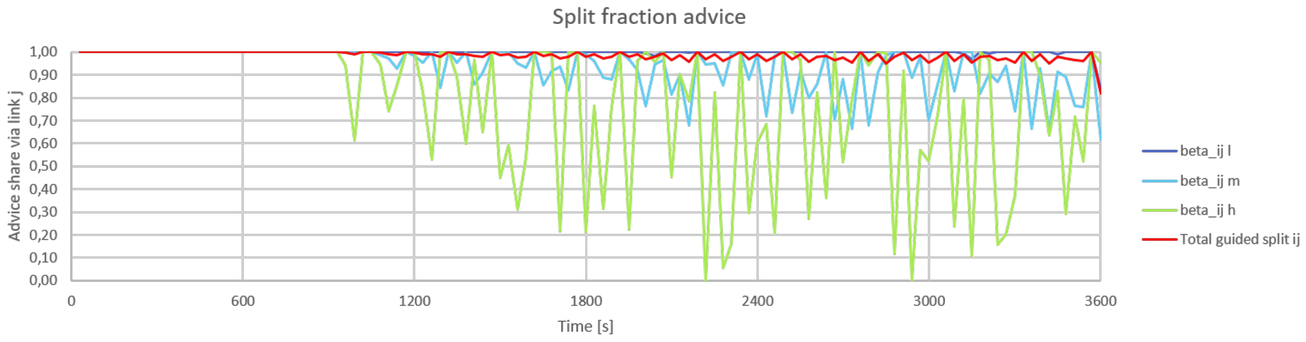

Figure D.3: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.4

Figure D.4: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.1

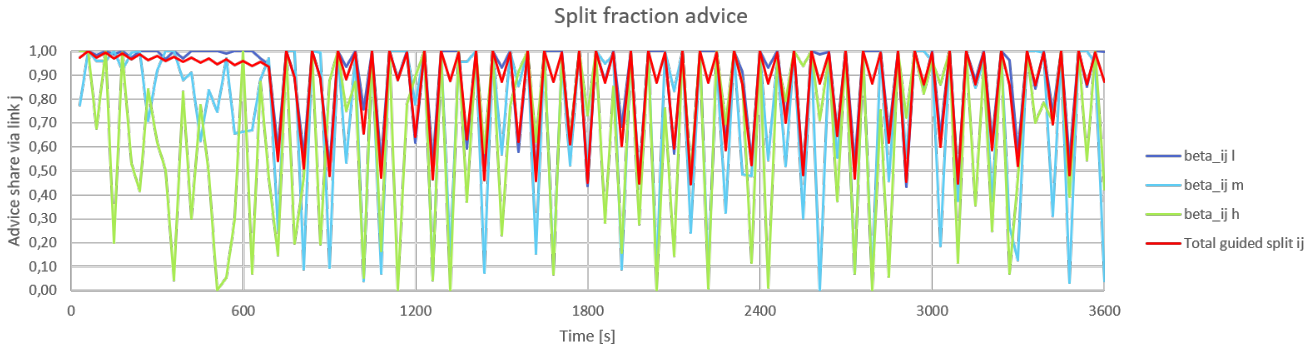

Figure D.5: Split fraction advice towards link j when optimising air quality with a compliance rate of 1

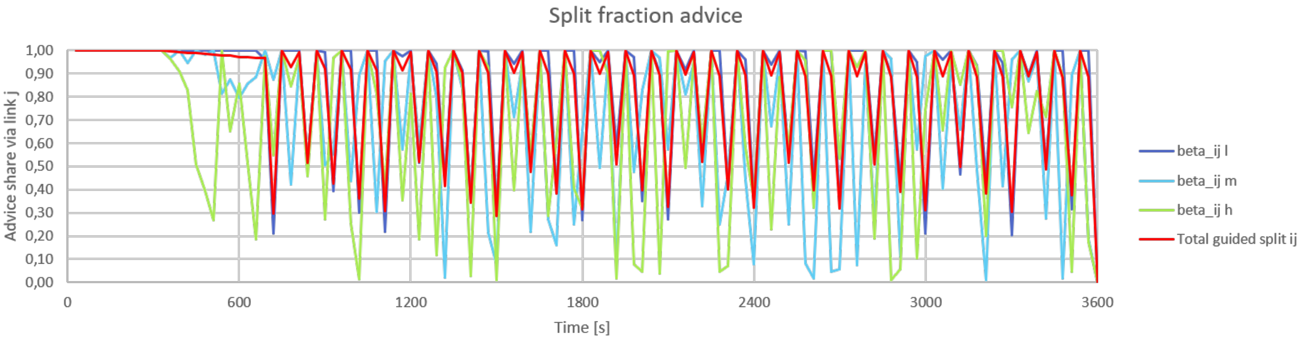

Figure D.6: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.7

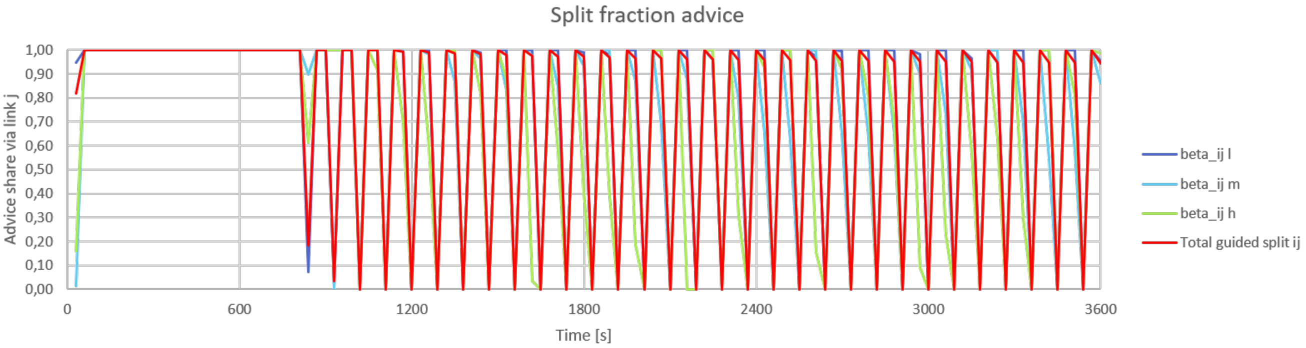

Figure D.7: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4

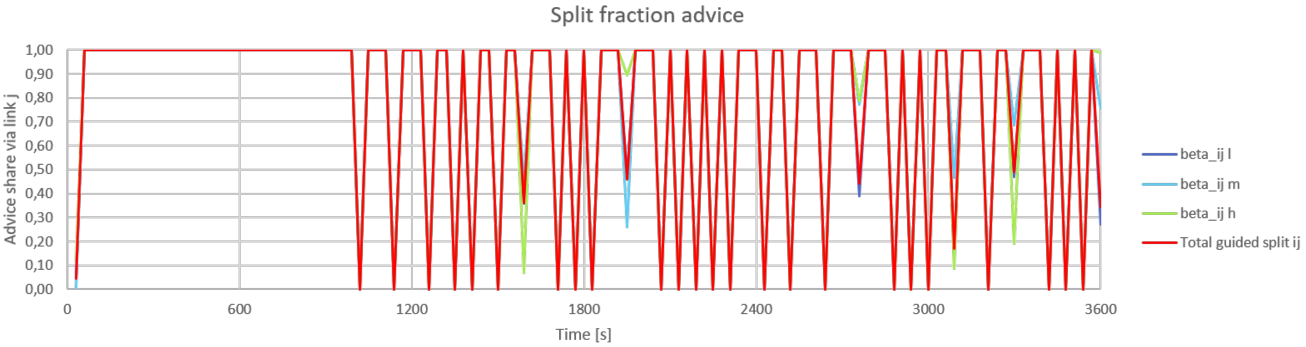

Figure D.8: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.1

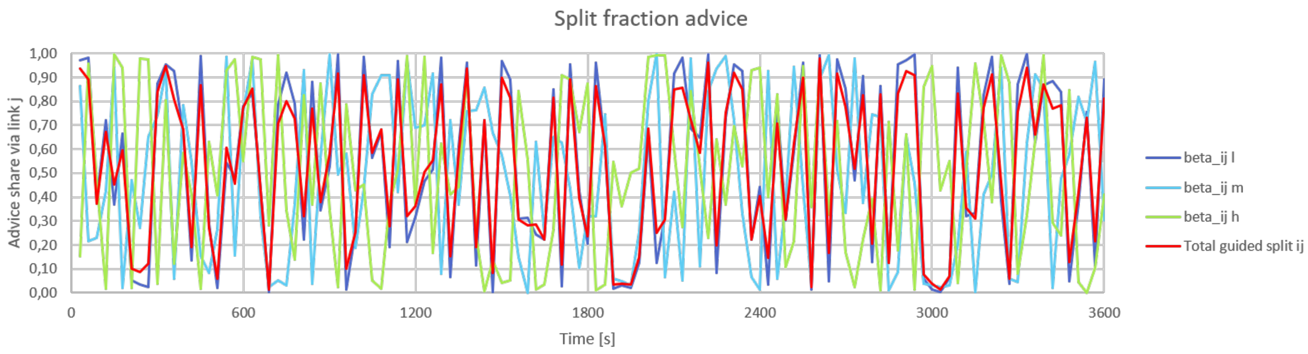

Figure D.9: Split fraction advice towards link j when optimising noise with a compliance rate of 1

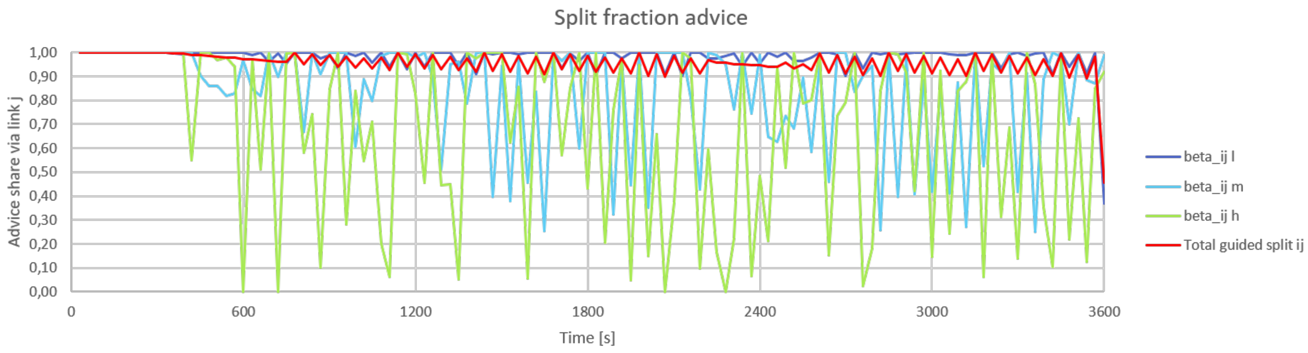

Figure D.10: Split fraction advice towards link j when optimising noise with a compliance rate of 0.7

Figure D.11: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4

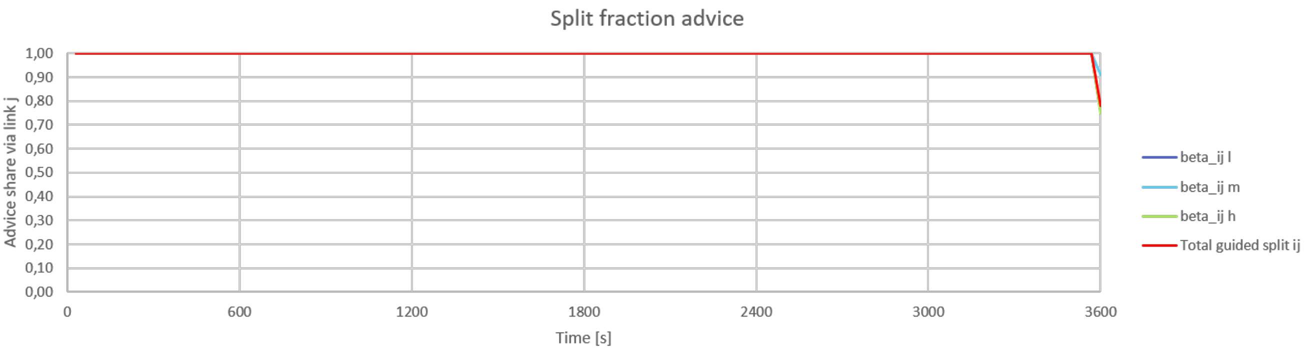

Figure D.12: Split fraction advice towards link j when optimising noise with a compliance rate of 0.1

Figure D.13: Split fraction advice towards link j when optimising accident risk with a compliance rate of 1

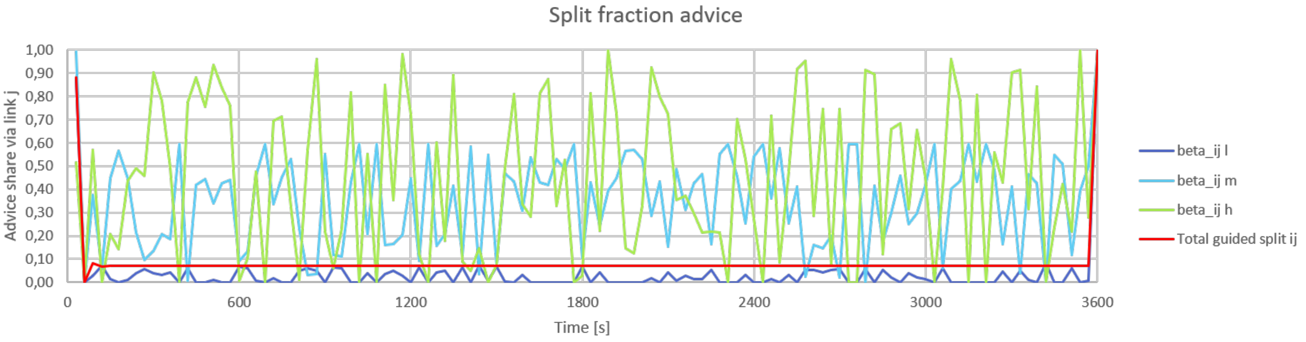

Figure D.14: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.7

Figure D.15: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4

Figure D.16: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.1

Sensitivity analysis

Figure D.17: Split fraction advice towards link j when optimising air quality with a compliance rate of 1, with schoolchildren given a double weight

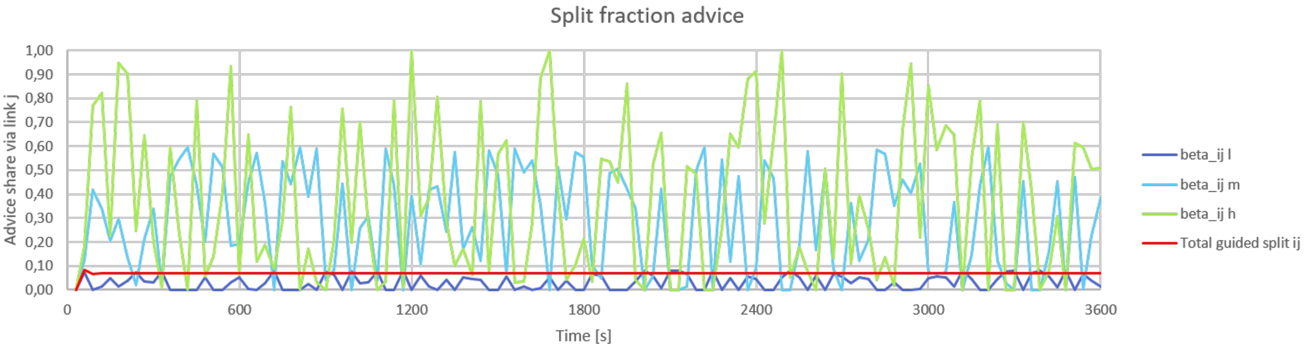

Figure D.18: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.7, with schoolchildren given a double weight

Figure D.19: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4, with schoolchildren given a double weight

Figure D.20: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.1, with schoolchildren given a double weight

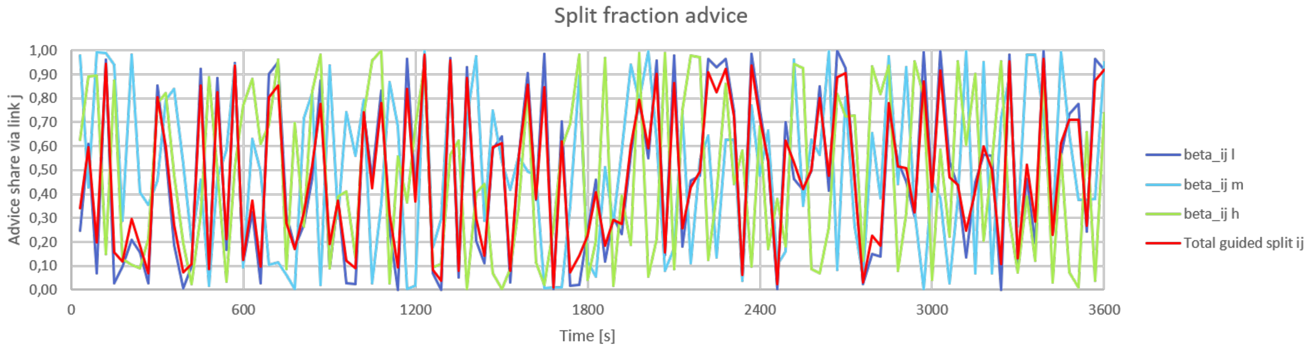

Figure D.21: Split fraction advice towards link j when optimising noise with a compliance rate of 1, with schoolchildren given a double weight

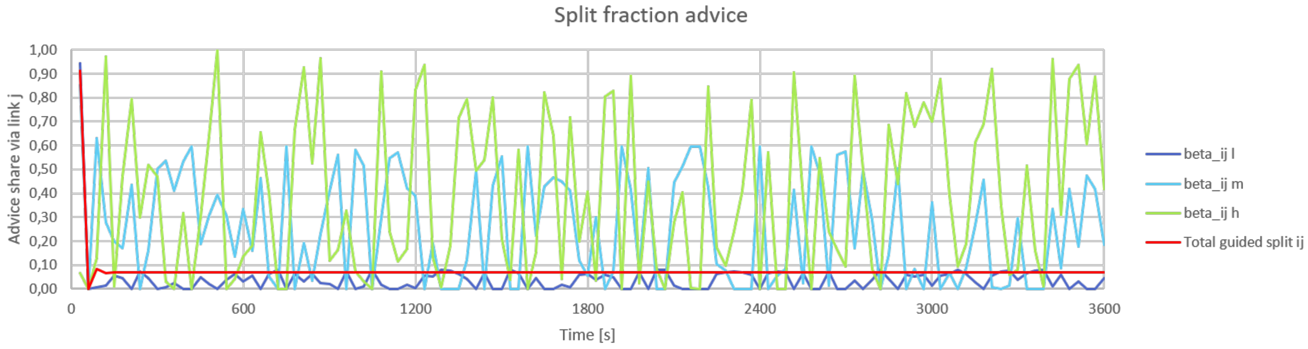

Figure D.22: Split fraction advice towards link j when optimising noise with a compliance rate of 0.7, with schoolchildren given a double weight

Figure D.23: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4, with schoolchildren given a double weight

Figure D.24: Split fraction advice towards link j when optimising noise with a compliance rate of 0.1, with schoolchildren given a double weight

D.2. Parallel road

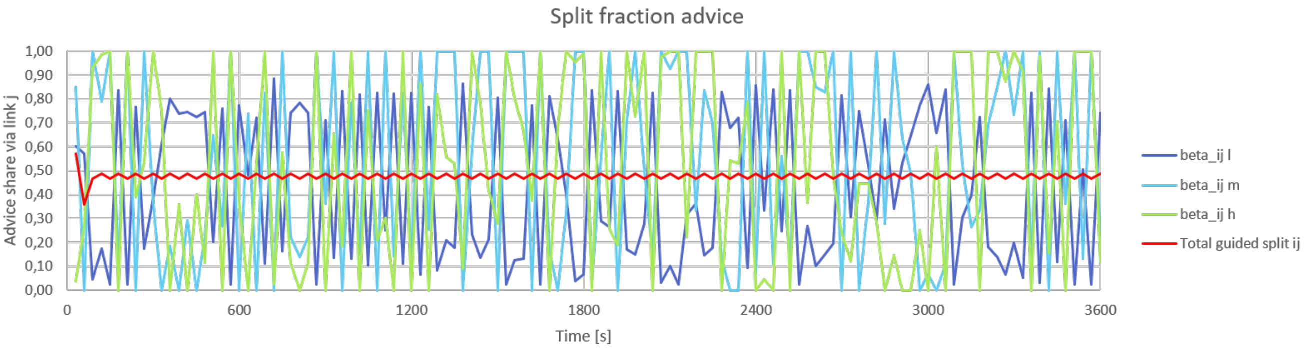

Figure D.25: Split fraction advice towards link j when optimising travel time with a compliance rate of 1

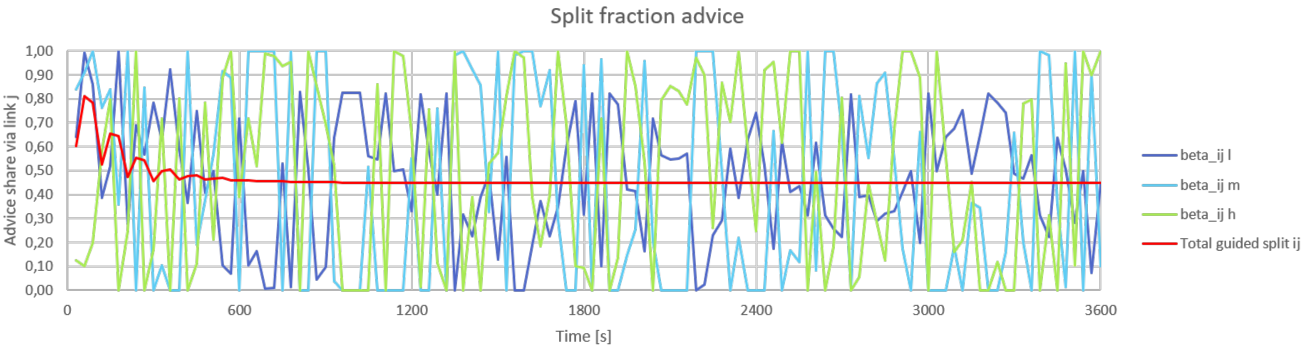

Figure D.26: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.7

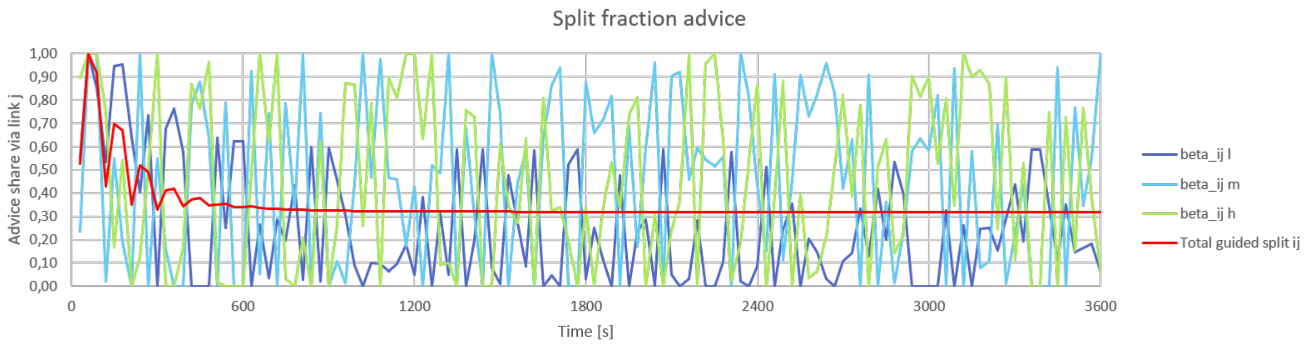

Figure D.27: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.4

Figure D.28: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.1

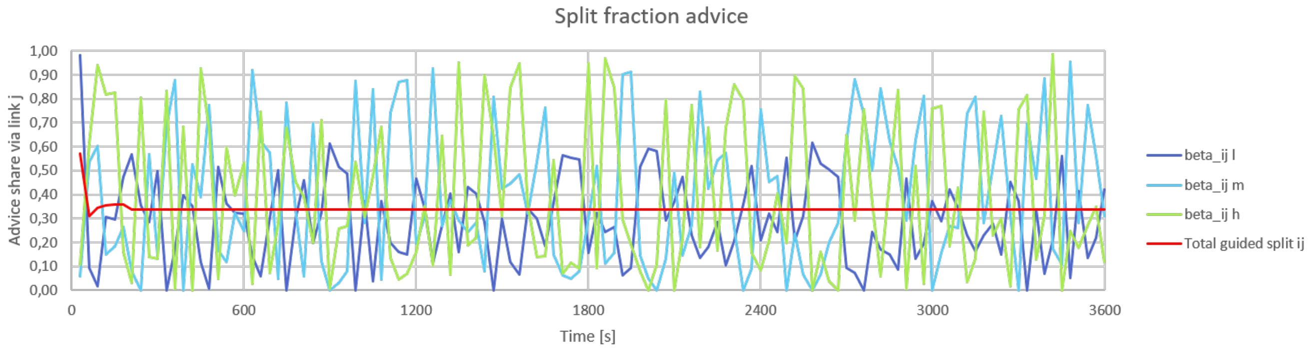

Figure D.29: Split fraction advice towards link j when optimising air quality with a compliance rate of 1

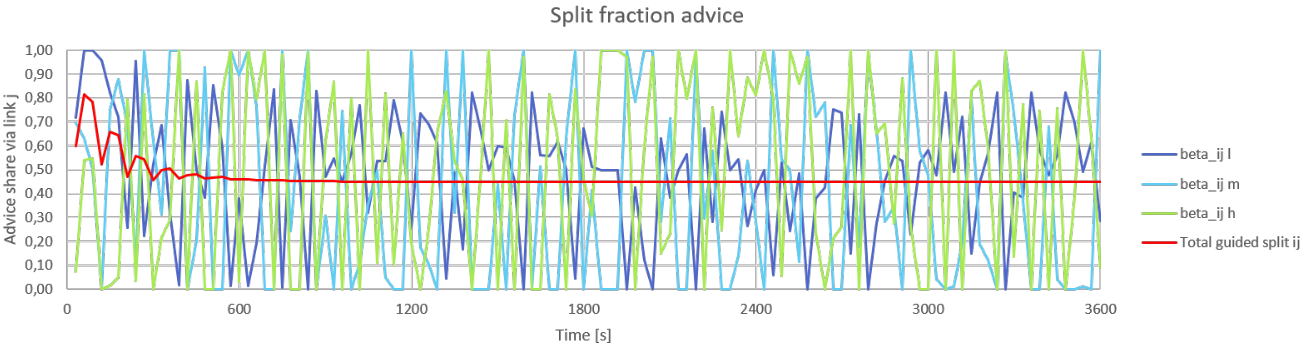

Figure D.30: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.7

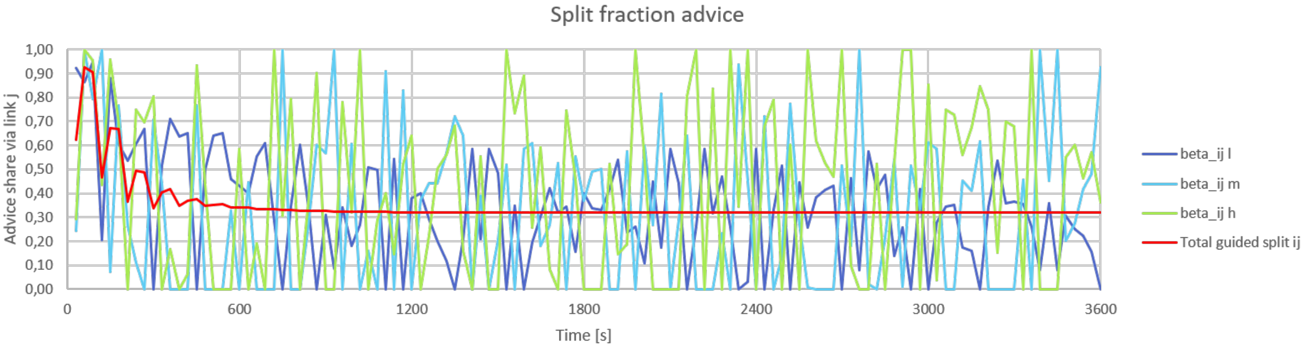

Figure D.31: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4

Figure D.32: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.1

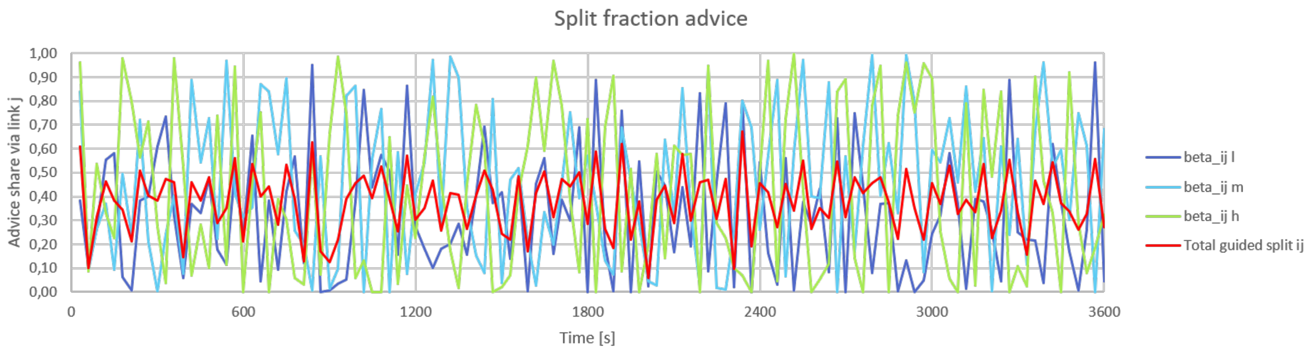

Figure D.33: Split fraction advice towards link j when optimising noise with a compliance rate of 1

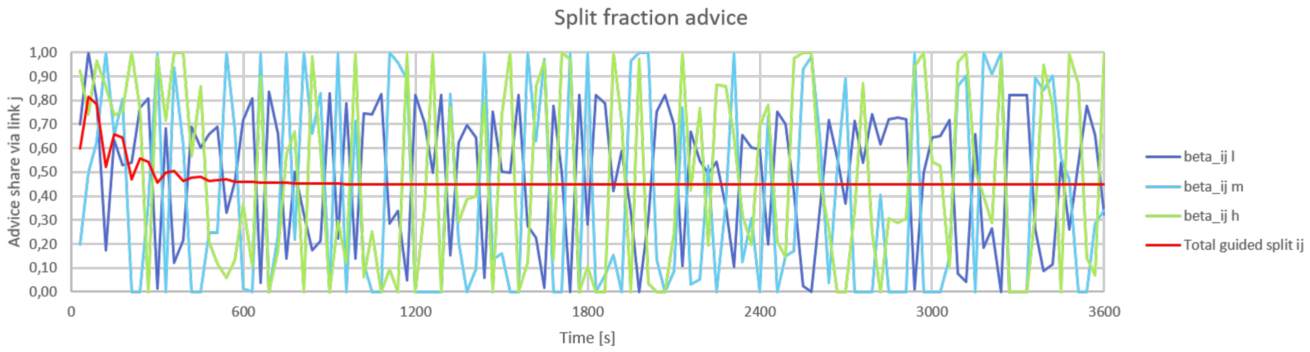

Figure D.34: Split fraction advice towards link j when optimising noise with a compliance rate of 0.7

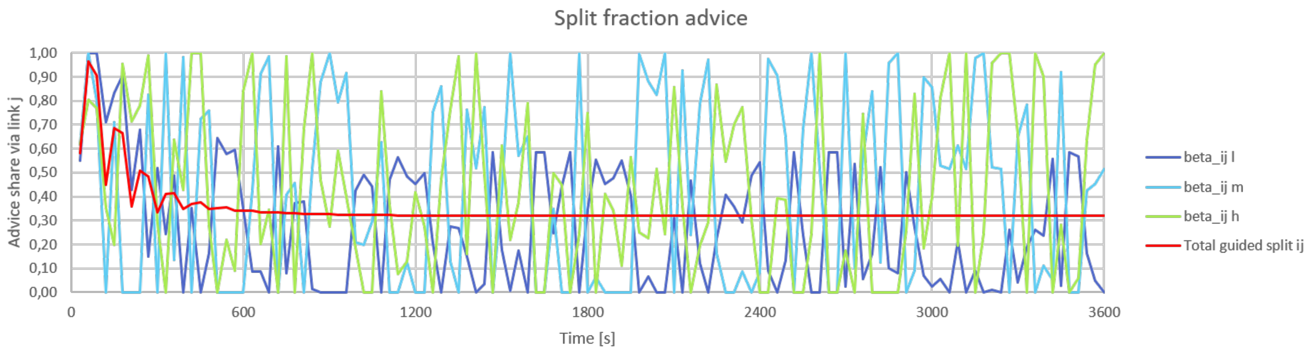

Figure D.35: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4

Figure D.36: Split fraction advice towards link j when optimising noise with a compliance rate of 0.1

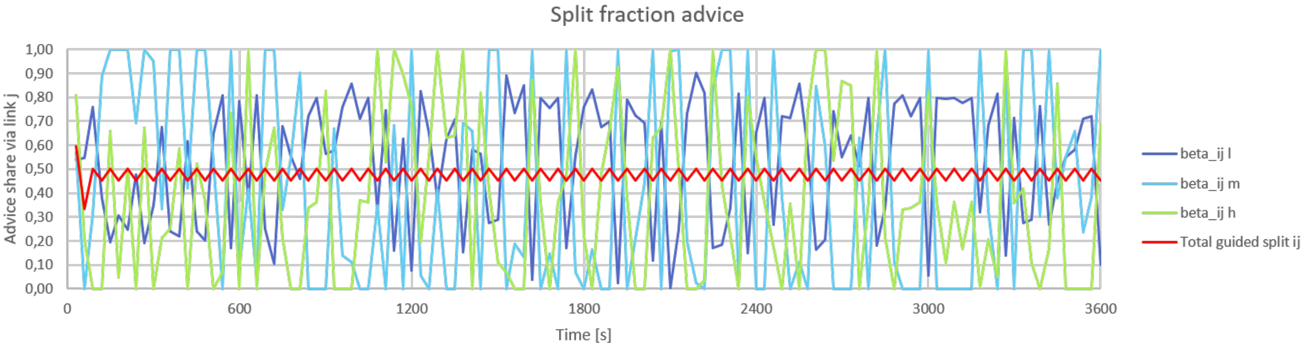

Figure D.37: Split fraction advice towards link j when optimising accident risk with a compliance rate of 1

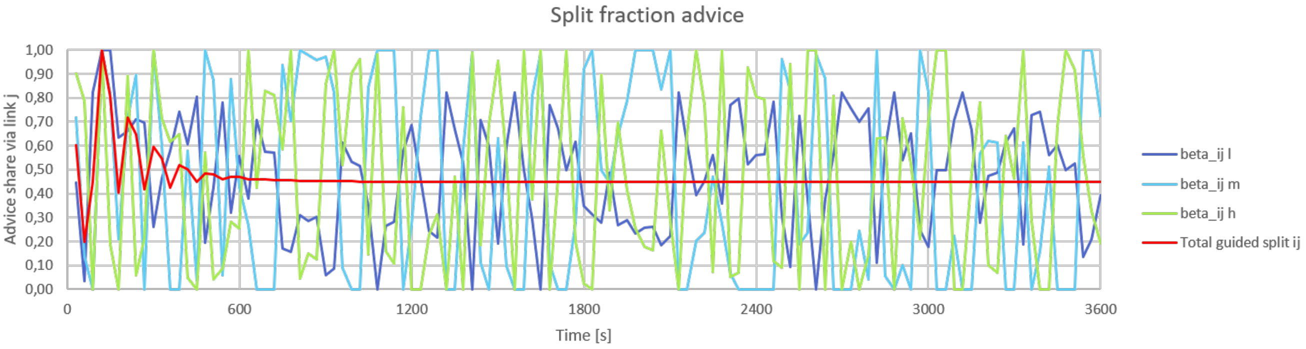

Figure D.38: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.7

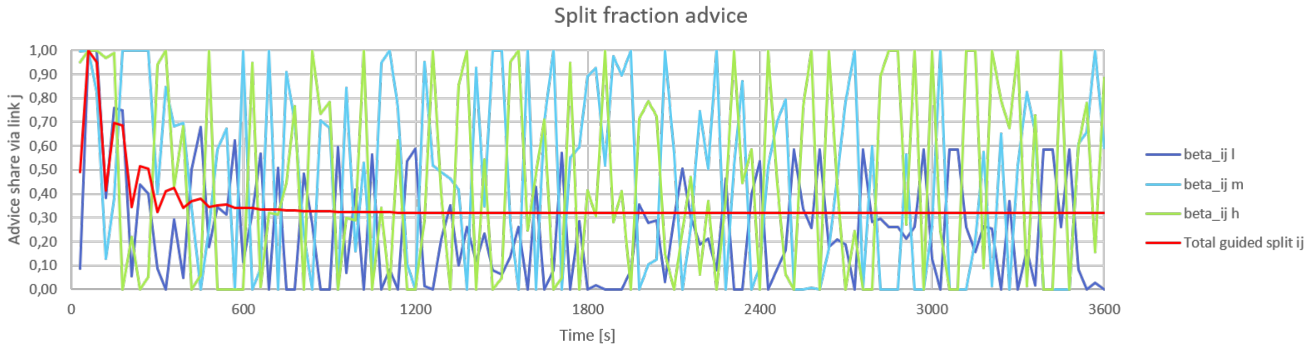

Figure D.39: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4

Figure D.40: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.1

D.3. Restricted for heavy traffic

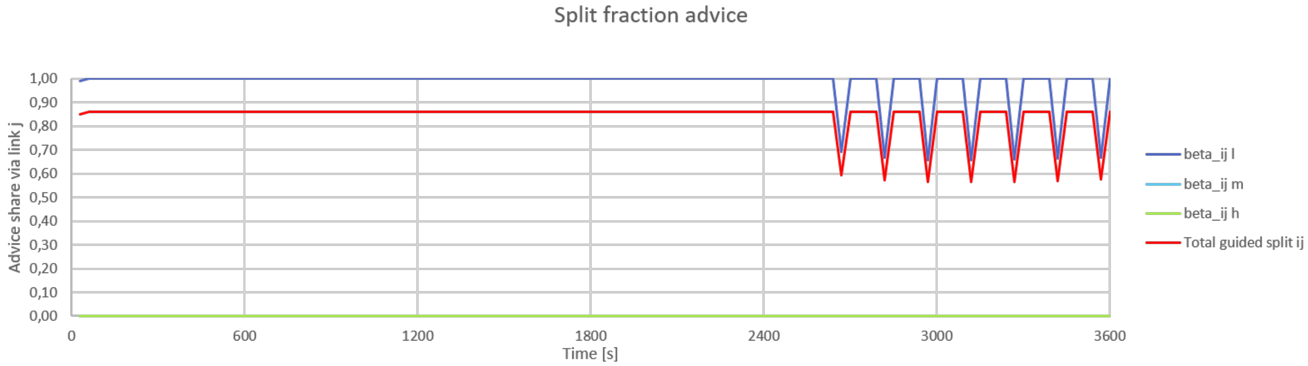

Figure D.41: Split fraction advice towards link j when optimising travel time with a compliance rate of 1

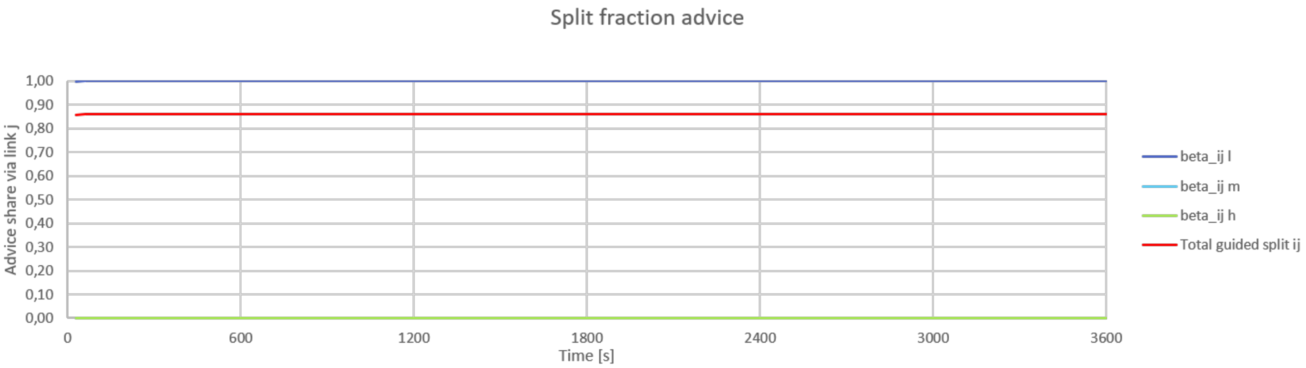

Figure D.42: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.7

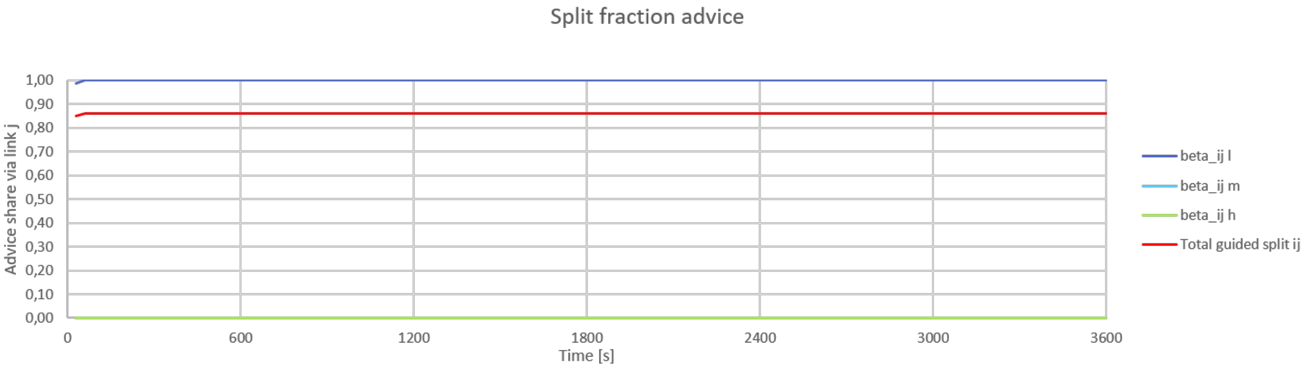

Figure D.43: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.4

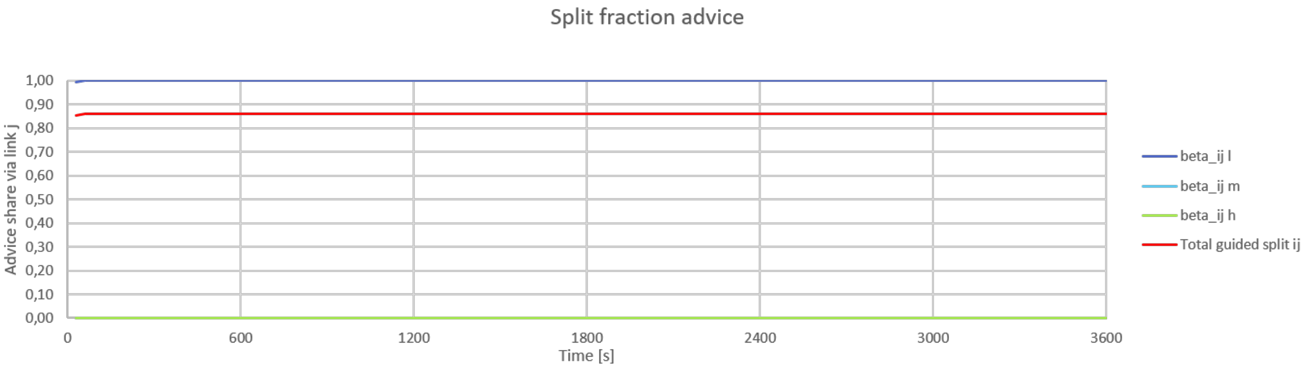

Figure D.44: Split fraction advice towards link j when optimising travel time with a compliance rate of 0.1

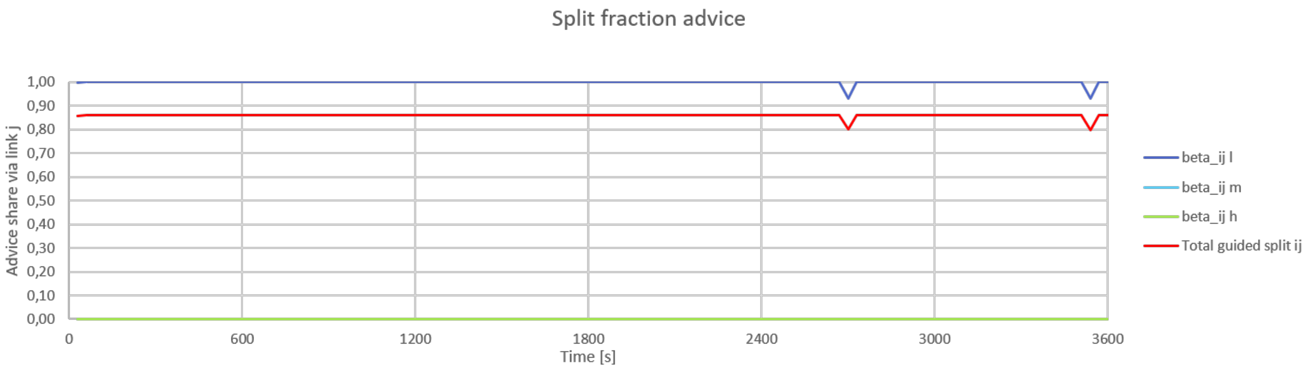

Figure D.45: Split fraction advice towards link j when optimising air quality with a compliance rate of 1

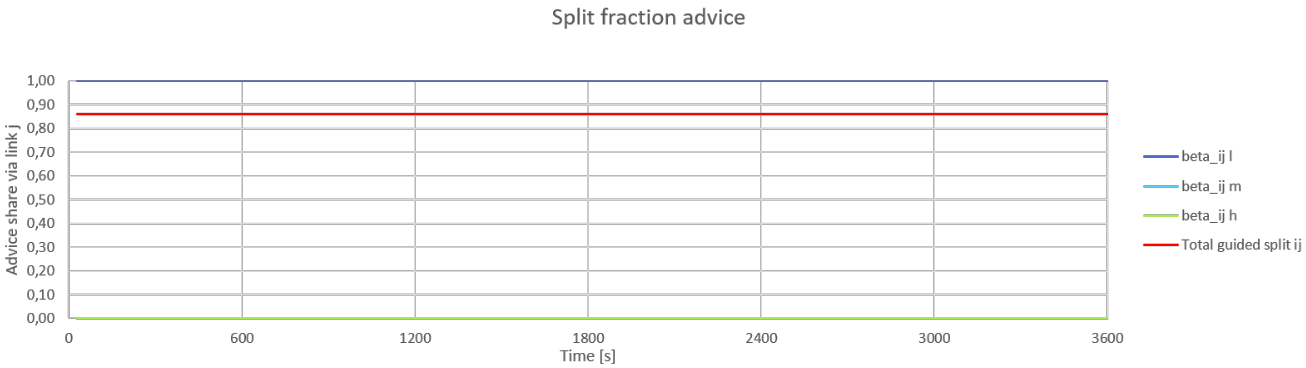

Figure D.46: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.7

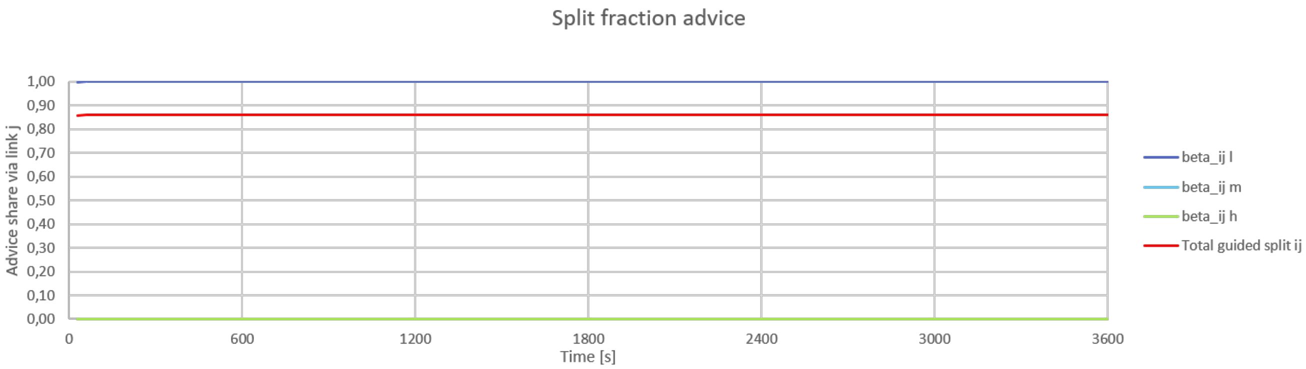

Figure D.47: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.4

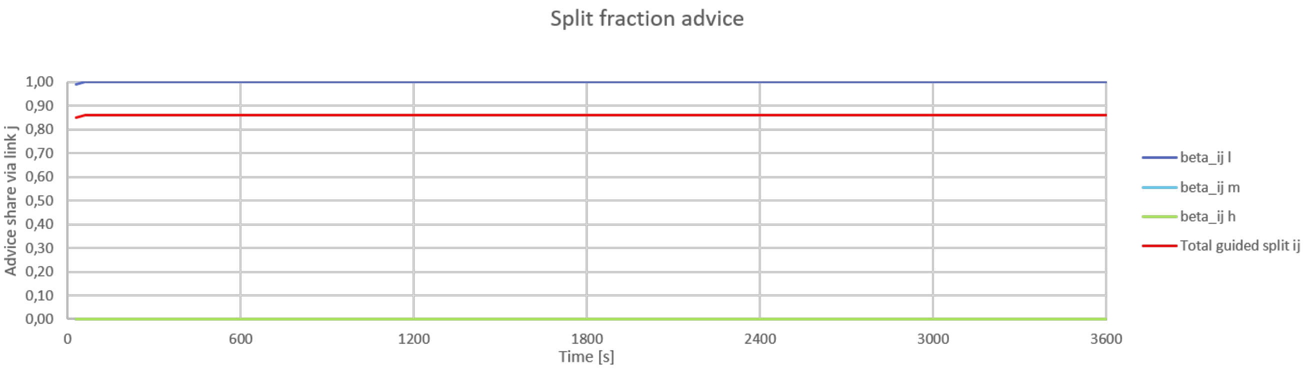

Figure D.48: Split fraction advice towards link j when optimising air quality with a compliance rate of 0.1

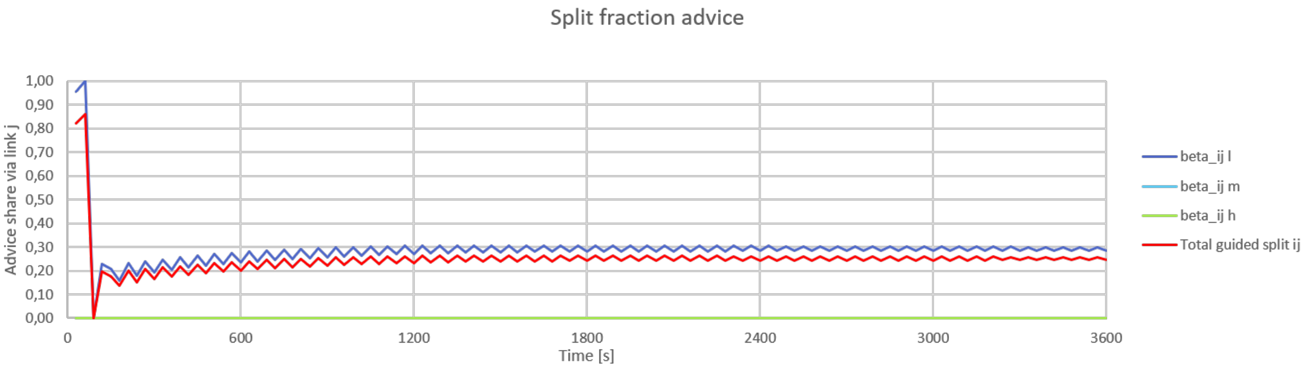

Figure D.49: Split fraction advice towards link j when optimising noise with a compliance rate of 1

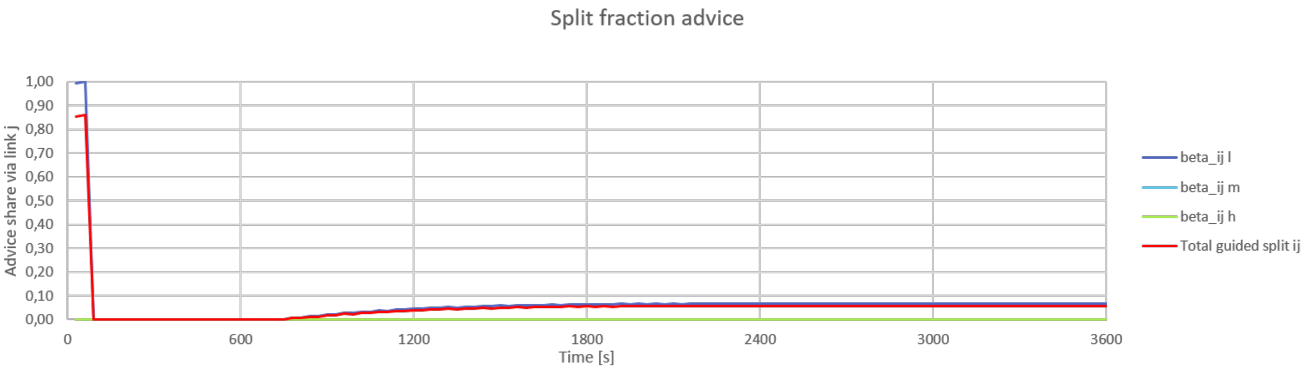

Figure D.50: Split fraction advice towards link j when optimising noise with a compliance rate of 0.7

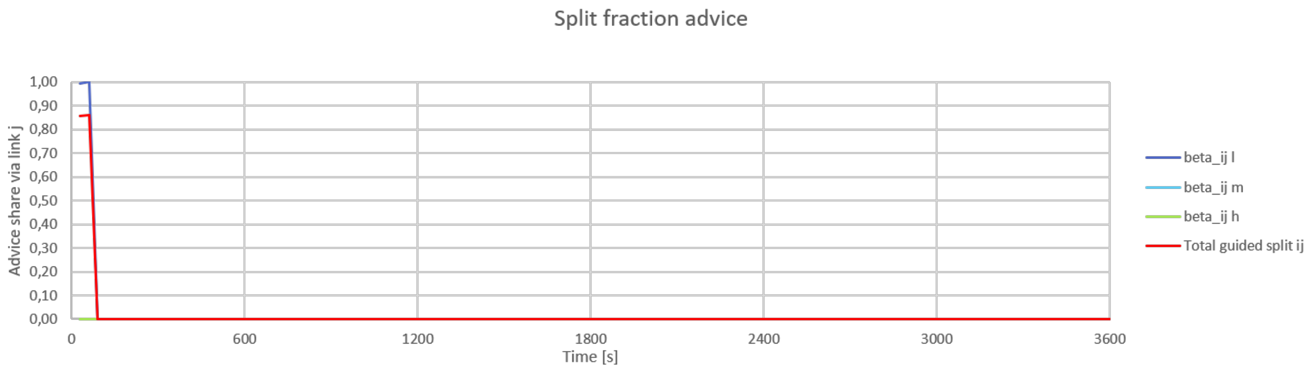

Figure D.51: Split fraction advice towards link j when optimising noise with a compliance rate of 0.4

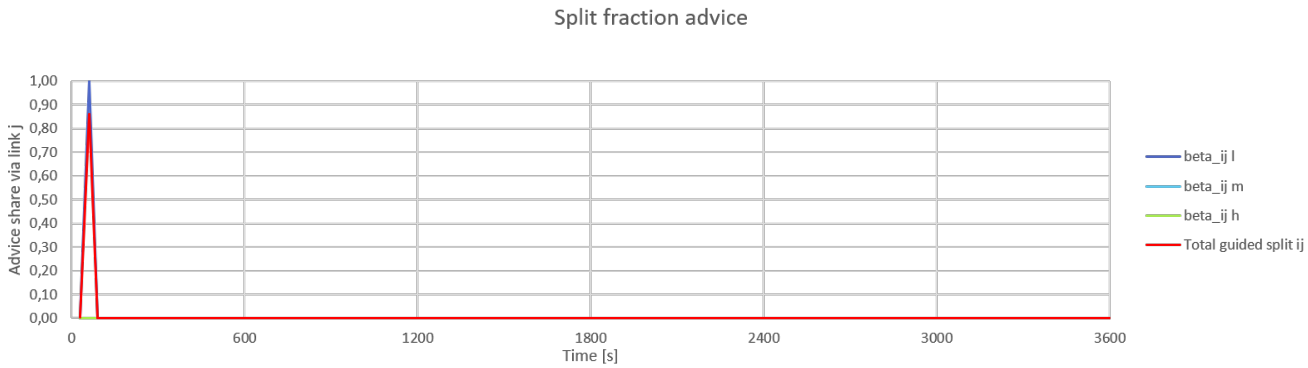

Figure D.52: Split fraction advice towards link j when optimising noise with a compliance rate of 0.1

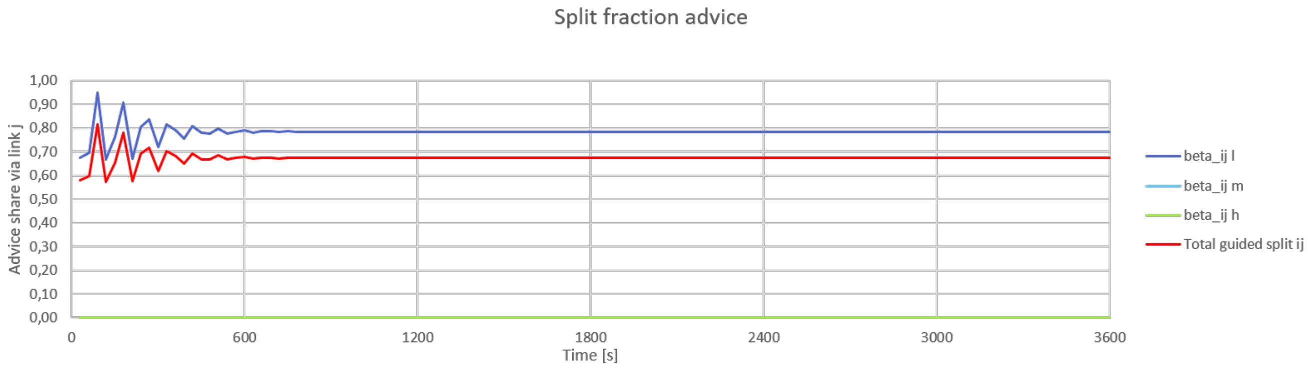

Figure D.53: Split fraction advice towards link j when optimising accident risk with a compliance rate of 1

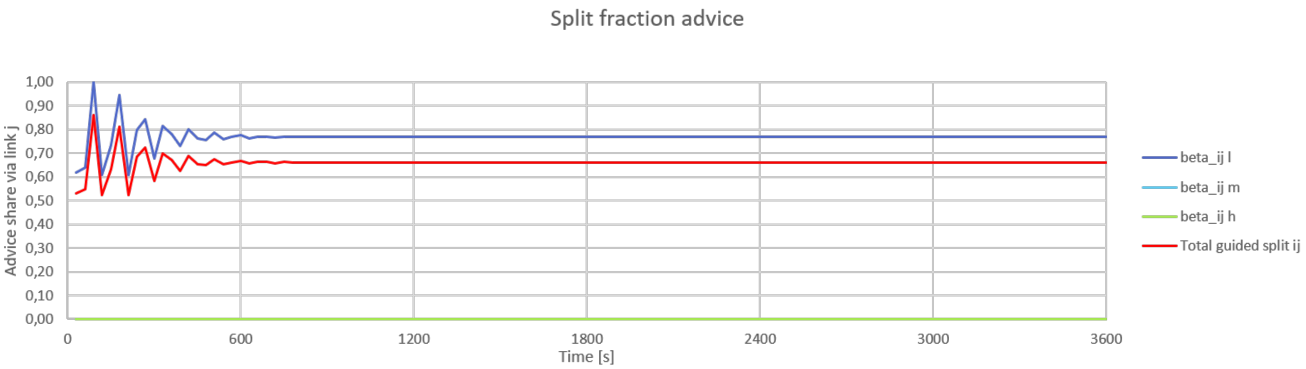

Figure D.54: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.7

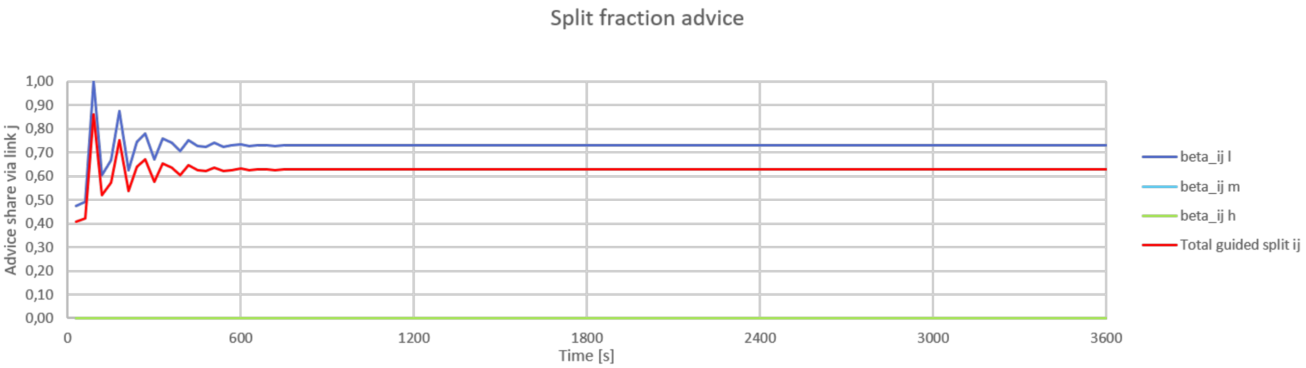

Figure D.55: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.4

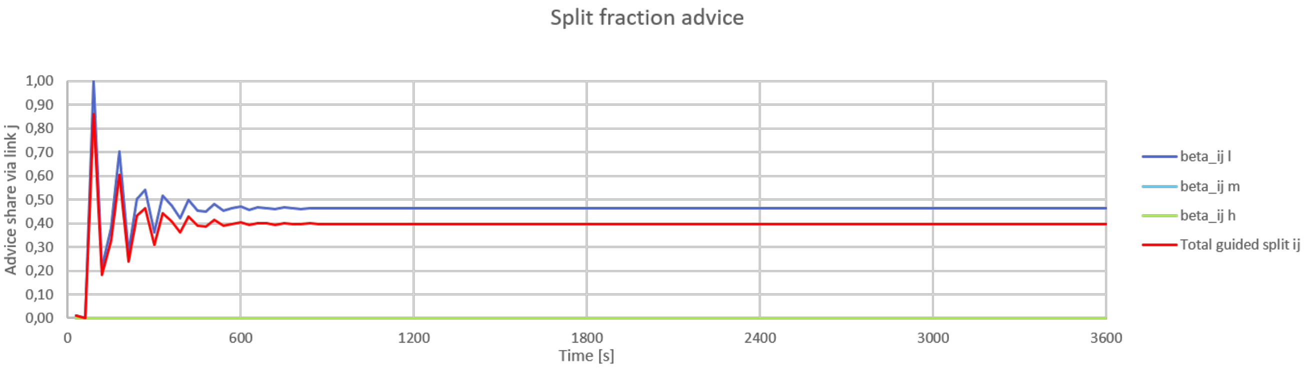

Figure D.56: Split fraction advice towards link j when optimising accident risk with a compliance rate of 0.1