

EXTERNALITIES AS OBJECTIVES FOR DTM SOLVING A DYNAMIC MULTI-OBJECTIVE NETWORK DESIGN PROBLEM

Luc Wismans

University of Twente & Goudappel Coffeng, The Netherlands

Eric van Berkum

University of Twente, The Netherlands

Michiel Bliemer

The University of Sydney Business School, Australia

1. INTRODUCTION

There is an increasing interest in the effects of traffic on externalities. Research has also shown that in many countries the costs of external effects are even larger than the costs of delay. Therefore it can no longer suffice to view a transport system as feasible or optimal if only accessibility is considered. Dynamic traffic management (DTM) measures are often used to improve efficiency only, which means that traditionally the optimization of DTM measures considers the single objective of “improving accessibility”. However, these measures are potentially also powerful instruments to reduce emissions of substances related to air quality and climate, emissions of noise and number of accidents. Because there is a proven relation between traffic dynamics and these externalities, DTM measures can be used on a local level, but can also be used on a network level to influence route choice of road users and therefore influencing to what extent certain roads are used. To assess a certain deployment of DTM measures transport models can be used. Because traffic dynamics are important explanatory variables for these externalities and time dependent DTM measures are considered, the usage of a dynamic traffic assignment (DTA) model to assess a certain deployment of DTM measures is recommended. In addition, a DTA model can be used to overcome the widely recognized limitations of static traffic assignment in particular for oversaturated traffic conditions.

Implementing DTM measures to influence supply of infrastructure is a specific example of a network design problem (NDP). The NDP is typically formulated as a bi-level optimization problem in which the lower level describes the behavior of road users that optimize their own objectives (travel time and travel costs). The upper level consists of the objectives that have to be optimized for solving the NDP. By formulating the optimization of an objective using DTM measures as an NDP the optimal solution results in a DTM strategy comprising the best possible cooperative employment of DTM measures on a network level. However, the presence of multiple conflicting objectives makes the optimization problem interesting and more challenging to solve. Since no single solution can be termed an optimum solution, the resulting multi-objective (MO) NDP resorts to a number of trade-off optimal solutions, known as Pareto optimal solutions. This Pareto optimal set consists of all solutions for which the corresponding objectives cannot be improved for any objective without degradation of another. The Pareto optimal set provides valuable information for the decision making process, e.g. trade-offs between objectives can be determined, which would not have been available if the compensation principle would have been chosen (i.e. solving a single objective NDP with a weighted sum of all objectives). The Pareto optimal set also provides information to what extent the different objectives are aligned or opposed and the optimal designs for the single objectives. In addition, the Pareto optimal set provides valuable

information for research. Knowledge obtained by optimization of realistic cases can be used to attain knowledge about incorporation of externalities as an objective when optimizing traffic systems using DTM measures.

This knowledge on the possible network effects of DTM measures on externalities, the relations between accessibility and these externalities on this level taking, the trade-offs and the consequences of the (simultaneous) optimization of these objectives for a traffic system is limited. The contribution of this paper is providing such knowledge for optimization of DTM measures on a strategic level incorporating externalities as objectives. For this purpose the general relations are discussed as well as the results of a MO optimization (i.e. the Pareto optimal set) of a realistic case. In addition, we solve this highly complex dynamic MO NDP using a DTA model which we connected with externality models which take traffic dynamics into account. To the best of our knowledge the simultaneous optimization of all externalities as a result of actual transport activities using DTM measures taking route choice behavior and traffic dynamics into account has not been addressed earlier as well as the results for a realistic network.

2. NETWORK DESIGN PROBLEM

The NDPs are typically grouped into discrete problems (DNDP), in which the decision variable is a discrete variable (Gao et al., 2005; Poorzahedy and Turnquist, 1982), continuous problems (CNDP), in which is assumed that the decision variable is a continuous variable (Chiou, 2005; Dantzig et al., 1978; Friesz et al., 1993; Meng et al., 2001; Xu et al., 2009, Zhang and Lu, 2007)), and mixed problems, which is a combination of both (Cantarella et al., 2006). Based on demand, NDPs can be grouped into fixed demand (Meng et al. 2001, stochastic demand (Waller and Ziliaskopoulos, 2001; Chen et al, 2010) and (stochastic) elastic demand (Ukkusuri and Patil, 2009). Based on the way time is considered, NDPs can be classified into static, in which stationary travel demand and infrastructure supply is assumed (used in all but one above mentioned studies), or dynamic, which is rarely used (Waller and Ziliaskopoulos, 2001; Brands et al., 2009). Traditionally, the NDP is associated with the minimization of the total travel time using infrastructural investment decisions under a budget constraint. Most of the previous studies consider fixed demand, and use a static user equilibrium to model the lower level.

In most cases, single objective network design problems are studied in which accessibility is optimized, where accessibility is expressed as the total travel time in the traffic network (Zhang and Lu, 2007; Gao et al., 2005). Different studies incorporated the investment costs within the objective function. Chiou (2005), Meng et al. (2001) and Xu et al. (2009) optimized total travel time in which the investment was translated in time using a conversion factor. Or in which travel time is translated into cost (Poorzahedy and Turnquist, 1982; Drezner and Wesolowsky, 2003). Occasionally other costs, like environmental costs (expressed in money) are added to the travel cost (Cantarella et al., 2006; Mathew and Sharma, 2006).

There are also other design variables of networks that can be considered as an NDP. Brands et al. (2009) studied for example optimal tolling and Cantarella et al. (2006) and Cantarella and Vitetta (2006) the optimal signal setting in combination with lane layout. The latter one is related to the NDP which is considered in this paper. Most of this research handles a single objective, minimizing delay in signal timing control (e.g. Cantarella and Vitetta, 2006; Cantarella et al. 2006; Sadabadi et al., 2008; D'Acerno, 2012). In addition, almost all

research is on calculating mutual consistent signal settings by formulating it as a asymmetrical equilibrium assignment problem in which the signal settings are locally optimized and static traffic assignment (STA) is used. However, it is shown that the resulting settings are in general not optimal and therefore performs less than solving a bi-level optimization problem in which the upper level anticipates on the behavior of the lower level (Ceylan and Bell, 2004; Chen and Ben-Akiva, 1998). In addition, Chen and Ben-Akiva (1998) also showed that incorporation of traffic dynamics (i.e. using DTA) results in better solutions than a control strategy based on average traffic flow (i.e. using STA). However, almost all research on this subject also when global optimization is considered still uses STA to model the lower level.

There are less papers that use multiple objective functions in the upper level. Chen et al. (2010) use travel time and construction costs as two separate objective functions and used an evolutionary algorithm. Friesz et al. (1993) focuses on minimizing the transport costs, construction costs, vehicle miles traveled and dwelling units taken for rights-of-way and used a weighted sum approach in combination with simulated annealing. Cantarella and Vitetta (2006) considered travel time, walking time and CO emissions in their optimization using a genetic algorithm. Yin and Lawphongpanich (2006) also used an evolutionary algorithm in combination with a weighted sum approach to optimize the same objectives. Some studies optimize multiple objectives concerning equity and/or robustness (Ukkusuri and Patil, 2009; Sharma et al, 2009; Duthie and Waller, 2008; Santos et al., 2009). Sumalee et al. (2009) optimized road charging design using evolutionary algorithms in which social welfare improvement, revenue generation and equity are considered.

In this research, the optimization problem is also formulated as a NDP in which DTM measures are used to influence supply of infrastructure. Because traffic dynamics are important explanatory variables for the externalities of traffic and DTM measures are modeled as time dependent measures, a dynamic traffic assignment (DTA) model is used to operationalize the lower level. In addition, multiple objectives are of interest, and by not choosing a compensation principle in advance, optimization yields a set of Pareto optimal solutions that provides valuable information. Instead of using static traffic models, focusing on a single objective, we therefore propose a dynamic MO NDP. This MO NDP is used to analyze the outcome of such an optimization to obtain knowledge about the consequences of incorporation of externalities as an objective when optimizing traffic systems using DTM measures.

3. OPTIMIZATION PROBLEM AND FRAMEWORK

The MO optimization problem is formulated as the following MO MPEC (mathematical problem with equilibrium constraints):

$$\min_{S \in F} \begin{pmatrix} z_1(S) \\ z_2(S) \\ \vdots \\ z_I(S) \end{pmatrix}, \quad \text{subject to } (q(S), v(S), k(S)) \in \Gamma^{DTA}(G(N, A(C(S))), D), \quad (1)$$

in which S is a set of applications of strategic DTM measures to be selected from a set of feasible applications F , and $z_i(S)$, $i=1, \dots, I$, is the i^{th} objective function of the link flows $q(S)$, the link speeds $v(S)$, and the link densities, $k(S)$, expressed as $z_i(S) = f_i(q(S), v(S), k(S))$. These objectives in our case concern efficiency, climate, air

quality, traffic safety and noise. Furthermore, the link flows, speeds, and densities are assumed to follow from solving a dynamic user equilibrium problem, indicated by Γ^{DTA} , for which the supply of infrastructure is given by network G with nodes N and links A (with corresponding characteristics C), and the (dynamic) travel demand D . The link characteristics without any DTM measures, which we denote by C_0 , include the outflow capacity, the number of lanes, the free-flow speed, the speed at capacity, and the jam density, and are all captured in a fundamental diagram. The DTA model Streamline (Raadsen et al., 2010), which is a multi class model with physical queuing and spillback, is used to solve for this dynamic user equilibrium. To solve the upper level optimization problem the non-dominating non-dominated sorting genetic algorithm II (NSGA-II) developed by Deb et al. (2002) is used.

The DTM measures defined in S are modeled as measures that influence the characteristics C of the links where the measures are implemented. This means for example that if a Variable Message Sign (VMS) is used to change the speed limit, the free-flow speed and capacity of the links connected with this measure are changed. The characteristics C of links can therefore vary over time depending on the settings of the DTM measures, S . The impact of a measure depends on the actual settings, e.g. the green time for a certain direction on a signalized intersection. Activation times and settings of the DTM measures are discretized, hence the upper level becomes a discrete optimization problem where for each time period a certain DTM measure with a certain setting is implemented or not. The set of feasible solutions, F , is assumed to be a discrete set of possible applications of strategic DTM measures. If we assume that there are B different DTM measures available in the network, the application of the DTM measures in time step t is defined by $S(t) = (s_1(t), \dots, s_B(t))$, where each $s_b(t)$, $b = 1, \dots, B$, can have M_b different settings, which we simply number from 1 to M_b . The set of feasible solutions can therefore be written as $F = \{S \mid s_b(t) \in \{1, \dots, M_b\}, \forall t = 1, \dots, T\}$, such that there are $(\prod_b M_b)^T$ possible solutions. The set of applications of the DTM measures for all time periods is defined by $S = (S(1), \dots, S(T))$ and forms a possible solution for the optimization problem.

4. CASE

4.1 Description of Case

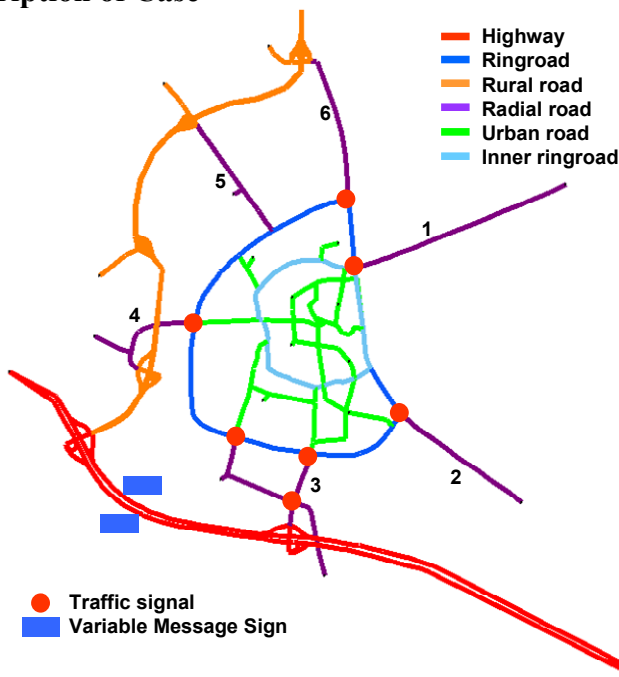


Figure 1. Network Almelo

A case study is used to obtain knowledge on the optimization of externalities using DTM measures. We consider a realistic network of the city of Almelo in the eastern part of the Netherlands, consisting of 636 links, 257 nodes, and a total travel demand of 45,218 vehicles, differentiated between passenger cars and trucks. The model contains the major roads and there are 9 DTM measures available as shown in Figure 1. The model has been extracted from a calibrated larger model of the Twente Region. Each of the seven traffic signals distinguishes nine pre-defined settings and the two variable message signs (to change the speed limit) three different settings. In total six time intervals for the DTM measures are distinguished, equally divided into 30 minute slices. A three-hour morning peak is simulated and the used OD-matrix is manipulated to increase congestion problems to a more challenging level. As a consequence, the feasible set contains 6.36×10^{45} possible solutions.

4.2 Objective Functions

Based on an extensive literature review (Wismans et al., 2011), for each objective i an objective function f_i is defined, where the input stems from the DTA model. Efficiency is defined in terms of the total travel time in the network. Traffic safety is measured in terms of the total number of injury accidents and calculated using a risk based safety model (Jansen, 2005). Climate is represented by the total emission of CO₂ and air quality is defined as the weighted total amount of emissions of NO_x. The emission calculations are based on the ARTEMIS traffic situation based emission model (INFRAS, 2007), which means dependent on the level of service of traffic flows. Finally, noise is calculated as the average weighted sound power level, in which emissions are based on a load and speed dependent emission function (RMV, 2006). The weights of noise emissions and emissions related to air quality depend on the level of urbanization. The objective functions used, which all should be minimized, are listed in Table 1.

Table 1. Overview of measures and objective functions used

<i>Objective</i>	<i>Measure</i>	<i>Remark</i>
Efficiency	Total travel time (h)	Because fixed demand is assumed, minimizing total travel time is equal to minimizing vehicle lost hours.
		$z_1 = \sum_a \sum_t \sum_m \frac{q_{am}(t) \ell_a}{v_{am}(t)} \quad (2)$
Traffic safety	Total number of injury accidents	Calculation based on using the relation between exposure and risk per road type.
		$z_2 = \sum_a \sum_t \sum_m \sum_d q_{am}(t) \delta_{ad} R_{md} \ell_a \quad (3)$
Climate	Total amount of CO ₂ emissions (grams)	Calculation based on traffic situation based emission model ARTEMIS.
		$z_3 = \sum_a \sum_t \sum_m \sum_d q_{am}(t) \delta_{ad} E_{md}^{CO_2}(v_{am}(t)) \ell_a \quad (4)$
Air quality	Weighted total amount of NO _x emissions (grams) Weighted total amount of PM ₁₀ emissions (grams)	Calculation based on a traffic situation based emission model ARTEMIS. Two substances NO _x and PM ₁₀ are assessed.
		$z_4 = \sum_a \sum_t \sum_m \sum_d w_a q_{am}(t) \delta_{ad} E_{md}^{NO_x}(v_{am}(t)) \ell_a \quad (5)$
Noise	Weighted average Sound Power Level at the source (dB(A))	Calculation based on the standard calculation method (RMV) used in the Netherlands.

$$z_5 = 10 \log \left(\frac{\sum_a \sum_w \delta_{aw} \ell_a 10^{\frac{\bar{L}_w - \eta_w}{10}}}{\sum_a \sum_w \delta_{aw} \ell_a} \right), \quad \text{with } \bar{L}_w = 10 \log \left(\frac{\sum_a \sum_t \delta_{aw} \ell_a \Delta t \sum_m 10^{\frac{L_m(v_{am}(t))}{10}}}{T \sum_a \delta_{aw} \ell_a} \right),$$

$$\text{where } L_m(v_{am}(t)) = \alpha_m + \beta_m \log \left(\frac{v_{am}(t)}{v_m^{\text{ref}}} \right) + 10 \log \left(\frac{q_{am}(t)}{v_{am}(t)} \right) \quad (6)$$

with

- z_1 : Objective function efficiency (= total travel time) (h)
- z_2 : Objective function traffic safety (= number of injury accidents)
- z_3 : Objective function climate (= total amount of CO₂ emissions) (grams)
- z_4 : Objective function air quality (= weighted total amount of emissions of substance s) (grams)
- z_5 : Objective function noise (= weighted average sound power level at source) (dB(A))
- $q_{am}(t)$: Vehicle type m inflow to link a at time t (veh)
- $v_{am}(t)$: Average speed of vehicle type m on link a at time t (km/h)
- R_{md} : Injury accident risk of vehicle type m for road type d (injury accidents/(veh*km))
- $E_{md}^{\text{CO}_2}(\cdot)$: CO₂ emission factor of vehicle type m , depending on average speed (grams/(veh*km))
- $E_{md}^{\text{NO}_x}(\cdot)$: Emission factor of NO_x of vehicle type m on road type d , depending on average speed (grams/(veh*km))
- $L_m(\cdot)$: Average sound power level for vehicle type m , depending on the average speed (dB(A))
- \bar{L}_w : Weighted average sound power level on network part with urbanization level w (dB(A))
- ℓ_a : Length of link a (km)
- δ_{ad} : Road type indicator, equals 1 if link a is of road type d , and 0 otherwise
- δ_{aw} : Urbanization level indicator, equals 1 if link a has urbanization level w , and 0 otherwise
- η_w : Correction factor for urbanization level w (dB(A))
- w_a : Level of urbanization around link a
- α_m, β_m : Parameters dependent of vehicle category for noise calculations
- v_m^{ref} : Reference speed dependent of vehicle category

4.3 Analysis

The presented objectives are used to determine optimal settings of the DTM measures and therefore the Pareto optimal set. Within the analysis the final Pareto optimal set provided by the NSGAII algorithm is used. The total number of Pareto optimal solutions is larger, but because of the truncation procedure in the NSGAII algorithm not part of the final set. Based on this Pareto optimal set, the optimal designs for the individual objectives. Additionally, the results are analyzed in more detail. For this purpose parts of the network are distinguished and cluster analysis is used (i.e. k -means clustering). Using cluster analysis the Pareto optimal solutions are clustered in the total objective space (i.e. solutions that perform similar on the different objectives are clustered). Because the Euclidean distance is used within the k -means clustering, the results on the different objectives are normalized by scoring them between 0 and 1 in which 0 represents the minimum score and 1 the maximum score on that objective. In this paper the main findings are presented. An extensive analysis of the outcomes can be found in (Wismans et al., 2012). Based on these results and the general relations, a possible general strategy is formulated.

5. GENERAL RELATION TRAFFIC DYNAMICS AND EXTERNALITIES

The relation between traffic dynamics and the externalities on a local level will be discussed based on the relation between speed and externalities. This relation has been earlier described by one of the authors in Beek et al. (2007). In this paper it is concluded that travel speed seems the connecting factor concerning the effects on accessibility, safety, air quality and

climate and if travel speed can be managed the right way it should be possible to optimize traffic streams.

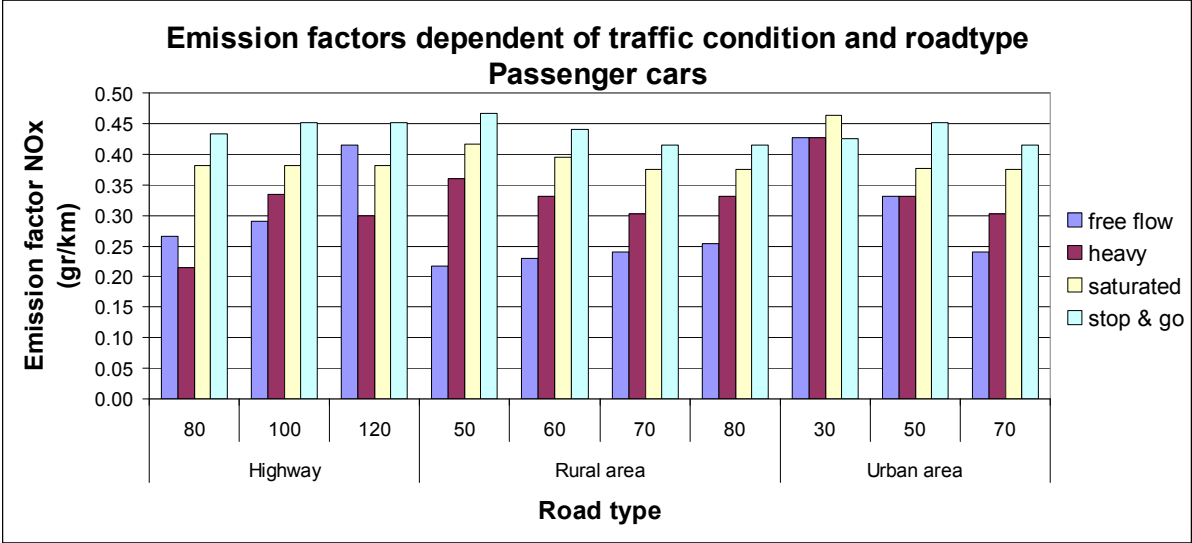


Figure 2. NO_x emission factors dependent of traffic condition

Figure 2 presents the relation between traffic condition and externalities for different road types based on the ARTEMIS emission model. Four different traffic conditions are distinguished and 10 road types. The importance of traffic dynamics is obvious, based on the differences in emission factors dependent of traffic condition. Emissions increase when traffic conditions get saturated and can be higher at high speeds. Similar relations can be found for other substances like PM₁₀ and CO₂. For trucks not presented in this paper the emissions are especially higher for stop & go traffic conditions.

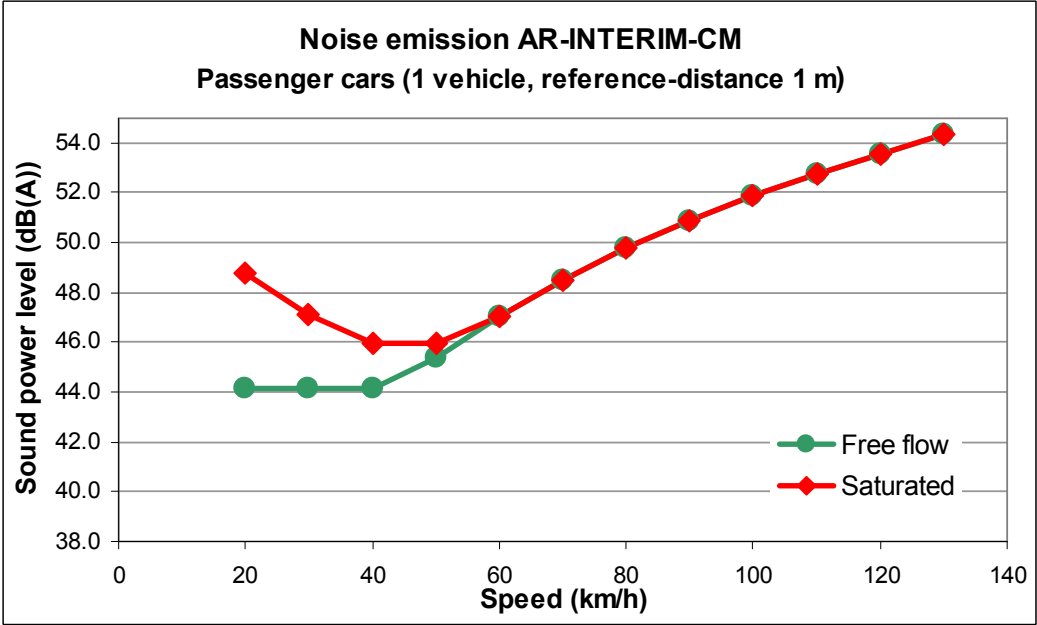


Figure 3. Noise emission dependent of traffic condition

The relation between speed and noise is presented in Figure 3 and based on the AR-INTERIM-CM model (AR-INTERIM-CM, 2003). The figure illustrates that emissions increase in saturated conditions, because of an increase of vehicles accelerating and because

at low speeds the propulsion noise becomes the dominant source for noise. For trucks a similar relation exist, however in this case propulsion noise stays dominant at higher speeds and as a result the emissions for trucks in saturated traffic conditions can be higher than in free flow conditions on highways

Finally, knowledge of the relation between traffic dynamics and traffic safety is less available, especially for urban roads and saturated traffic conditions. It is known, based on risk figures, that there exist relatively safe roads and unsafe roads. It is also known, at least for motorways, that risk increases when speed increases and when speed differences are larger. Unfortunately, there is inconsistency in found effect of congestion on traffic safety (Marchesini and Weijermars, 2010; Aarts and Van Schagen, 2006).

In general efficiency improves when congestion is avoided, which is also better for the emissions of substances. However when the speed is high (approximately above 80 km/h) emissions increase. For noise reducing speed also reduces sound emissions. However, when traffic conditions are saturated, propulsion noise is the dominant source for sound and increases as a result of more accelerations and decelerations. For highways the emission of sound is lower for saturated conditions than free flow conditions, but for urban roads the emissions of sound can be higher in saturated conditions compared to free flow conditions. Avoiding congestion on urban roads can therefore also be relevant to improve noise. For traffic safety the impact of local traffic dynamics is not incorporated in the assessment method, but it is known that higher speeds results in an increase in risk.

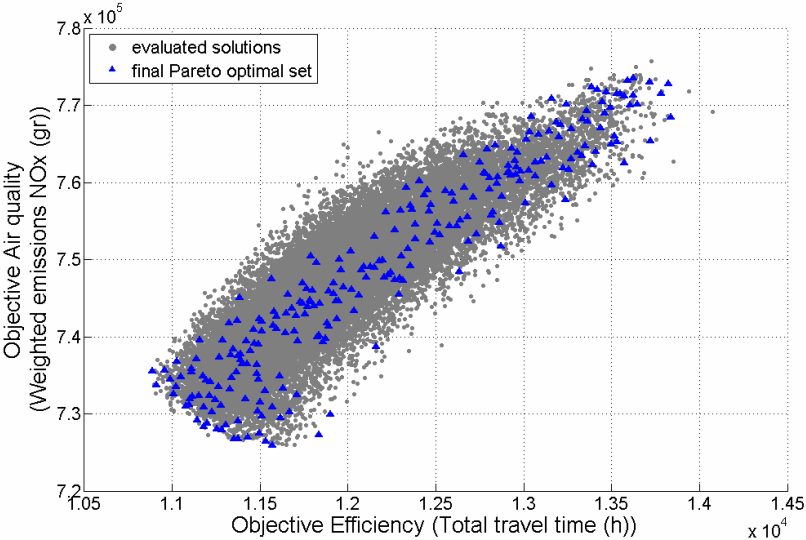
Complexity increases when considering the differences between cars and trucks, especially for externalities but also when taking into account the interaction between these two vehicle classes. For efficiency a high percentage of trucks can increase travel times, because it becomes more difficult to overtake these vehicles but also as a result of shock waves. For the emissions of substances, the relation between traffic dynamics and emissions is similar for trucks as for cars, however the emissions by trucks in absolute values is much higher than for cars (i.e. for CO₂ 5 times higher and for NO_x 25 times higher for free flow, heavy and saturated traffic conditions and for CO₂ 8 times higher and for NO_x even 45 times higher for stop and go conditions). This means that the contribution of trucks in emissions of substances is significant and can be even dominant if it is assumed that the percentage of trucks is on average 10% of traffic. However, higher percentages of trucks can also decrease speeds of cars at highways which can decrease the emissions of cars. Propulsion noise is the dominant source of sound emission of trucks at higher speeds as well (approximately till 80 km/h which in the Netherlands is the maximum speed limit for trucks at highways). As a result sound emissions of trucks in stop and go traffic conditions are higher for highway roads than for free flow conditions. The absolute values of sound emissions are also higher for trucks than for cars (can be 20% higher measured in dB in stop and go traffic conditions and 10% in free flow conditions). However, because noise is measured on a logarithmic scale the influence of trucks on the sound emissions can be large as well (i.e. in sound energy emissions of trucks can be 10 times higher in stop and go traffic conditions). However, in free flow conditions the energy emissions of trucks is 4 times higher. As a result the emission of sound of the combination of trucks and cars is still higher in free flow conditions (assuming a share of 10% trucks) than it is in stop and go traffic conditions. In general, the influence of the percentage of trucks is therefore larger for the emissions of substances than it is for the emissions of sound. For traffic safety less is known about the influence of trucks. It is known that higher percentages of trucks on highways can reduce the number of accidents, however if trucks are involved in accidents the severity of accidents is often higher.

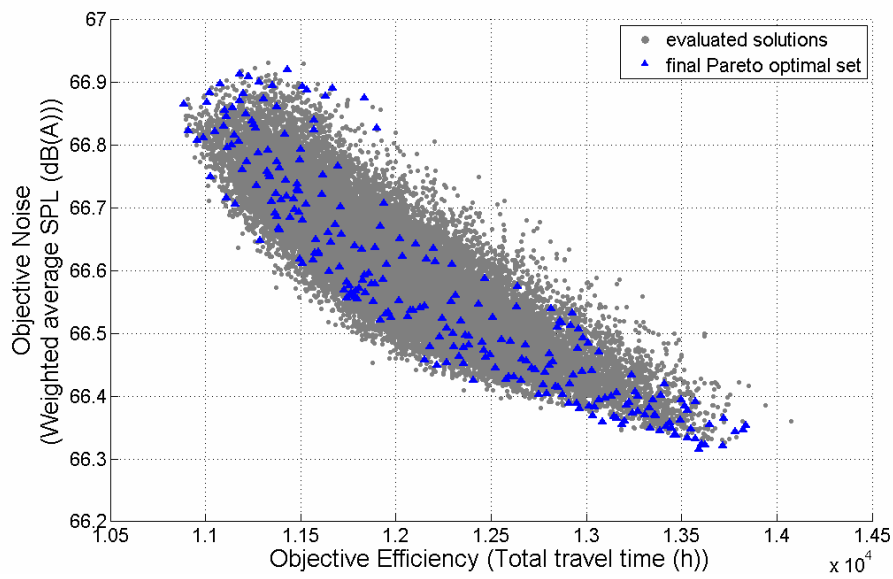
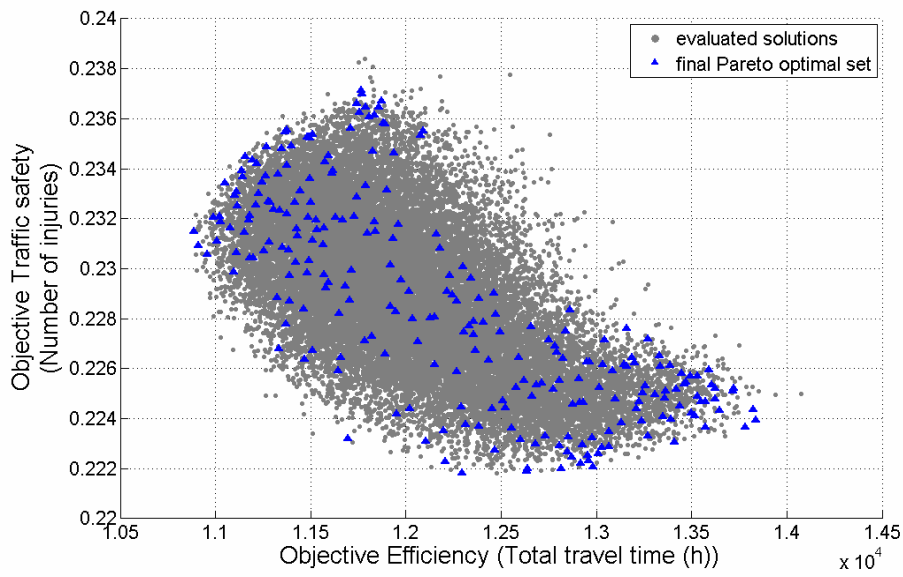
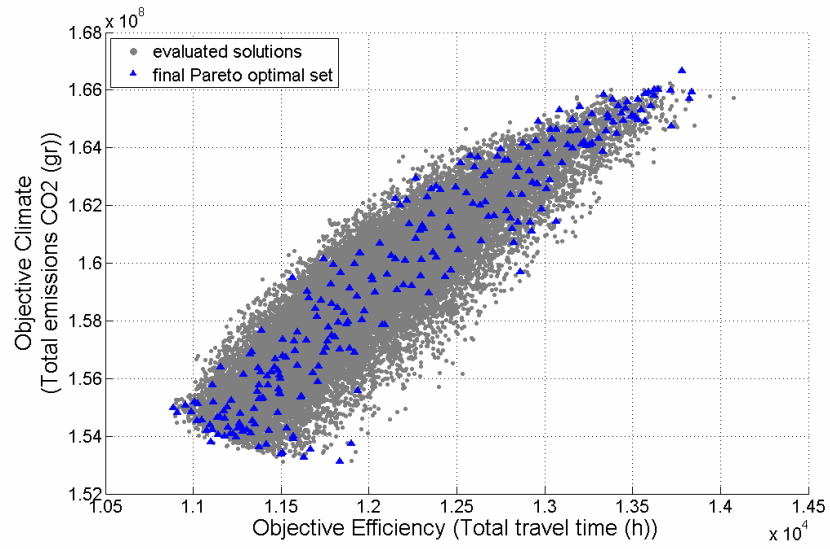
The additional complexity of this research is the incorporation of interaction between links and the route choice effects of a certain deployment of DTM measures. For noise as well as air quality the location of emissions are relevant, because it is important to take into account the number of people which are confronted with these emission. For climate the location is not relevant, because the global emission is important. However, for all three objectives the absolute level of emissions differs per road type or speed limit. For emissions of substances for example the free flow emissions at a 80 km/h road are lower than at 50 km/h road, while for noise emissions it is exactly the other way round. For traffic safety the risk figures differ per road type, which means that there are relatively safe roads and relatively unsafe roads. To be able to seduce traffic using the preferred roads to achieve preferred traffic conditions as well, it is needed to influence the utilities (i.e. travel times) of the various routes using the DTM measures. The case study in which a MO NDP is solved provides insights in how the objectives are related taking into account route choice effects of road users.

5. RESULTS CASE

5.1 Pareto Optimal Solutions

Figure 4 shows all Pareto optimal solutions found in two dimensional plots. Note that these are the resulting Pareto optimal solutions if optimizing efficiency, air quality, climate, traffic safety and noise simultaneously.





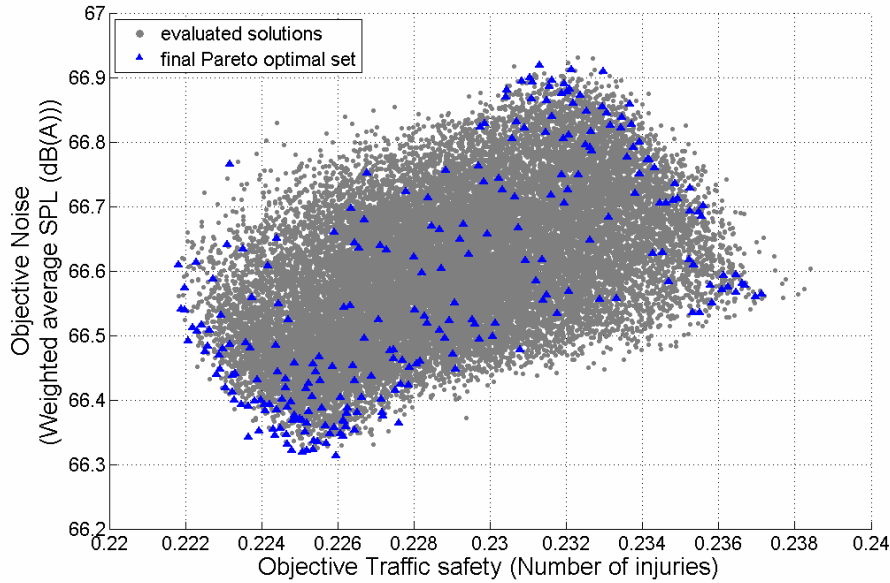


Figure 4. Pareto optimal solutions.

As depicted, the objectives efficiency, climate and air quality are mainly aligned and mainly opposed to traffic safety and noise. The objectives traffic safety and noise are neither aligned, nor opposed. Although there are aligned objectives, this does not mean that there is a single solution which optimizes the three aligned objectives simultaneously. The solution that minimizes NO_x emissions, for example, results in approximately 6% higher total travel time; in vehicle lost hours this is 28%. The solution that minimizes efficiency results in 1.2% more CO_2 emissions compared to the optimal design for climate, which equals 1.3 ton CO_2 emissions. Table 2 presents the interaction between the externalities, in which the columns represent the optimal design for a certain objective and the rows the relative performance per objective compared to the minimum of that objective.

Table 2. Interaction between objective values for optimal designs (Wismans et al., 2012)

	Optimal design for objective				
	Efficiency	Air quality	Climate	Traffic safety	Noise
Efficiency	100.0	106.3	108.7	112.9	124.9
Air quality	101.3	100.0	100.2	103.0	106.5
Climate	101.2	100.5	100.0	104.2	108.4
Traffic safety	104.4	104.4	104.5	100.0	101.9
Noise	100.8	100.8	100.8	100.4	100.0

Analyzing the optimal designs for the different road segments shows that optimizing efficiency aims at avoiding congestion using full capacity of the available routes and trying to assign the available capacity in such a way that also on a local level delay is minimized (distributed over directions). The travel times on the radial roads are in this solution much lower than the other optimal designs. Avoiding congestion is also good for minimizing CO_2 emissions, however, since congestion cannot be avoided, the optimal design for emissions queues certain directions in favor of others and by doing this also avoids detours and congestion on other parts of the network. The queued directions are primarily the directions which do not affect other parts of the network (blocking back) and therefore the optimal design for emissions accepts congestion on specific locations in the network, while efficiency

will distribute the delays more. The same goes for minimizing NO_x emissions, but now the optimal design searches for the best trade-off between minimizing traffic using the urban roads and the rural road and the queued direction is also influenced by the level of urbanization of the upstream links. This means that the concept of metering and using buffers at specific locations can be interesting to reduce emissions. Traffic safety aims at maximizing the use of the relatively safe highway route and avoiding use of the urban routes. Optimizing noise aims at lowering the driving speeds as much as possible and also avoiding traffic using the urban routes. Based on the Pareto optimal set the trade-offs can be determined, which are presented in Wismans et al., 2012.

5.2 Cluster Analysis

The results are also analyzed in more detail using *k*-means clustering. This method is used to divide the solutions in ten clusters. To analyze the outcome of the different clusters on the different objectives, the averages are presented in Figure 5 in which these are normalized between 0 and 100 (i.e. the best scoring cluster on an objective scores 0 on that objective and the worst scoring cluster 100). Cluster 1 scores for example well on efficiency, air quality and climate, but cluster 1 is also the worst cluster for noise and scores low on traffic safety. These results show, as concluded earlier, that the objectives efficiency, air quality and climate are aligned and those are opposed to traffic safety and noise. Due to the used clustering method, the optimal solutions of the aligned objectives are part of the same cluster. However, as shown earlier, the optimal designs are different. Using this cluster data, the average trade-offs between the clusters can be determined. For instance, solutions part of cluster 10 compared with cluster 1 results on average in 20% higher travel time, 5% higher weighted NO_x emissions, 8% higher CO₂ emissions, 3% less injury accidents and 1% less weighted sound power level.

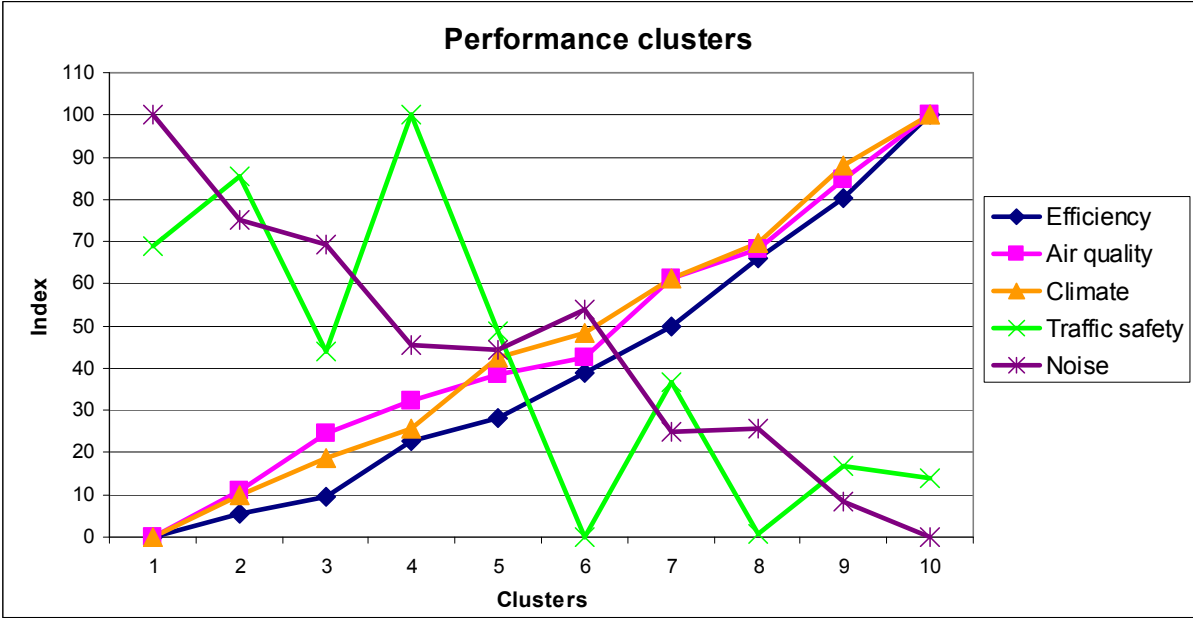


Figure 5. Objective scores clusters

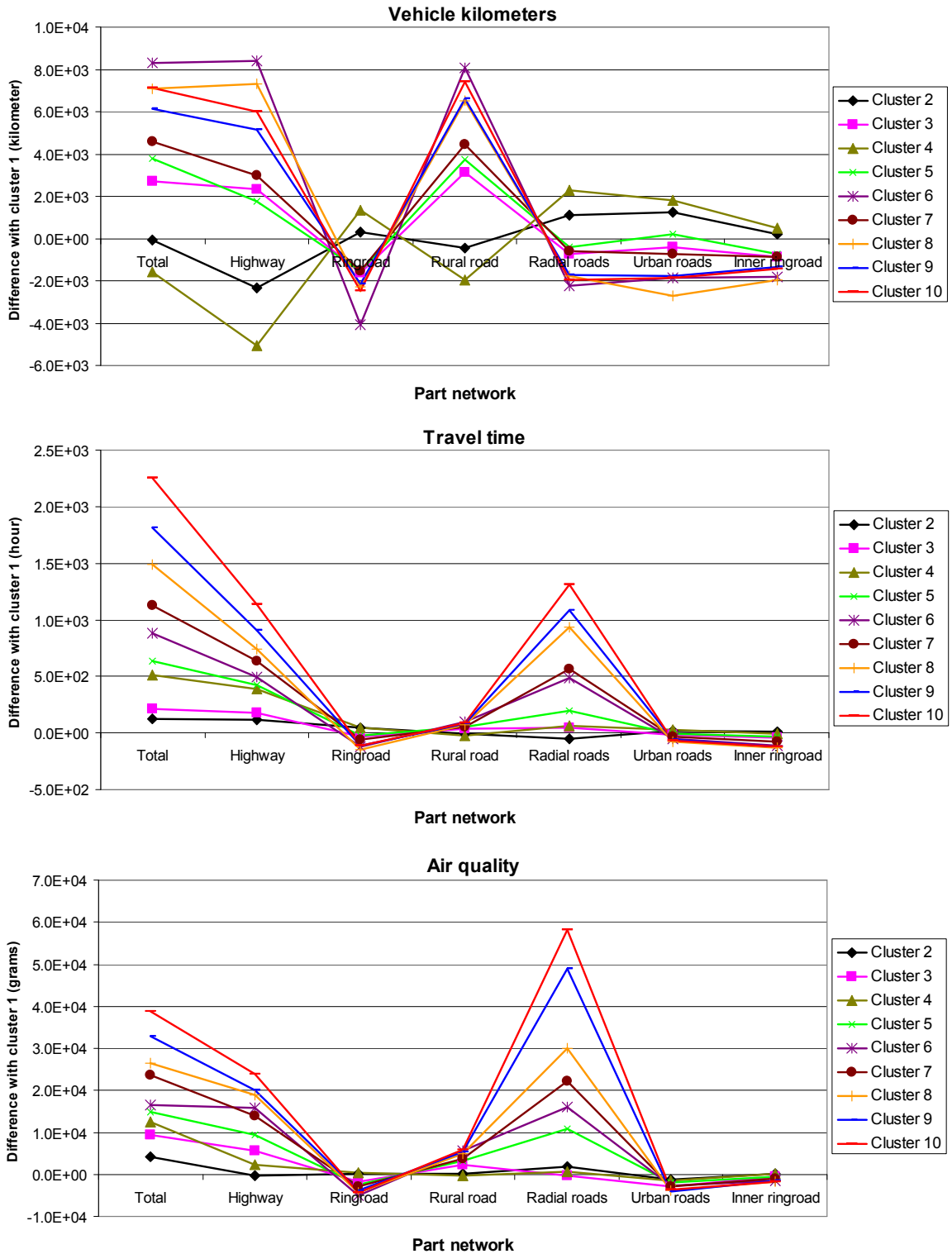


Figure 6. Objectives for different network parts per cluster

Focusing on different parts of the network shows that the relative largest differences for congestion, air quality and climate between the clusters are on the radial roads (see Figure 6). This could partly also be expected because most DTM measures chosen in this case study influence the travel times on these radials. On the highway the relative differences are small, however in absolute figures these differences are large and can substantially influence the total outcome of most objectives. In terms of vehicle kilometers the absolute differences are

largest on the rural roads and highways. The relative differences are large for the ring road, rural roads and urban roads. The results also show that the clusters which perform better on noise and traffic safety show relative higher emissions and travel times on the radial roads and rural road and less on the urban roads and ring road. Within the clusters that perform better on noise and traffic safety the measures available, mainly situated on the ring road, meter traffic on the radial roads improving the level of service on the ring road. As a result more traffic uses the rural road to approach the city on the east side and less traffic is using the urban roads. This also shows that metering and buffering is of interest for air quality, because the clusters in which traffic is metered at the radial roads results in general in less emissions on the urban roads. However, because of the used weighting dependent of urbanization the total emissions can be higher if traffic is metered to much.

Although the Pareto optimal solutions are clustered based on their performance in objective space, there can still be large differences between solutions part of the same clusters. As already mentioned the optimal designs for air quality, climate and efficiency are part of the same cluster. When concentrating on the optimal designs, the deployment of DTM measures differs. For air quality and climate traffic is more often metered to improve travel times on the ringroad, avoiding use of urban roads. However, also between air quality and climate are differences in locations to meter, because for air quality the location of emissions is of importance and weighted within the objective function. Analyzing the results shows that additional criteria like complexity or equity can be of interest to select the solution to implement. Within cluster one there are for example solutions in which delays on certain radials are much higher than others, while in other solutions the delays are more even spread, but still perform similar on the objective functions.

6. CONCLUSIONS

Externalities are of increasing interest when policy decisions regarding traffic and transport are made. Traffic dynamics are important explanatory variables for these externalities. Based on the relation between traffic dynamics and externalities presented in this paper, DTM measures can be powerful measures to improve externalities on a local level. However, deployment of DTM measures in a certain way can result in behavioral responses of which changing routes can be expected. Therefore a case was used in which the optimization of externalities was formulated as a dynamic MO NDP. The test case showed that the objectives efficiency, climate and air quality are mainly aligned and mainly opposed to traffic safety and noise, but there exist not one single solution which optimizes all objectives simultaneously. Therefore compensation principles are needed to determine the best compromise solution. For externalities the concept of metering and buffering traffic is also of interest when route choice effects are taken into account. Given the relations between the objectives and results found in the presented case it is possible to formulate a general strategy which can be used in many cases to reduce externalities. Because highways are often situated in less urbanized area's and are the relative safest roads, a general strategy could be to facilitate traffic on higher order roads possibly decreasing the speed limit and metering and buffering vehicles at smart locations (often at the borders of the urbanized areas), while facilitating traffic in the city avoiding congestion. The metering of traffic should be used to avoid congestion in urban area's and to influence route choice of traffic in such a way that mainly the higher order roads are used. However, where traffic should be exactly metered and buffered and to what extent depends on the routes available, spatial planning and demand in the specific case and can therefore be complex to determine in practice without solving a MO NDP. The solutions which perform similar in objective space can be distinct in solution space (i.e. same outcome

but different solutions). This means that it is possible to address criteria like complexity or equity afterwards to select the best compromise solution to implement.

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