SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

Intermediary report - January 2003

SUSTAINABILITY EFFECTS OF TRAFFIC MANAGEMENT SYSTEMS
CP-40

KULeuven – RUG - UCL

SPSD II

PART 1

SUSTAINABLE PRODUCTION AND CONSUMPTION PATTERNS

- GENERAL ISSUES
- AGRO-FOOD
- ENERGY
- TRANSPORT

This research project is realised within the framework of the Scientific support plan for a sustainable development policy (SPSD II)

Part I "Sustainable production and consumption patterns"

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“Sustainability Effects of Traffic Management Systems”

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2.1 – Context and summary

When thinking in a sustainable mobility framework, one approach could be to limit the traffic demand and to balance this demand over different traffic modes. As a complementary approach, one could also try to optimise the use of the existing infrastructure. In this project we will look in detail at the second approach. More specifically, we will look at advanced traffic management systems (ATMS) as a means to enlarge the traffic capacity of the Belgian highway network without constructing new roads.

In this report, a short overview of the six most relevant aspects of our research is given. These include (A) inventarisation of ATMS and data analysis, (B) modelling of traffic flows, (C) dynamic OD-estimation, (D) model calibration and validation, (E) construction of a sustainable cost function and (F) control techniques and optimisation. Following this overview, the expected outcomes, which span two areas (scientific knowledge and practical use of the results), are outlined. Sections 3 (*scientific methodology*) and 4 (*intermediary results*) of this report give details on the specific work done, with respect to the six previously mentioned aspects, during the first year of the project :

- Regarding the data analysis (A), a higher-order macroscopic traffic flow model will be used (based on Payne and Papageorgiou). The goal is to develop a model-based filter that estimates traffic densities and mean speeds from measurements obtained by the inductive loops and video cameras. Advanced non-linear adaptive filtering techniques are needed in order to cope with the nonstationary and highly nonlinear process of traffic flow on highways.

- Part (B), about modelling, discusses the construction of macroscopic and microscopic models. The former is based on a heterogeneous extension of the well-known Lighthill-Whitham-Richards first-order fluid-dynamical model. The latter is based on the cellular automaton programming paradigm, which discretizes both time and space.

- The initial construction of the sustainable cost function is outlined in part (C). First the context is discussed, followed by some general considerations and the general setup that is to be used. A small elaboration on incorporating accident costs in the cost function is given.

- The last aspect considered, is the ensemble of control techniques and optimisation in part (F). We look at a succesful implementation of model predictive control (MPC) applied to a ramp metering setup along the E17 highway Ghent-Antwerp, resulting in a 4% decrease in vehicle-hours during the morning rush hour.

The fifth section (*future prospects and planning*) provides pointers to extensions of the previously four discussed parts (A), (B), (E) and (F).

The report concludes with a list of references and publications.

2.2 – Objectives

The project's objectives are split into six different topics (A)-(F). We'll give a brief overview of each topic in the next few paragraphs. Sections 3, 4 and 5 of this report also relate to the work done regarding these six topics.

The proposal's objectives are outlined as follows :

(A) Inventarisation of ATMS and data analysis

An inventarisation of the available and relevant data is being made. For traffic measurement data, we look at the currently implemented technologies as there are loop detectors, traffic cameras, … These technologies all provide data with different levels of accuracy. In order to monitor traffic (traffic situation, incident detection, …) or to model traffic, attention is paid to data consistency. Conflicting or missing measurements are corrected or estimated (for accurate modelling additional data is needed). The weather has definitely a non-negligible effect on traffic but also maintenance works on the highways, incidents influence, … are taken into account.

(B) Modelling

Two major types of traffic models can be distinguished: microscopic and macroscopic highway traffic models. The microscopic models describe the behaviour of the individual vehicles in detail while the macroscopic models are lumped models that use relationships (difference or differential equations) between aggregated variables like average speed, flow, density, … to describe the evolution of the traffic state. In a previous project (see "*Het fileprobleem in België : wiskundige modellen, analyse, simulatie, regeling en acties*" by Bart De Moor, Ben Immers, Tom Bellemans and Steven Logghe, final report DWTC-project MD/01/024 en MD/01/025), we have built expertise on microscopic and macroscopic modelling by modelling the E17 highway Ghent-Antwerp.

(C) Dynamic OD-estimation

As already mentioned, traffic measurements are important for building simulation models of highway networks. The measurement data are used to estimate the model parameters. During traffic simulation, the inputs of the model are provided to the model as origin-destination (OD) matrices. The dynamic estimation of OD matrices, based upon the available traffic measurements, is currently an area of research.

(D) Model calibration and validation

The parameters of the dynamic highway traffic models are tuned using real-life datasets during the model-fitting (calibration) phase. The set of parameters, that causes the dynamical model to mimic the real traffic conditions best, is looked for. Within this step, several historical traffic patterns (e.g., incidents, congestion, holiday, ...) are used to test and to improve the model. After calibration of the model, the model is thoroughly validated using new datasets. The ATMS is then used as actuators to interact with the traffic. These ATMS are calibrated and validated in detail as well.

(E) Sustainable cost function

In order to be able to assess the 'quality' of a simulated traffic situation, we define goals we would like to achieve, or stated in control terms : a cost function. In the scope of this project on sustainable mobility, a definition of the cost function includes penalisations for pollution (environmental cost), congestion (socio-economic cost), noise emissions, dangerous situations (like shock waves, incidents, …), … . The cost function is expressed in terms of the states of the model and is evaluated during simulation. The exact definition of the cost function is subject to research and alternatives will be evaluated.

(F) Control techniques and optimisation

An ATMS consists of actuators that interact with the highway traffic flows and of a control strategy that attempts to minimise the cost function. ATMS implementing ramp metering, velocity harmonisation, … are studied in detail. Starting with controllers for one actuator, the research evolves towards co-ordinated control of multiple actuators. Using the right optimisation techniques and simulation models, that find the correct trade-off between level of detail and computational complexity, will greatly influence the optimality of the resulting controller.

2.3 – Expected outcomes

The results of this research can be split up in the following categories :

(I) Scientific knowledge

The research will result in extensive new scientific knowledge that will be presented on congresses and will be published in journals. New knowledge and experiences can certainly be found within :

- The processing of traffic data from traffic detectors.
- The set-up of a dynamic model on a regional scale.
- The mixed use and the tuning of macroscopic and microscopic dynamic traffic models.
- The dynamic OD estimation.
- The set up and the implementation of a sustainable cost function for the evaluation of dynamic traffic patterns.
- The development and calibration of dynamic models can be linked to the static equilibrium approach. The marginal cost function for congestion that is one of the fundaments of the external pricing theories can be controlled from a dynamic point of view.
- The design of new control strategies for ATMS.
- The application of optimisation within traffic research.

(II) Practical use of results for Belgium

The results of this research will be of importance for Belgium.

First of all the federal road administration can exploit the results to improve the Belgian transportation system. A lot of new ATMS will be installed in the near future. The new control strategies can be implemented immediately in these systems. The project will set up a model of part of the Belgium road network. This model can be used for other purposes by the road administrator. This project will generate quite some expertise for these future developments and will improve the practical knowledge in Belgium of dynamic traffic flow modelling.

Secondly the members of the user comittee will be involved in the transfer of technology and knowledge. A web site (http://dwtc-cp40.dyns.cx) spreads information towards the interested public. There is also a possible knowledge transfer towards university spin-offs (cfr. Transport & Mobility Leuven – http://www.tmleuven.be).

3 – Detailed description of the scientific methodology

The paragraphs in this sections all refer back to the six topics pointed out in section 2.2 (*Objectives*).

(A) Inventarisation of ATMS and data analysis

Analysis and accuracy estimation of camera data for traffic management

The sensor data characterizing the traffic flow on highways and urban traffic networks are corrupted due to various reasons: e.g., sensor calibration errors, data link errors, lack of measurements caused by sensor failures, … . Furthermore, due to measurement errors, the measured data (such as average speeds or vehicle counts) may have physically impossible values, such as negative values for vehicle counts or speed. Missing or faulty data calls for on-line data processing algorithms that can accurately and quickly improve the accuracy of the traffic measurements. This analysis is a further continuation of the study initiated in [2,1] with statistical methods [6].

The aim of the analysis is to pre-process the data, remove outliers, estimate the accuracy of the measurements in order to make them useful for the next processing step, building up adequate traffic models, as well as for traffic parameters estimation and prediction.

The statistical analysis of the raw data will provide confidence intervals, characterizing the accuracy of the raw data. The accuracy bounds of the raw data will allow calculation of confidence intervals around predicted future values, in combination with mathematical models of the traffic dynamics.

Distributed Smoothing of Data

In view of the fact that the data are collected in different points of the highway, a distributed processing of them will be conducted. The motivation for this choice is that centralized processing is unreliable and not very robust. This analysis will allow us to apply robust smoothing algorithms to the data observed on line along several Belgian freeways.

(B) Modelling

Within this part, the use of traffic flow models is dealt with. In a first section, a short overview of transportation models with their utilities, purposes, assumptions and properties will be set up. Secondly two types of dynamic traffic flow models that will be used in the project will be treated. At last a short description of an extended dynamic macroscopic traffic flow model will be given.

Transportation models

When some properties of our transportation system are described by a set of mathematically formulated assumptions, a transportation model is born. Because there is a wide range of intended properties to describe, there exist a lot of transportation models. This set of transportation models can be classified in several ways. Within this discussion we will distinguish these models on the basis of the features of the transportation system they intend to capture.

Roughly the decision processes of travellers within the transportation system can be clarified with the help of figure 1.

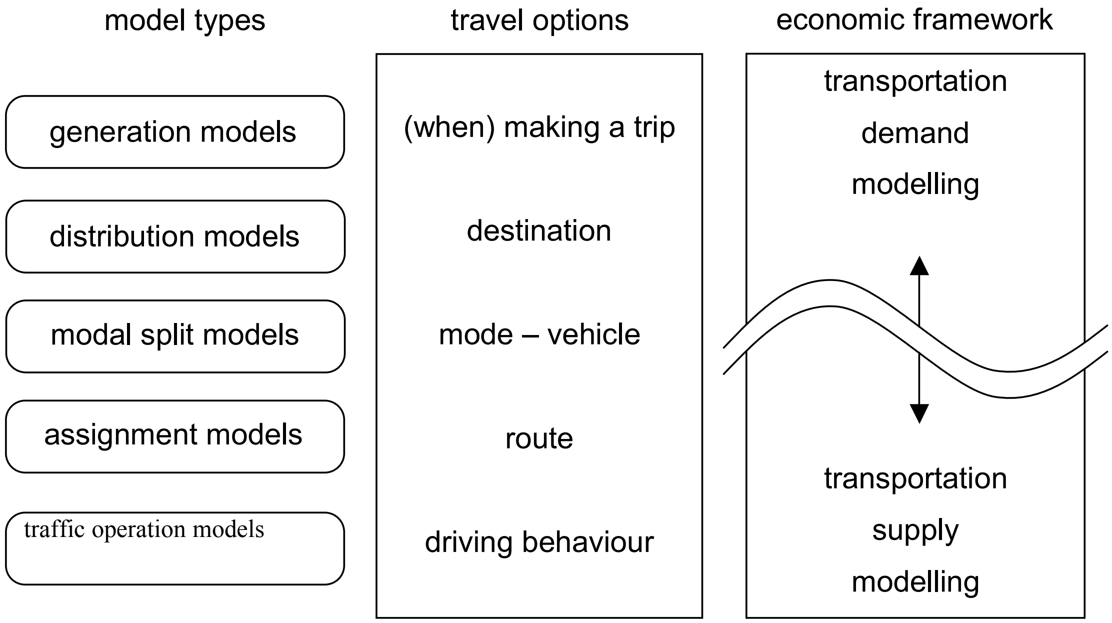

Figure 1 : Building blocks of the transportation system.

We distinguish five types of sub-models that are closely related to the described travel options :

- Models that focus on when and where people want to travel are grouped in generation models. These models describe the complex decision processes that lead to the making of trips.
- Models that predict the destination of the trips are grouped within the distribution models. The distinction with the generation models can seem somewhat artificial. The decision of making a trip is often closely related to the choice of the destination of these trips.
- Within the proposed classification, the choice of transportation mode and vehicle type comes next.
- Within an assignment model, the route choice of all travellers is considered together. Given the amount of trips between several origins and destinations, and knowing the departure time and the modal choice of all travellers, an assignment model calculates the used routes and the resulting flows over a transportation network.
- A traffic operation model focuses on the driving behaviour of travellers. This detailed model is closely related with the observed traffic flow variables at road level.

When a particular transportation model is set up, some of these five sub-models are worked out. Within an economic framework we can state that every transportation model tries to describe an equilibrium between demand and supply. Depending on the considered travel options in the transportation system we can define a part as the demand modelling and a part as supply modelling . When considering an assignment model, the modal split will be considered as a result of the traffic demand. When setting up a generation model, the properties of the several transportation modes can be classified as transportation supply.

Traditionally, transportation economists focus on the generation, distribution and modal split sub-models. They are interesting in the results of the decision processes underlying the making of trips, the destination of them, the time of leaving and the transportation mode. Transportation engineers mostly work on the route choice and traffic flow operations.

Both economists and engineers have the purpose to improve the working of the transportation system. Transportation economists are searching to close the gap between the experienced and the real supply costs that travellers make. Transportation engineers' objective is to control traffic operations and route choice. The underlying idea for that, matches the economists viewpoint : there exists a difference between a user optimum and a system optimum.

Within this project the concepts of transportation economists will be projected on the traffic operation level. With the help of this, the control of traffic operations can be based on a complete and sustainable system optimum. Therefore an accurate mathematical description of traffic operations becomes necessary, justifying the use of dynamic traffic operation models.

Traffic flow models

Because traffic operations on the highway network are the main research area of this project, we can focus on traffic flow models. Different types exist that can describe the present traffic operations and can predict the effect of control measures. Based on the way vehicles on the highway are considered, we distinguish tree types of traffic flow models :

- **Microscopic**
  Microscopic models consider each vehicle separately. Within these simulation models the driving decisions of each driver are considered at every time step. This process comprehends effects of the vehicle properties, the infrastructure lay-out and the interaction with other vehicles.

- **Mesoscopic**
  Mesoscopic models are based on gas models. The vehicle stream is then seen as a stream of molecules. The underlying assumptions are also based on the interaction and moving properties of molecules. The difference between vehicles and molecules is that the amount of particles related to the dimensions of the encapsulated 'tube' or 'road', is much larger for gas models then for traffic.

- **Macroscopic.**
  Macroscopic models describe traffic as a homogeneous fluid in a tube. Simplifications are made about acceleration and the speed is assumed to be a function of density.

Within our project two types of models will be combined.

Macroscopic models can calculate in a fast way the state of traffic operation on a road. Therefore, this type of model will be used in real-time model based control strategies. Because of the simplifications made in these models, the effect of a control measure on a detailed scale is needed as input and not as result within these models.

Microscopic models will be used in off-line calculations to predict the detailed effects of some new control measures. The results of these off-line simulations can lead to new parameters (e.g. a modified fundamental diagram) that will be used as input in the on-line macroscopic model. The microscopic model will also function as a mirror of the real world when testing the on-line macroscopic-model based control.

(E) Sustainable cost function

The following provides a brief overview of the economic approach to modelling the costs of transport schemes. Using this general framework and given our current understanding of the traffic model which is being used for the advanced traffic management system (ATMS) scenarios, the components of the sustainable cost function have been developed for a feasible, limited network.

When calculating transport costs from an economic point of view, there are a number of approaches available for modelling traffic flow. The choice of model depends on the aspects of the traffic situation that are of interest. For example, the effect of implementing regulatory policies on the transport network as a whole does not require detailed information on a road by road basis but allows for public/private road transport and non-road transport options (e.g. rail, ferry etc). Thus, in this case, an "aggregate" model is the most appropriate. For the present study however, the traffic model is a dynamic, micro-simulation model. Hence speed (u), density (k) and flow (q) vary over a given link, in contrast to the static traffic model, for which these variables have constant values. Given this level of detail, it is not appropriate to calculate transport costs by aggregating all the traffic information onto one generalised "link". Table 1 summarises three basic types of traffic model and the travel options they incorporate.

Table 1: traffic models

Model	travel options				
	choice of mode	choice of departure time	choice of route	choice of vehicle	driver behaviour
Aggregate multi-modal models (e.g. TRENEN, typical strategic models)	yes	peak/off-peak only	no	yes	standard
Bottleneck models (e.g. METROPOLIS)	no	yes	yes	no	standard
Model for this study (micro-simulation type)	no	no*	no*	no	individual driver response

Departure time and route have been fixed to simplify the model for this study (see below) but need not be in general.

Traffic network model considered for ATMS

In order to be able to generate a manageable and meaningful cost function, certain limitations have to be imposed on the traffic network. The basic approach would be:

- Consider only a small section of the motorway network, with several possible control strategy options (e.g. ramp metering).
- Admit a fixed profile of vehicles onto the network section over time period ΔT (typically 1 hour), each with a fixed departure time and travelling in one direction only.
- The destination of each vehicle is assumed to be at the exits of the network section and they do not change their route.
- The vehicles are not all identical, with a mix of freight and private transport. The private transport can have different levels of occupancy, emissions technology, fuel type, representative of the current Belgian car fleet. However, there is no option to change between private and public transport.
- The network section is divided into links of varying length ΔX, so that there are surfaces $S(\Delta X, \Delta T)$ over which k, q, and u are defined. Within each S of the macro-model, the dynamic model calculates the traffic variables in smaller cells (Δx) at a time interval Δt (typically 1s).
- Given the fixed onset flow, the traffic control model compares the total cost over the network section of implementing different control strategies. The minimal cost strategy is implemented.
- Given the existing traffic situation, control measures are implemented to improve traffic conditions over the period ΔT. They are normally updated at time interval Δt ($<<\Delta T$), typically 5 minutes, to take account of how the modelled traffic pattern fits the observations.

Sustainable Cost Function

The formulation of the sustainable cost function will also depend on the traffic model used. In all cases there are user costs which can be broken down into resource costs (vehicle purchase, maintenance, fuel etc), taxes and time costs. For the aggregate model, the travel time for each transport mode is usually approximated as an exponential function of the traffic demand and this is multiplied by a value of time (VOT), again for each mode. In the bottleneck model, the time costs consist of a component due to the extra time an individual spends in his vehicle plus components due to the amount of time that he is early or late to work. Each of these components has an associated shadow price (or VOT). The total time cost is then obtained by summing over the number of vehicle-km travelled in a given time period or the number of individuals, respectively. For the present study, the additional time spent queuing and the time late are required. The corresponding VOTs, which will developed by the ETE group, will take account of the vehicle fleet mix, income etc.

It is also possible to calculate external costs for each model category. Air pollution costs reflect the damage to society and future generations from vehicle emissions. This is normally calculated from the product of the damage cost per unit of emission (e.g. euro/g), the emission per vehicle-km and the vehicle-km travelled. For the ATMS study, the emissions are unlikely to be uniformly distributed and will be a function of the dynamic variables, flow, density and speed, with greater costs likely under congested conditions.

External accident costs cover the average accident costs not covered by insurance: in particular, the pure economic costs of police, ambulances etc. They can also include the cost of increased accident risk. The costs depend on the probability of accidents of differing severity occurring between different modes (e.g. freight and private car), which is difficult to determine. For the present study, the probability need not be constant over all vehicle-km but could depend on the traffic density and speed.

External noise costs can probably be ignored if the motorway section is away from built up areas. Otherwise techniques based on hedonic house pricing and equivalent noise level functions have to be used to determine the noise costs.

To summarise, the cost function for the ATMS will consist of (at least) the following:

- Minimum travel time cost. i.e. if no congestion related time costs.
- Resource costs and taxes.
- Cost of queuing i.e. additional time spent in vehicle (with associated VOT).
- Schedule delay cost (cost of being late). We will assume that all vehicles following the same route allow the same fixed time to get to their destination. The VOT for being late to work (or other activity) will be derived.
- External air pollution costs. Possibly a function of dynamic traffic variables instead of constant marginal cost.
- External Accident costs. Using the dynamic model this could depend on speed, density and traffic composition and has a probabilistic component.
- Infrastructure costs. The cost of implementing a particular control strategy.

It is possible to consider the problem in terms of the maximum welfare gain to society instead of the minimal sustainable cost of each control strategy. The user costs are transformed into a consumer surplus. Then the social welfare function consists of the sum of the consumer surplus, the producer surplus of the suppliers of vehicles, fuel etc and government tax revenue minus the total external costs.

(F) Control techniques and optimisation

We give an example of a dynamic traffic management (DTM) strategy for a highway : ramp metering. We begin with a description of the ramp metering setup after which we discuss the cost function that generally follows from the policy and practical issues. This cost function describes the quality of the realized traffic state. After this, we show how MPC based control leads to an optimisation problem with constraints; we illustrate this by means of simulation results.

Description of a ramp metering setup

Ramp metering is a DTM measure that consists of allowing vehicles to enter the highway by drops. Each highway has a critical traffic density, beyond which the traffic flow declines with increasing traffic density. The idea behind ramp metering is to keep the traffic flow of vehicles on the highway as optimal as possible, by keeping the traffic density always below the critical density. In practice, this can be realized by positioning a traffic light at the on ramp of a highway, this in order to limit the number of vehicles that is allowed to enter the highway. The control parameter which allows influencing the state of traffic on the highway is the number of vehicles that are allowed on the highway. Or in other words, the duration of the green phase of the traffic light. When a practical implementation of ramp metering is concerned, it is necessary to accomodate enough space on the on ramp in order to hold the waiting the queue of vehicles, without causing any hindrance to the underlying road network.

In figure 2 we see a schematic representation of a highway with an on ramp. At this on ramp, a traffic light is placed and room is provided in order to accomodate a waiting queue.

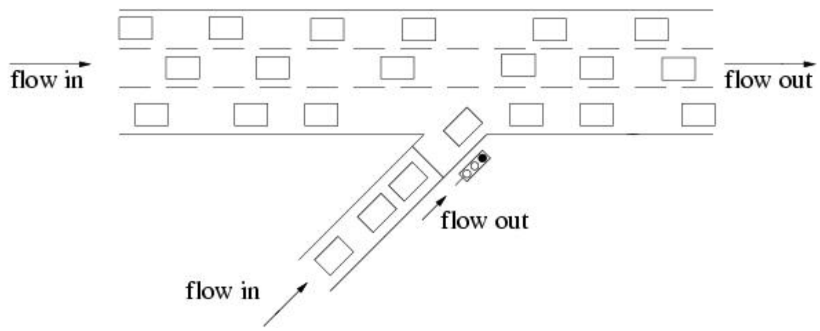

Figure 2 : Schematic representation of a ramp metering setup : two consecutive highway sections and an on ramp with a traffic light and waiting queue.

A practical advantage of ramp metering is the simplicity with which it can be compelled. Drivers are obliged to stop in front of the red light, so as not to cause any heavy traffic infringment. It is thus supposed that no vehicle enters the highway during the red phase of the traffic light. Furthermore, it is easy to quantify the number of vehicles that enter the highway : by keeping the duration of the traffic light's green phase very small, we can dose the flow on a vehicle by vehicle basis.

Model predictive control

Model predictive control (MPC) is an on-line control technique that is used for optimal control of a ramp metering setup. MPC uses a model in order to predict the future evolution of the traffic state, given a known traffic demand. A control signal is searched for in order to minimize a predefined cost function. MPC uses a rolling horizon, which means that a prediction horizon N_p is defined such that at each time instant k of the prediction horizon the N_p control signals can be calculated by minimizing the cost function over the prediction horizon. These control signals are the number of vehicles that are allow to enter the highway at time instant k. The value of the cost function over the prediction horizon is calculated by using a traffic state that is simulated by a traffic model. Here the METANET model, described by Papageorgiou, was chosen as a traffic model.

The calculation of the N_p control signals for the prediction horizon is rather computationally intensive, especially with an increasing size of the prediction horizon. Therefore, a control horizon N_c is defined as the period during which the control signals are allowed to vary. The length of the control horizon is smaller than or equal to the length of the prediction horizon. After the control horizon has passed, it is assumed that the control signal remains constant (see figure 3). By the control horizon's definition, the number of parameters to optimize (and as such, the computational complexity) is reduced. In the context of a rolling horizon, only the first control signal of the prediction horizon is applied to the system. The other signals are discarded. The traffic state is then updated by means of measurements, the control and prediction horizons are advanced in time and the whole cycle starts over again. The parameters N_p and N_c are to be chosen such that a balance is found between on the one hand the complexity and on the other hand the accuracy of the controller.

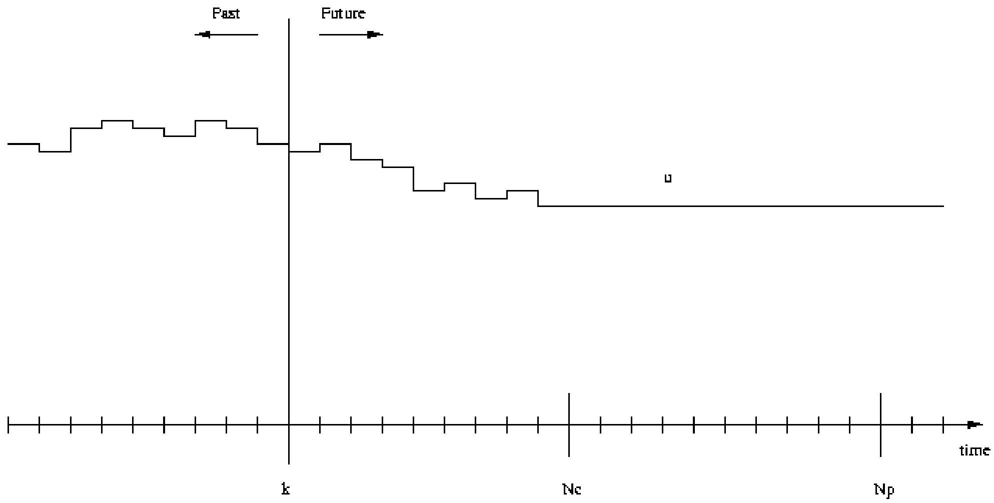

Figure 3 : Schematic representation of the rolling horizon principle used in MPC. At timestep k we look with the model over a prediction horizon N_p and trie to establish a control signal that minimizes the cost function. The control signal itself is allowed to vary during timesteps k to k+ N_c, after which it remains constant. The first step of the control signal is then applied, after which both horizons advance one timestep.

The cost function

A governmental traffic policy might consist of keeping the flows on the highways at maximum capacity. We can translate this to the control of the ramp metering setup in the following way : the total time spent in the system has to be minimal. The total time spent is composed of the time spent by the vehicles on the highway and the vehicles in the waiting queue at the on ramp. This results in the following cost function :

$$J = \sum_{k=k_0}^{k_0+N_p-1} \left(\sum_{i=1}^{S} \rho_i(k) v_i n_i \Delta T + \sum_{j=1}^{R} w_j \Delta T \right)$$

.

In this formula, k_0 is the starting time, N_p is the prediction horizon, S is the number of sections on the highway, i is the section under consideration in the summation, $\rho_i(k)$ is the density on section i at time k, v_i is the flow on section i at time k, n_i is the number of lanes on highway section i, ΔT is the time step with which the discrete controller is updated (typically 1 minute), R is the number of ramps, j is the ramp under consideration in the summation and w_j is the waiting time on the on-ramp.

4 – Detailed description of the intermediary results, preliminary conclusions and recommendations

(A) Inventarisation of ATMS and data analysis

Adequate models of the vehicular traffic are needed in traffic flow prediction, incident detection, traffic control. The various traffic models available in the literature can be classified into two groups: micro- and macroscopic models [3, 5, 4]. In microscopic models the behavior of individual drivers is explicitly described which imposes a considerable amount of computations. The macroscopic models are aggregate models. The computational effort is considerably reduced compared to the microscopic models, but on the other hand they are less detailed. Since macroscopic traffic models are better suited for model-based estimation techniques, we will use these in our study.

Traffic flow on freeways is a nonstationary and highly nonlinear process. A trade-off between the model realism and feasibility of estimation procedures has to be achieved. Current investigations are concentrated on the macroscopic freeway traffic model developed by Payne [9, 10, 3], improved by Papageorgiou [8, 7], and its application for traffic prediction.

The traffic flow is described with the model, consisting of two partial differential equations :

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = 0,$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{V^e(\rho) - v}{T} + \frac{\dot{V}^e(\rho)}{2\rho T}\frac{\partial \rho}{\partial x},$$

where x stands for the space variable, the distance from a fixed origin along the freeway, and t is the time variable. V^e is the average speed in equilibrium, q is the flow, ρ is the density, v is the speed and T is the relaxation time. The first equation represents the conservation-of-vehicle principle, stating that no cars can vanish, nor appear out of the blue. The second equation describes the evolution of speed in time. According to this equation, the speed is determined by three terms: convection, relaxation and anticipation. Several schemes have been proposed to numerically solve this equation. For the purposes of the prediction problem to be solved afterwards, it is more appropriate to discretize at first with respect to the space such that a stretch of the freeway is split up into sections with measuring loops at the boundaries of each section. This way a connection between the state model and the observation equation is achieved. After that the equations will be discretized with respect to the time.

The measurements provided by inductive loops and video cameras consist of counts of passing cars and their speeds at each of the measuring sites. In order to control the advisory speed signals, or the on-ramp metering signals in an optimal way, we need a good estimate of the state of traffic at all time instants. Hence, our goal is to develop a model-based filter that estimates traffic densities and mean speed from measurements. Studying the traffic model will allow us to get deeper insight into the traffic phenomena. At first simulation experiments will verify the adequacy of the model. Second, this behavior may be compared to the behavior of traffic in practice.

Due to the specificity and nonlinearity of the process, the standard stochastic filtering techniques, like Extended Kalman filters meet difficulties. Advanced nonlinear adaptive filtering techniques will be applied for traffic prediction and estimation of its parameters. These nonlinear filters will combine traffic simulations, based on macroscopic models, as well as real-time data (pre-processed raw data). The techniques will allow us to predict the driving time and speed along some parts of the freeways, the fuel consumption and air pollution.

(B) Modelling

A heterogeneous macroscopic traffic flow model

In macroscopic vehicular traffic models, the flow on a one-directional road is traditionally idealized as an homogeneous fluid. Driver-vehicle entities are supposed to act as identical particles in a fluid tube stream. This equalization of all vehicle types contradicts with the vehicle type distinctions transportation economists model at the modal split level. Without considering route choice and traffic operation, the type of vehicle is than one of the major supply cost properties. Especially when considering environmental costs (emission, noise, …) and accident costs (vehicles vs. lorries) the homogenisation of the traffic stream is a huge simplification. Furthermore the distinction of vehicle types in a traffic stream can lead to a more complete and accurate description of traffic operations. Lane changing interactions can not be modelled within a homogenized traffic stream.

In this research heterogeneous properties are introduced. To this end the homogeneous population is split into classes. Each class consists of driver-vehicle entities with homogeneous properties. Modelling heterogeneous traffic flow is now reduced to describing homogeneous class flow and the interactions between these classes.

The properties of a class are defined by the maximum speed, the vehicle length, and the capacity. The capacity is the maximal possible flow on the road when only vehicles of the specified class drive on the road.

The interactions between several classes is based on a user optimum. Each driver is assumed to maximize his own speed. Furthermore it is assumed that faster vehicles cannot affect the speed of slower driving vehicles. Therefore the slow vehicles acts as moving bottlenecks for the faster ones.

The model consists of a mathematical formulation that can be solved analytically. Furthermore a numerical scheme is set up. This enables us to implement the model with a computer and calculate approximate solutions in a fast way.

A Traffic Cellular Automaton

Another approach towards the alleviation of road congestion, consists of the development of a flexible testbed environment – based on a traffic cellular automaton – that is capable of providing us with a simulation model of a real-world road network (which is, in our case, the Flemish primary highway network and its secondary national road network).

The testbed is constructed in two stages : construction of a traffic flow model and simulation of the road network. At this moment, we are completing the first stage.

The core of our testbed consists of a microscopic traffic flow model, based on the cellular automata programming paradigm as a discrete dynamical system for the modeling of traffic flows. The system's state is changed through synchronous position updates of all the vehicles (i.e., the cells). This level of detail is needed in order to fully grasp the emergent effects of the dynamical processes behind traffic flows. Our traffic cellular automaton (TCA) model is able to handle highway traffic, thus explicitly including the car-following and lane-changing dynamics [16]. Routing is done on a higher layer (for the moment we'll assume dynamic origin-destination (OD) matrices in the sense that they only change in time to mimic the daily flow patterns).

The dynamics of the TCA are be modeled as rule-sets that reflect the rule-based behaviour of a cellular automaton evolving in time and space. Our motivation is largely driven by the fact that classical TCA models (i.e., CA-184, NaSch's STCA, …) suffer from several deficiencies and are therefore more suited for theoretical studies. We remedy this situation by constructing a new TCA model that alleviates the problems of the aforementioned TCA models and at the same time includes advanced traffic characteristics (such as metastability, hysteresis, time-based headways instead of space-based headways, …) [13]. Most of the already developed models either exhibit the aforementioned deficiencies, or they're not suited for large scale application in an integrated real-life road network. Our modeling efforts provide the necessary significant innovation.

Several generic qualitative measurements are also performed. They act as testing tools to assess the validity of the developed TCA model (as well as the classical TCA models). These tests will include histograms of lead gap distributions, measuring the time needed to travel a congested section or to completely dissolve mega-jams, measuring the life-time and size of congestion waves, … [11].

(E) Sustainable cost function

We'll first describe the context in which the GSCF is constructed, then we'll consider some general assumptions followed by an outline of the general setup of the GSCF. We'll conclude with a description of the different sustainability costs involved in the GSCF.

Context

In order to guarantee the optimal operation of the traffic flow, we'll implement certain control measures such as ramp metering, velocity harmonisation, ... which influence the drivers. In this way, we can formulate the context as a control problem. Within the optimization loop of the controller, a cost function is used which is used to find the optimal operation. This cost function incorporates several different costs associated with incident probabilities, air pollution (by emissions of chemical compounds, noise, ...), travel time, ... The result is a sustainable cost function. The general applicability arises from the fact that we don't need an explicit specification of the underlying traffic flow model used (it can be a macroscopic, mesoscopic or microscopic variant). This generality implies that we'll use the greatest common divisor of these models, namely that traffic flow measurements can be extracted over a certain place during a certain time period. In practice, this means that we'll divide the time/space plane into cells of arbitrary size.

General considerations

The following preliminaries should be taken into account :

- the road network used, consists of a limited network (preferably a highway corridor for example) with possible on/off-ramps,
- we only consider uni-directional links in the network,
- all vehicles have a fixed departure time and don't have the availability of route choice. We do however assume the origin-destination (OD) matrices to be dynamic in the sense that they change in time to mimic the daily flow patterns.
- The vehicle fleet mix (consisting of two classes, namely cars and trucks) is representative of a given route (i.e., a Belgian highway in the study area). The difference between cars and trucks is expressed as passenger car units (PCUs).

General setup

It is our goal to compare the costs of different control strategies. This is done by assigning a value to certain individual costs (related to accidents, chemical emissions, noise, ...). The general sustainable cost function (GSCF) is thus constructed by the summation of individual terms. These terms each contribute a certain weight to the total cost, reflecting the different sustainability measurements that we perform.

The cost function is calculated for each cell in the time/space plane individually (i.e., we only consider one cell at a time). This allows us to visualize how the behaviour of each individual cost evolves when the daily flow pattern changes, when control measures are taken, ...

As an example, we'll give some details of the contribution to the GSCF by accident costs.

When considering the cost of an accident, we only consider the influence that this accident has on the current cell. We implicitly assume that the consequences of an accident (e.g., the formation of a long waiting queue) are propagated through the traffic flow by the traffic flow model itself. It is therefore unnecessary to take these side-effects of accidents explicitly into account. Because of this simplification, we only need to consider the time it takes to clear up the road and remove the accident. We assume the accident cost is fixed, but we do however introduce a probability measure for the accident occurrence itself. This results in the multiplication of the accident probability for a certain road with the fixed accident cost. This accident probability depends on the traffic density (which can be used to characterize the traffic regime) and the dimensions of a cell in the time/space plane.

(F) Control techniques and optimisation

As an illustration, an experiment was performed based on a model of a section the E17 highway between Ghent and Antwerp. A ramp metering setup was simulated at the on ramp at Linkeroever (i.e., the first left on ramp). The total time spent during a simulated morning rush hour was compared with and without an MPC controlled setup. Figure 4 gives an overview of the simulated section of the highway. The total time spent in the network is used for the cost function. The prediction horizon Np was taken to be 10. Because the sampling step of the controller was considered to be 1 minute (it's rather useless to adapt the metering rates more frequently), the controller only 'looks into the future' for about 10 minutes. In order to limit the needed computation power, the control horizon was chosen to be 5, or in other words, the control signal can vary during the first 5 minutes of a simulation period, after which it is considered to remain constant. A big advantage of MPC based control is the fact that certain constraints can be imposed to the optimisation. For example, it is assumed that the available space on the on ramp can only accomodate at most 100 vehicles. Besides the maximal length of the waiting queue, other constraints can be imposed.

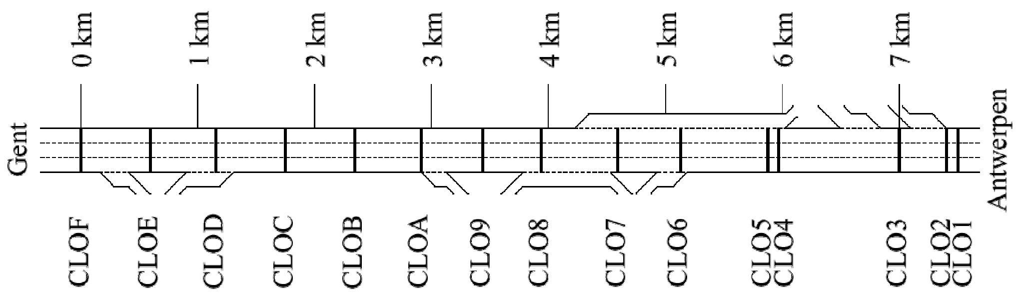

Figure 4 : Schematic representation of the simulated section of the E17.

The simulated morning rush hour runs from 5h until 10h. Figure 5 shows a summary of the simulation results. In the first plot, the course of the traffic demand on the on ramp is shown. It can be seen that this traffic demand increases until it decreased after the morning rus hour. The second plot shows the control paramter, which is the metering rate or the fraction of the total capacity of the on ramp which is allowed to enter the highway. We can see that the metering rate initially equals 1 and that all vehicles that want to enter the highway are allowed to do so (the length of the waiting queue is shown in the third plot and is zero). In the fourth plot we can see the course of the traffic density in time. The dotted line represents the critical density of the highway, or in other words : if this density is exceeded, the flow of the vehicles on the highway begins to decline with increasing density (i.e., congestion). We can see that because of the increased traffic demand, the density on the highway begins to increase. However, we traffic density on the highway tends to exceed the critical density, the ramp metering control is applied : the metering rate declines, reducing the inflow on the highway below the traffic demand, resulting in the formation of a waiting queue at the on ramp. The density on the highway fluctuates about the critical density (this is the density at which the flow on the highway is maximal). At a certain moment, the length of the waiting queue reaches its maximal value (100 vehicles) and the controller is necessitated to increase the metering rate, causing an increase of the density on the highway beyond the critical density. The accompanying average speed on the high way is shown in plot 5. After a while, traffic demand decreases, which results in a dissolvement of the waiting queue (this can be seen in the first plot, in which the real inflow of vehicles to the highway is greater than the demand).

If we look at the total time spent in the network (i.e., highway and waiting queue), we can see that, in case no ramp metering is applied, this is equal to 2960 vehicle-houres during the complete morning rush hour. However, when MPC based control is performed, the total time spent in the network is reduced to 2843 vehicle-hours, resulting in a reduction of 117 vehicle-hours (4%) during the morning rush hour (*i.e., when ramp metering is active*). While the queue on the on-ramp is building up, the morning rush hour jam is shorter in time than without ramp metering. Once the maximal queue length is reached, congestion sets in.

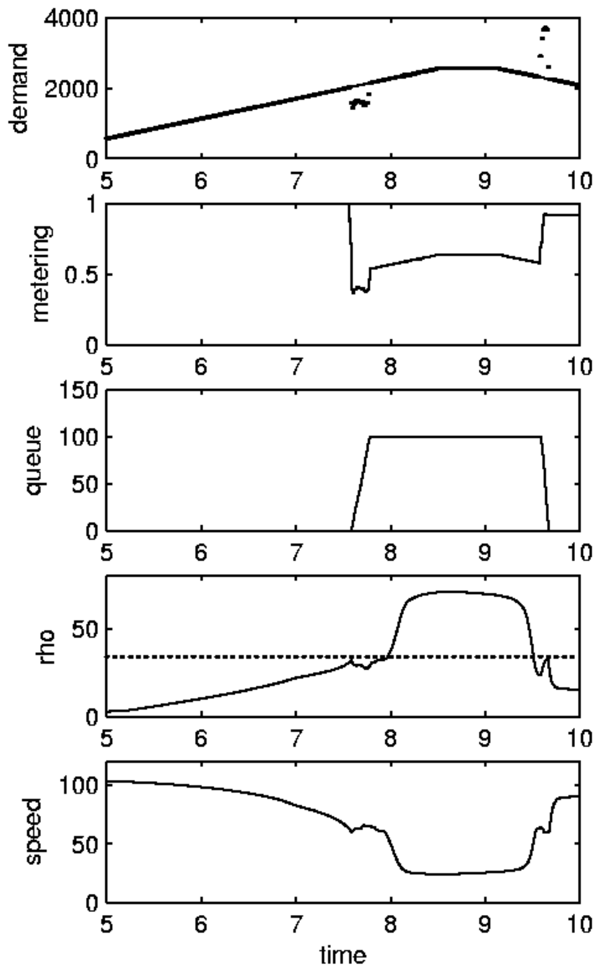

Figure 5 : Overview of the simulation results for a morning rush hour and MPC based control at the E17 highway between Ghent and Antwerp.

Conclusion

The setup of a model based dynamic traffic management (DTM) system starts with the definition of a policy. This policy is then translated into a cost function. An MPC based controller uses the concept of a rolling horizon. The control signals which lead to a minimum value of the cost function are searched by means of optimisation. In this process, a traffic model is used. Only the first control signal is applied to the system, after which the model is adapted to the changed traffic state on the highway and the horizons are advanced. MPC is capable of finding a solution which adheres to strict constraints (e.g., a maximal length of the waiting queue). In order to suppress the computational complexity, a control horizon is defined besides the prediction horizon.

In the presented example, a simple application of MPC based ramp metering on a single on ramp was shown. This resulted in a 4% reduction of the total time spent on the considered section of the E17 highway.

5 – Future prospects and planning

(A) Inventarisation of ATMS and data analysis

After obtaining the traffic data, we'll construct meaningful filters that can be applied. This is closely related to the correlations between consecutive measurements in space and time. Noise estimation will form a key aspect in this research. Conflicting or missing measurements will be corrected and/or estimated. Since the weather has a definitely non-negligible effect on traffic, we'll try to obtain and process climatological data. The same holds for incident related statistics.

(B) Modelling

A heterogeneous macroscopic traffic flow model
At this moment the model framework is worked out. During the next report period the development of this model can be finished and applied within the model based control strategy.

A Traffic Cellular Automaton
The second stage in the development of a microscopic traffic simulation model, consists of the construction of a testbed that allows us to simulate the road network [14].

Our developed model will form the core of a testbed of a real-life road network environment. Its scope is the Flemish major road network whose physical modeling will be done by employing data available from satellite images and geographical information systems (GIS).

Calibration and validation of the system are required in order to tune the model parameters to the dynamic traffic state on the already existing road infrastructure [15]. All the data needed for real-time simulation is gathered by sensors in the road network and stored in a database by Flander's Traffic Centre. This database contains the macroscopic flow, occupancy and average speed measurements as time series (with a sampling interval of one minute).

Furthermore, constructing the fundamental diagrams from these time series, allows us to investigate the transient phenomena associated with traffic flow operations; meta-stability and hysteresis can be observed and checked for in the developed TCA model [12].

(C) Dynamic OD-estimation

When the modelling step is completed, we can construct the OD-matrices containing the vehicle trips. These origin-destination (OD) matrices form the inputs of the model. The dynamic estimation of OD matrices, based upon the available traffic measurements, remains an area of research.

(D) Model calibration and validation

Using the traffic data, we can classify several historical traffic patterns (e.g., incidents, congestion, holiday, ...) to test and to improve the model. After calibration of the models, they are thoroughly validated using new datasets. The ATMS is then used as actuators to interact with the traffic. These ATMS will be calibrated and validated in detail as well.

(E) Sustainable cost function

Once the general sustainable cost function is derived, we'll apply it to the different traffic models. We'll also have to gather the relevant data (traffic data, sociological data, economical data, …) and devise a way for calibrating and validating this data (after assessing it's quality). Furthermore, the cost function should be integrated in the optimisation loop of the controller.

(F) Control techniques and optimisation

Having discussed local (individual) ramp metering, we'll increase it's effectiveness by applying coordinated ramp metering, in which several consecutive on-ramps are coupled together to give a global optimisation.

The following time-table gives an overview of the several steps in the project. Three identifiers are used to denote the current state : DONE, BUSY and SCHEDULED (note that some 'future' steps are already being researched, e.g., construction of the sustainable cost function).

TASK	Year 1	Year 2	Year 3	Year 4
1. The inventarisation of technology and monitoring systems				
1.1 ATMS in Belgium	DONE			
1.2 Monitoring systems and available traffic data	DONE			
1.3 Design and application of methodologies to process traffic data	BUSY			
1.4 Research influences on traffic patterns of: weather, incidents, maintenance works, …	SCHEDULED			
2. Set up a modelling framework	BUSY			
3. Dynamic OD-estimation		SCHEDULED		
3.1 Design and application of methodology for Belgium	BUSY			
3.2 Esatimation of OD-tables for hypothetical and future traffic conditions		SCHEDULED		
3.3 Real-time OD-estimation		SCHEDULED		
4. Model fitting, calibration and validation				
4.1 Calibration of data processing	SCHEDULED			
4.2 Calibration of dynamic OD-estimation		SCHEDULED		
4.3 Calibration of dynamic traffic model		SCHEDULED	SCHEDULED	
5. Sustainable cost function				
5.1 Design of a cost function			BUSY	
5.2 Testing and calibrating cost function			SCHEDULED	
6. Control techniques				
6.1 Modelling and calibration ATMS			BUSY	
6.2 Design framework control strategies for ATMS			BUSY	
6.3 Design co-ordinated ATMS and control strategies			SCHEDULED	
7. Optimisation				
7.1 Optimisation of ATMS control strategies			SCHEDULED	
8. Interaction with authorities	DONE	SCHEDULED	SCHEDULED	

6 – Annexes

6.1 – References

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6.3 – Detailed results

All results were integrated in section 4 (*Detailed description of the intermediary results, preliminary conclusions and recommendations*).