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Toward effective strategies for energy efficient network management

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Abstract—**Trade-offs in efficiency, equity and acceptability arise as a central feature in traffic management. Today's urban traffic network management strategies focus on overall system performance and often overlook the interests of the individual road user. In addition, the emphasis is on travel time savings and scarcely on the environmental impact of traffic. This research contributes to knowledge on the trade-offs between collective and individual interests (multi-level) and accessibility, and the environment (multi-objective). The objective is to integrate these trade-offs in new strategies for energy efficient network management and evaluate these strategies with the ecoAdaptive Balancing and Control application of the eCoMove project. This paper discusses findings from literature review and presents the design of a Ph.D. research.**

I. Introduction

Urban areas suffer from the increasing demand for transportation, i.e. moving people and goods. The performance of the transportation system determines an area's economic and social health. Every year, nearly 1% of the EU's GDP is lost to the European economy as a result of congestion, with risk of social segregation and inequity in mobility, whereas urban traffic is responsible for 40% of CO_2 and 70% of emission of other pollutants that arise from transport [1]. To be effective, urban mobility policies need to be based on an approach which is as integrated as possible, combining the most appropriate responses to each individual problem.

In urban traffic network management, or short: network management, there already has been movement into this direction. Network management aims to optimize the overall performance of a network from a societal perspective rather than solving local problems individually. More specifically it is the execution of a set of functions to control, plan, allocate, deploy, coordinate and monitor the resources of a road network covering a larger area [2]. Network management strategies have proven to make better use of the available road capacity and improve the overall performance. However, measures of effectiveness should not only include the efficiency of the transportation system, but also its equity or fairness, its effect on the environment, and the qualitative experience that users enjoy [3]. So far, these have not been considered in great detail, which leads to multiple dilemmas. For instance, in a dense transportation system it is likely that management strategies are unable to make improvements without making anyone else worse off. On the contrary, it is more probable that they create unfavorable conditions for (certain groups of) individual road users, such as increasing travel time or cost. In the light of utility maximization, that best describes the behavior of an individual road user, this is hard to justify and accept. Therefore network management also receives criticism and leads to unintended side-effects that diminish the initial effects or cause new problems. Besides, network management has particularly focused on the optimization of travel times and delays, and not so much on the environmental effects of urban transportation as new regulation requires. Without consideration of the perspective of individual road users, urban traffic network management strategies risk being ineffective. Especially in case of energy efficient network management, where the trade-off between societal and individual interest is of even greater importance.

This research addresses the equity and acceptability aspects, and the environmental side of network management. The aim of this research is to incorporate user acceptability and optimization of energy use in traffic network management strategies, and evaluate these from an effectiveness perspective. On the objective (system) side, effectiveness is described by efficiency, while on the subjective (user) side it is described by quality indicators. It is research on the intersection of engineering, economics and social sciences, where trade-offs in efficiency, equity and acceptability arise as a central feature. The main questions of research are concerned with the integration of these trade-offs and consideration of both the collective and the individual interests in the definition of management strategies. This research is linked to the European research project eCoMove that aims to reduce the overall fuel consumption in traffic by 20 percent by means of energy efficient driving behavior and energy efficient traffic management and control [4]. Much of the actions and criteria of the strategies will be derived from the eCoMove project as described in Section V.

This paper is written at an early stage of the research with the intention to present the research design and explain the key concepts based on findings in literature. Section II elaborates on traffic network management and its effects. Factors of importance to equity and acceptability are presented in Section III, while behavioral response is discussed in Section IV. The research design, the relation

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with the eCoMove project and the expectations are presented in Section V. Section VI concludes.

II. TRAFFIC NETWORK MANAGEMENT

A. Equilibrium Theory

The aim of network management is to balance three optima: the user optimum, the system optimum and the societal optimum [5]. In a user optimum each individual road user aims to increase its own utility, like minimum travel time or minimum travel cost. In case of a user optimum the travel times of all routes used are equal or less than those which would be experienced by a single vehicle on any unused route (Wardrop's 1st principle) [6]. This state is also referred to as user equilibrium (UE). In other words, no single road user can increase its own utility by changing route. In a system optimum (SO) road operators aim to optimize the use of the available road capacity. In case of such optimum the average or network travel time is minimal (Wardrop's 2nd principle) [6]. In a societal optimum, also other constraints are considered like livability, traffic safety and economic and spatial development. Although these are all optima that may exist in one system, their outcomes can be very different. A societal optimum for instance not necessarily leads to a system optimum, a system optimum may be unfavorable for individual road users (user optimum) while a user optimum does not always optimize overall performance. Game theory is often used to understand and describe travel behavior in equilibrium situations. One of the best known examples is the Prisoner's dilemma that demonstrates why two people might not cooperate even if it is in both interests to do so. The notion of this dilemma plays an important role in the trade-offs which are discussed in this paper.

B. Network Design Problem

Optimization of the transportation system and convergence to an equilibrium state is an iterative process and can be described as a bi-level network design problem [7]. Behavior of travelers plays an important role in this process, which is presented schematically in Figure 1.

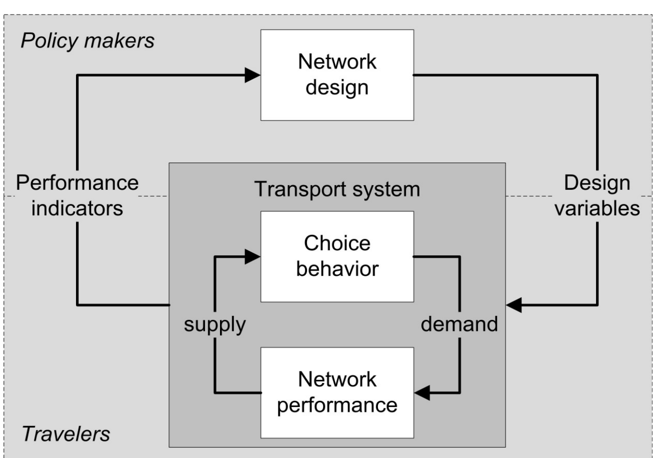

Fig. 1. Schematic representation of a bi-level network design problem. It is an iterative process in which the network design affects the system performance, which affects a traveler's choice behavior and vice versa [7].

The transportation system is a market place where the demand and supply for transport find a balance. The network design, which represents the road network and traffic management strategies to control traffic, as set by policy makers and road operators, has an effect on the transportation system. In response to changes in the performance of the transportation system travelers might change their behavior as other destinations, routes or modes may have become more attractive. According to Wardrop's first principle travelers are likely to adapt their choice when a better alternative is available. In return, the performance of the transport system changes again, which might require redesigning the road network to satisfy policy objectives.

Ideally, changes in travel behavior should already be considered when a traffic management strategy is defined. For instance, [8] proposed a game-theoretical approach for anticipatory control and studied a case of signal control combined with ramp metering. In this case, anticipation on the behavior of travelers significantly improved equity in the network and decreased the total delay with up to 40%. Knowledge is missing whether and to what extend travelers are actually able to recognize changes in network performance. For instance in traffic light control, a decrease in delay of about 10% is regarded as very beneficial. However, this 10% may be equal to less than 3 seconds, which is hardly impossible to observe while traveling. More research is needed on this topic.

C. Mathematical approaches

Equilibrium theory and the network design problem have been thoroughly studied as a mathematically using traffic assignment and equilibrium models [9-11]. Key aspects are: existence and uniqueness of an optimum, convergence to a solution, and stability of the equilibrium. The complexity and computational effort significantly increases when dynamic and stochastic attributes as well as user-heterogeneity and multiple objectives are considered [12-13].

Traffic assignment approaches are based on assumptions for driver preferences and system-level objectives. While 'equilibrium' solutions often satisfy supply-side (system) objectives, there is little evidence that expectations of individual drivers are met [14]. The challenge is to find and implement solutions that achieve an efficient reallocation of network capacity over time and space without seriously violating any individual user's preferences for mode, route, and departure and/or arrival time. Multi-agent systems have been proposed to steer drivers towards paths that will satisfy their individual needs while also improving overall network performance as a result of negotiation [14-16]. This approach presumes cooperation, which is not naturally present in reality as indicated in the previous section. Contrarily, a phenomenon called the price of anarchy describes the degradation in network performance caused by selfish behavior of non-cooperative network users. It is defined as the ratio between system cost in user equilibrium and system cost in system optimum which is proven to be bounded [17] and independent of the network topology [18]. The inefficiency of user equilibriums is underlined by

Braess' paradox which shows that an extension of the road network may cause a redistribution of traffic which results in longer individual running times [19-20]. This is similar to the rebound effect [21] which occurs when a roadway improvement increases travel speed, therefore attracts more traffic which diminish the improvement.

A disadvantage of the mathematical models that are used to study equilibrium problems is that they presume ideal conditions which do not reflect the real world realistically. Especially the human component, the traveler and its behavior, is not represented well enough in many studies. There is a need for research that is more focused on practical operations and on the traveler's perceptive.

D. Evaluation of effects

Evaluation studies of urban road network traffic management strategies mostly focuses on network and route (group) effects and less on local (individual) effects [22]. In addition, the emphasis is more on accessibility indicators and less on traffic safety, livability and road user behavior. In practice, engineers, economists, managers and planners appear to be primarily concerned with public (i.e. system) interest. These professions generally take the viewpoint of the 'objective' central planner measuring mobility, utility, productivity and accessibility respectively, rather than the 'subjective' perspective of the traveler [3]. As pointed out before, there is not enough knowledge on how to combine both the objective and subjective views in one strategy. [23] points out the risk that not knowing the exact effects of a measure in a complex environment, that is difficult to manage let alone control, likely leads to disproportionate and unintended behavioral changes when the measure is implemented.

For a more empirical look on the matter, evaluation studies of three adaptive urban traffic light control systems have been analyzed. All three UTOPIA [24], BALANCE [25] and MOTION [26] claim to combine network optimization with flexible local traffic light control to balance collective and individual interests. However, a look at the evaluation studies confirms that emphasize is on overall performance with little interest in possible negative side effects locally or for specific groups of individuals. When the local effects were determined they were not considered relevant although the possibility of rebound effects was not analyzed. In these three cases, figures from simulation and floating car data illustrate that network control improves the overall network performance with roughly 15%, but that for certain road users, depending on direction, route and class, the average delay increases with 78% as well. In an extreme case, a case of buffering on the edge of the network, the delay even increased with 281%. In the light of effectiveness such effects are hard to accept.

More experience with balancing needs exists in ramp metering [27] and road pricing [28]. In particular the latter is very sensitive to political attractiveness and public acceptability. Based on theoretical literature and empirical findings there is consensus in both fields that equity issues can be addressed. However, it is critical to have a good understanding of the strategies that are being debated and a precise definition of equity. Equity in relation to acceptability is discussed in Section III. In addition, information provisioning to travelers can significantly contribute to the acceptability of a strategy, but also raises new questions about the content, format, timing and goal of information [29]. Section IV discusses information provisioning in relation to behavioral response.

III. EQUITY AND ACCEPTABILITY

In line with the previous sections it is argued that different (groups of) users are not treated equally when looking at today's network operation [30]. Studies showed that process and distributive justice (equity), the extent to which various groups are affected by transport policies, is closely related to acceptability judgment. They affect to what extend policies are perceived to be fair [31]. Many studies conclude that perceived fairness is of crucial importance of policy acceptability. To solve the equity versus efficiency problem it has to be recognized that in complex, politically driven, mature systems like transportation, *equity is efficiency* [28]. Although each study defines equity differently, two main categories of equity can be distinguished [28]. Opportunity equity; the extent to which processes are fair, and outcome equity; the extent to which consequences are justifiable. The second category can again be sub-divided:

- Horizontal equity: the extent to which individuals in a class are treated similarly.
- Vertical equity: the extent to which member of different classes are treated similarly.
- Spatial equity: the extent to which benefits and costs are distributed equally over space.
- Temporal equity: the extent to which benefits and costs are distributed equally over time.
- Market equity: the extent to which benefit received is proportional to the price paid.
- Social equity: the extent to which allocation is proportionate to need.

For this research, spatial and market equity are selected. Spatial equity to reflect effects on individuals grouped by their location (e.g. origin, zone, route or link), and market equity as an indicator for fairness and acceptability.

As mentioned in Section I, traffic management in today's traffic system is likely to create both winners and losers. Therefore it is a game of give and take, which provided travelers with a dilemma. The conflict between individual and collective interests, that the demand for travel poses, can be typified as a commons or social dilemma [28] [32]. In a commons dilemma, people are tempted to act in their own interest in favor of the benefits, especially because individual contributions to mobility problems and their solutions seem futile. Paradoxically, this attitude has a negative impact on accessibility; the ability to reach places.

However, people do not always behave selfish. Theories exist, that explain why people make (short-term) sacrifices in order to safeguard collective interests such as the norm activation theory [31]. This theory was originally developed to explain altruistic behavior and has been applied to describe psychological processes that induce pro-environmental behavior [33]. According to this theory, behavior occurs in response to personal norms that are activated when individuals are aware of adverse consequences to others, or the environment and when they think they can adverse these consequences [31]. This suggests that environmental behavior results from personal norm; a feeling of moral obligation to act pro-environmentally. Various studies have revealed that this intrinsic motivation to contribute to solutions caused by car use, more strongly affects behavior than do structural strategies such as monetary incentives [31]. Analysis of altruistic behavior in a simulation study and travel feedback program showed that social or pro-environmental behavior has positive effect on both travel time and fuel consumption [34], but that a lack of suitable information on the traveler-side hinders the ability to actually act pro-environmentally [33]. However, even with information it is uncertain if travelers are able to recognize what is best and make a good decision. As stimuli do seem appropriate here, more research is needed, especially on the use of non-monetary stimuli.

IV. BEHAVIORAL RESPONSE

As demonstrated by means of the network design problem, transport policies may lead to various types of change, such as changes in driving behavior, travel behavior, vehicle ownership and location choice [31]. Driving behavior refers to factors related to driving style such as speed, use of brakes and changing gears. Travel behavior can best be explained with the classic four-stage transport model that is often used in traffic science to model and predict traffic flows [7]. The four stages are: trip production and attraction (what to do?), trip distribution (where to do it?), modal split (what mode to use to get there?) and traffic assignment (what route to take?). Travelers have to makes choices in each of these steps, which can change according to transport policies. For instance, travelers can decide to change their route, their destination choice, their mode choice, their departure time, the trip frequency or decide to combine trips. More rigorous are changes in vehicle ownership (also type) and location choice (residence and work), which are long term decisions.

Various studies acknowledge that car use and related driving and travel behavior is to a large extent habitual [32]. It means that automated cognitive processes take control and people will no longer make conscious decisions, but choose the same alternative again and again without even thinking about it [35]. This is a valuable insight to understand if and to what extend travelers are able to recognize and respond to changes in the network performance. In many cases the set of choice alternatives will not be changed, but when circumstances have changed (the performance of the transportation system) habits may not always yield optimal outcomes. To better understand this phenomenon, [36] studied the underlying cognitive mechanisms that lead to the choice strategies used by travelers. Verbal expressions collected in the course of route choice suggest that travelers consider at least four decision strategies:

- Comparison strategy, consisting in the comparison of travel times expected on alternative routes and choice of the route with the lowest value.
- Exploitation strategy, consisting in the habitual choice of one route.
- Exploration strategy, consisting in a random route switching, motivated by the search for updated information about travel times on other routes.
- Anticipation strategy, consisting in the anticipation of other drivers' choices and the choice of routes, expected to be preferred by the minority.

Based on the analysis of the expressions it was concluded that great diversity in observed behavior is caused by diversity in individual applied choice strategies [36]. However, a closer look at the results seems to reveal more. Obviously, the comparison strategy is used most, as travelers initially try to minimize their travel time. Surprisingly, in contrast with [32] the results also show that the exploitation strategy, which is based on habitual choice, is chosen the least. This suggests that travelers also act strategically rather than without thinking.

Strategic behavior is studied in more detail by [37] based on a stated preference survey also including risk attitudes. Strategic was defined as: "accounting for the future availability of information and for any detours that might be taken based on such information". Confronting subjects with deterministic and risky stochastic travel times and real-time information en-route, they found that only 15.8% of observations could be categorized as non-strategic, whereas 64% as strategic. Analysis of risk attitudes showed that subjects were more risk-prone when the probability of delay on the stochastic alternative (and thus the reliability) increased. From the above, it can be concluded that travel behavior in essence is habitual, but in general dominated by strategic aspirations of travelers. Nevertheless, risk is generally avoided and the more reliable alternatives are favored.

Although strategic thinking indicates that travelers compare the available choice alternatives, it does not mean that they will actually adapt their choice. This notion is referred to as indifference bands of schedule delay [38]. According to this principle, a choice alternative, leading to a travel time within the corresponding indifference band, is considered acceptable, whereas a travel time outside the indifference band leads to a change in choice. In an interactive simulation experiment is was found that travelers expect a trip time savings of 17-22% over their current path before they switch routes, and this trip time savings should be about 4 minutes [38]. In this study it was also concluded that route switching is more likely when traffic conditions are systematic and thus risks are low.

To summarize, there are roughly two strategies to change car use: psychological and structural [32]. Psychological strategies are aimed at changing individual perceptions, beliefs, attitudes, values and norms. While structural strategies intend to change the relative attractiveness of behavioral options by changing the external context. Examples of structural measures are: financial measures, legal legislations and psychological changes. Financial measures either attempt to lower the attractiveness of a choice alternative by means of penalties, or try to stimulate its use by means of rewards. These are so-called push and pull measures [32]. In contrast to push measures, pull measures are associated with positive effect, feelings and attitudes and therefore generally seen as more effective in changing behavior. Similar findings came from the project 'Spitsmijden' (literally: avoiding peak hour) in the Netherlands [39]. However, pricing policies may also have unwanted side effects when such policies reduce the intrinsic motivation as discussed before.

V. Research design

A. eCoMove Project

First of all, this research is linked to the European research project eCoMove that aims to reduce the overall fuel consumption in traffic by 20 percent by means of energy efficient driving behavior and energy efficient traffic management and control [4]. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication play a central role. eCoMove uses a system's engineering V-model path which starts with the definition of use cases and requirements and the integration and verification of prototypes, followed by field trials, prototype assessment and eventually a proof of concept. One of the applications that will be developed in the eCoMove project is 'ecoAdaptive Balancing and Control' (ecoABC). It combines rerouting of traffic, speed advice at signaled intersections and green priority into one strategy. Based on network and emission estimation and prediction modules, ecoABC on a central level seeks to distribute traffic over a network in the most energy efficient way. While on a control level vehicle drivers will be informed when and where there is a green wave, what speed they should maintain or speed profile to follow to stay within the green band, and which 'micro-route' would be best for their next trip segment. ecoABC will be implemented on test sites in Helmond (The Netherlands) and Munich (Germany) and evaluated on large scale effects in a simulation environment. This research provides input to the design of ecoABC strategies and evaluation of their effectiveness.

B. Research Aim

The previous sections showed that there is a growing need for network management strategies which reflect both the collective and the individual interests. Furthermore, there is insufficient knowledge about how to integrate trade-offs between efficiency and quality indicators such as equity, acceptability and the environment. This research has a two-way approach. One focuses on the system versus user paradigm (multi-level), whereas the other focuses on the trade-offs between accessibility and environmental objectives (multi-objective). The main questions of research are concerned with including these two trade-offs in the design of management strategies.

This research aims to incorporate user acceptability and optimization of energy use in traffic network management strategies. It requires acknowledgement of both objective and subjective measures of effectiveness. A strategy in this research is defined as a plan of action to achieve a particular goal including a criterion set which defines an action. It describes the 'how' rather than the 'what' and intended to help implement policies. Energy efficiency was chosen, because in this context both the multi-level and multi-objective trade-offs exist. This research is split in four steps:

1) Formulate a common ***definition*** for ***energy efficient traffic network management***.
2) Develop a ***theoretical framework*** to determine the factors that play a role in ***user acceptability*** for waiting, rerouting and speed adaptation to optimize energy efficiency, and to show the relation between those factors.
3) Determine the ***solution space*** and control variables for management strategies, and integrate the user acceptability constraints in the design process of strategies to create ***new ecoABC strategies***.
4) **Evaluate** new ecoABC strategies on effectiveness and robustness in a simulated environment and **validate** the results with data from the eCoMove field trials to conclude on **optimal strategies** for energy efficient network management.

C. Research Approach

The first phase of the research deals with understanding and describing the principles of energy efficient network management, its measurability and useful control variables. For this, literature, field practices and a user survey conducted in eCoMove will be used. The next phase will examine the factors which influence the acceptability of road users for rerouting, speed adaptation and waiting, referring to each of the three ecoABC functionalities. Also the relations between the factors, their dominance and indicators will be examined, and summarized in a causal model. Whether or not the model is realistic enough will be verified in a small scale simulator experiment through the collection of verbal expressions during driving, similar to [36]. The third phase is concerned with the integration of user acceptability constraints in the design process of strategies and the actual design of new ecoABC strategies. The first strategies will be derived from the eCoMove project. Identifying the allowable solution space of strategies plays a key role in this phase. In the last phase the new ecoABC strategies will be evaluated in a micro-simulation environment using VISSIM, to conclude on the definition of optimal strategies from both objective and subjective perspectives.

D. Expectations

This research contributes to knowledge on the trade-off between interests on different levels (i.e. collective and individual) and the trade-off between different objectives (i.e. accessibility and environment). This will lead to new strategies for urban network traffic management with higher effectiveness. The link with the eCoMove project ensures that the research results will be brought into practice on a real-world test site. From a societal perspective, equity and acceptability will get more attention, as does the environmental impact of traffic. Overall it is expected that better consideration of user acceptability and the use of vehicle-to-infrastructure interaction will improve the effectiveness of urban traffic network management strategies and stimulate pro-environmental behaviour.

VI. CONCLUSIONS

In political and public debate, mobility and accessibility are sensitive topics. Trade-offs need to be made between many interests, for instance collective versus individual, present versus future and economy versus environment. Such social dilemmas are inherent to complex environments like transportation, and when not sufficiently considered in management or control actions, such actions may lead to disproportionate outcomes. This research contributes to knowledge on the trade-off in interests on different levels (i.e. collective and individual) and the trade-off between different objectives (i.e. accessibility and environment). The main questions of research are concerned with including these two trade-offs in the design of management strategies. The aim of this research is to incorporate user acceptability and optimization of energy use in traffic network management strategies, and evaluate these from an effectiveness perspective. Strategies will be formulated for the eCoMove project's ecoAdaptive Balancing and Control application which combines rerouting of traffic, speed advice at signaled intersections and green priority strategies.

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