RAMP METERING WITH AN OBJECTIVE TO REDUCE FUEL CONSUMPTION

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ABSTRACT

Ramp meters successfully decrease congestion but leave a burden on the traffic situation at on-ramps. Chaotic queuing leads to many stop-and-go movements and causes inefficiency where fuel consumption is concerned. As part of the eCoMove project, complementary strategies are being designed and evaluated to reduce fuel consumption at metered on-ramps, using vehicle-to-infrastructure communication. This paper presents the design of two strategies, as well as their effect as derived from simulation using AIMSUN. The first strategy uses virtual stop lines to halt upstream parts of the queue, keeping them from stop-and-go movement, in combination with 'turn off engine' advices. Simulation shows that this strategy can reduce fuel consumption at on-ramps with 15 percent. The second strategy uses vehicle classification to discriminate between vehicles, lanes, branches and possible on-ramps. In this case, simulation shows that this strategy can reduce fuel consumption at on-ramps with 29.6 percent.

INTRODUCTION

An increasing demand for transport in urban areas has resulted in chronic congestion, with many adverse consequences such as delays and pollution. Traffic is responsible for 40% of CO_2 emissions and 70% of emissions of other pollutants (1). With funding from the European Commission the Integrated Project eCoMove (2), part of the 7th Framework Programme, aims to reduce the overall fuel consumption in traffic by 20 percent. The consortium consists of 33 partners from 10 different countries which represent car manufacturers, traffic system vendors, system integrators, service providers, research institutes and universities. This three-year project started in April 2010 and builds on the result of related projects like CVIS (Cooperative Vehicle-Infrastructure Systems), SAFESPOT, COOPERS (COOPerative systEms for intelligent Road Safety), Pre-Drive C2X and COMeSafety. Its vision is to make driving support and traffic management more ecologically friendly using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.

Many studies indicate the factors which cause waste in fuel consumption in road transport. 22% of all wasted fuel is caused by inefficient deceleration and/or a lack of anticipation. Congestion is responsible for another 15%, whereas excessive speed, inefficient traffic light control, construction sites and/or traffic accidents each account for another 11% (3). Consequently, eCoMove emphasizes on three major inefficiencies: inefficient route choice, inefficient driving performance and inefficient traffic management and control. This paper focuses on reducing fuel consumption at a ramp metering installation, which provides an interesting case that includes the last two of the three major inefficiencies addressed by eCoMove.

Vehicles enter a motorway mainstream via an on-ramp. This can be a single-lane or dual-lane and single branch or dual branch on-ramp. If the flow of the mainstream plus the flow on the on-ramp (is expected to) exceed the motorway capacity downstream of the on-ramp, the ramp meter becomes active. Traffic at a ramp metering installation is generally chaotic (4). The desired speed before and after the ramp meter is often too high which results in unnecessary acceleration, deceleration and eventually stops. This is inefficient in terms of fuel consumption and presents a safety issue. In addition, the behaviour of ramp control is often not sensitive to changes in traffic conditions on either the mainstream or the on-ramp. Generally, ramp meters operate solely on macroscopic indicators derived from aggregated data, making them too simplistic to deal with fluctuating traffic conditions. The aim of this research is to illustrate that the performance of ramp meters can be improved in a number of ways. For example, by including more detailed control variables such as vehicle characteristics, by applying different strategies for different designs of on-ramps, by informing vehicles about the best driving strategy, or by considering the in-flow and spillback of the urban network in the optimisation.

The outline of this paper is as follows. The following section gives an overview of the state-of-the-art of ramp metering strategies as derived from literature review. Next an overview is given of possible strategies for different ramp meter topologies with emphasis on the opportunities which vehicle-to-infrastructure communication has to offer. Next, the results of a simulation study to indicate the impact of a selection of strategies are presented. The final section concludes and discusses next steps.

STATE-OF-THE-ART

The aim of ramp meters is to ensure that total flow on the freeway does not exceed capacity at downstream bottlenecks. Ramp metering is one of the most efficient tools to mitigate congestion, other than adding more capacity to transportation infrastructure. A variety of ramp metering strategies are in use worldwide, ranging from local strategies to coordinated strategies and from fixed control strategies to traffic responsive strategies (6). The majority of strategies in operation are traffic responsive using measurements upstream of the on-ramp. They are called feed-forward strategies, for example RWS-DC as used in The Netherlands (5). It uses the traffic flow on both the motorway and the on-ramp as well as the speed on the motorway to balance traffic demand and capacity to prevent or postpone the event of congestion on the motorway. Recently, the ALINEA-algorithm which also takes into account measurements downstream of the on-ramp has proven more successful in reducing delays (6,7). This type of strategy is called a feedback strategy and aims to keep the occupancy downstream of the on-ramp on a certain pre-specified value: the occupancy set point. Equity concerns and network optimization problems can be addressed using coordination ramp metering strategies, often combined with one of the local algorithms earlier discussed. The remainder of this paper focuses on local ramp metering based on the ALINEA algorithm.

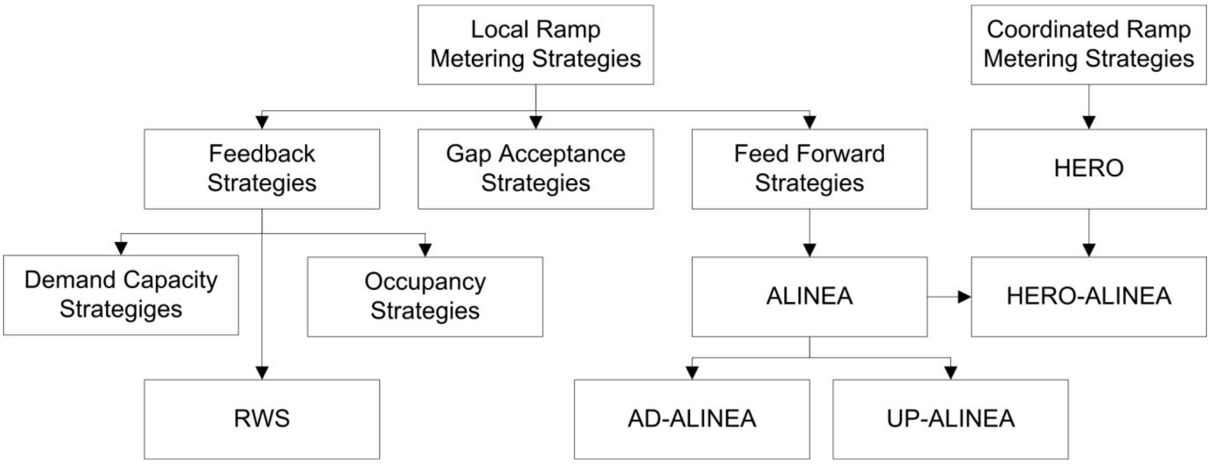

Figure 1 – Overview of ramp metering strategies

STRATEGY DESIGN

Being one of the most successful strategies in terms of preventing congestion on the motorway, it is likely that ALINEA also performs best in term of fuel consumption as compared to other ramp metering strategies. However, with the use of vehicle-to-infrastructure communication additional functionality becomes available which is believed to significantly reduce fuel consumption on on-ramps. Two strategies are discussed and evaluated in this paper: virtual stop line strategy (VSL) and truck priority strategy (TP).

VIRTUAL STOP LINE STRATEGY

Both strategies aim to reduce fuel waste caused by inefficient stop-and-go movement of vehicles. The first strategy uses virtual stop lines upstream of the actual traffic signal and is based on the principle that idling is more efficient than stop-and-go. In case of a long queue, these virtual stop lines halt parts of the queue while only the front of the queue is in stop-and-go mode. Once the most downstream section has cleared, the remainder of the queue can move forward at once, potentially saving a significantly amount of fuel. Additionally, it is foreseen to advice drivers to turn off their engine in case the waiting time at any of the virtual stop lines is longer than 10 seconds. The VLS strategy is illustrated in Figure 2.

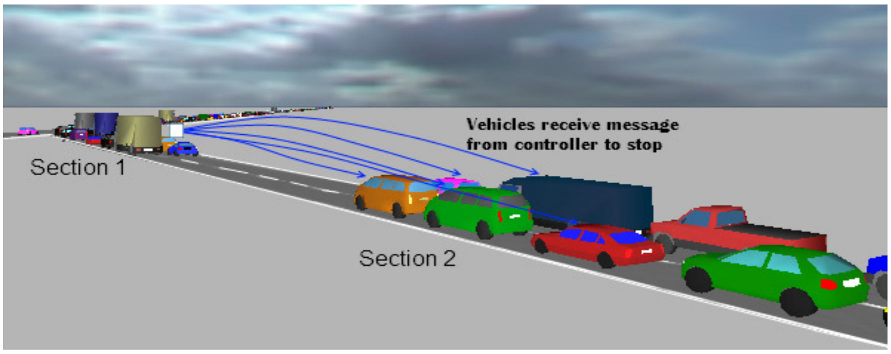

Figure 2 – Illustration of virtual stop line strategy

In this study the VSL strategy has been implemented using the control plan functionality of Aimsun. Two control plans were used. One control plan to regulate the ramp metering installation based on the ALINEA algorithm and a second control plan to control a virtual stop line 50 meters upstream of the ramp metering installation. In the simulation, the virtual stop line was implemented as a traffic light to represent queuing behavior of vehicles as if they received a message by means of V2I commendation telling them to halt (see Figure 3).

Figure 3 – Illustration of in-car messages

Consequently, the on-ramp is divided in two sections. When the VSL strategy is active, vehicles in section one will anticipate to the ramp metering installation based on the ALINEA algorithm as they normally would, while the vehicles in section two remain idle until the VSL strategy is deactivated. Also see Figure 4. The two control plans are activated and deactivated based on measurements from detectors and sections which are evaluated by triggers. In Aimsun, a trigger is a true or false expression based on a predefined criterion. Exploratory simulations teach that on-ramp traffic enters stop-and-go behavior when the on-ramp occupancy exceeds 80%. Hence, 80% occupancy was selected as an indicator for stop-and-go traffic. The control plan of the VSL strategy is activated when three conditions are met:

1. The occupancy at detector 1 is greater than 80%.
2. The queue formed at section 1 is greater than or equal to 10.
3. The occupancy at detector 2 is less than 80%.

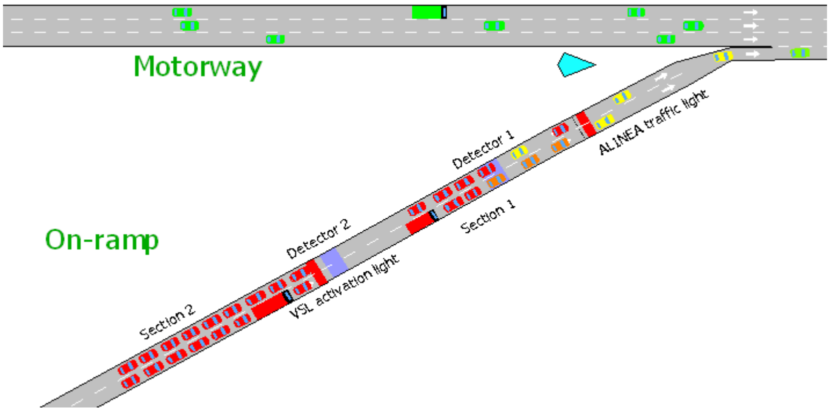

Figure 4 – Overview of on-ramp and VSL strategy activated

The first and second conditions are used to check if there is a queue formed at the on-ramp with more than 10 vehicles. The third condition checks if there is an overspill to the adjacent network. In short, the VSL strategy is only activated when there is no overspill to the adjacent network and there is queue of greater than or equal to 10 vehicles. The VSL strategy is deactivated again if one (or both) of two conditions are met:

1. The occupancy at detector 2 is less than 80%.
2. The queue formed at section 1 is less than or equal to 2.

Both conditions check if the vehicles in section 1 have been cleared to the motorway. If the section is nearly empty, the normal control plan is activated until the conditions for the VSL strategy are met again. The activation and deactivation process of the VSL strategy is summarized in Figure 5.

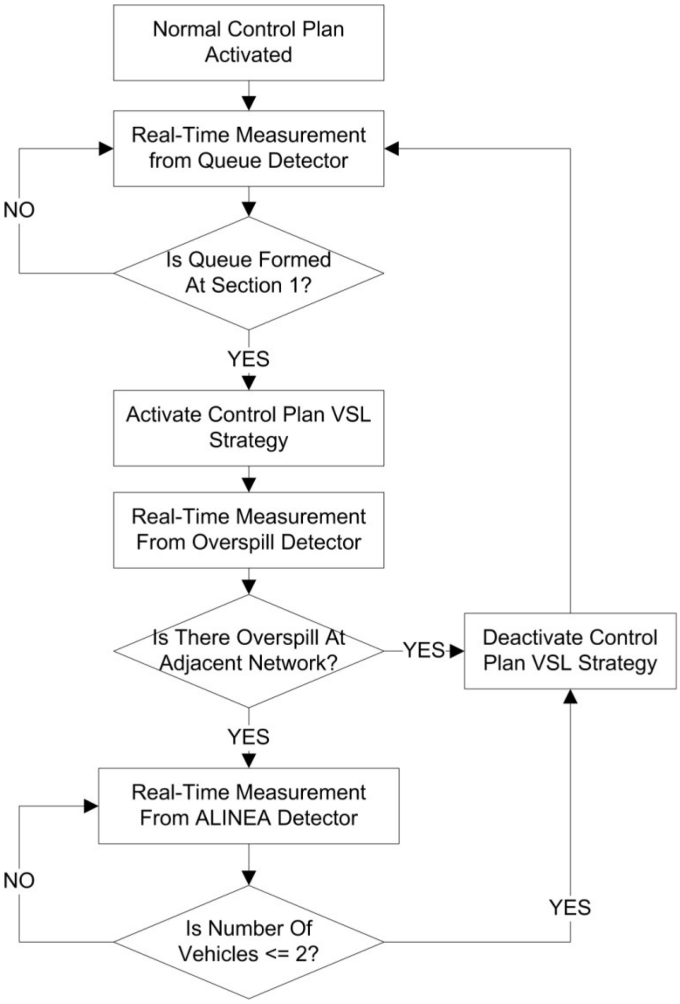

Figure 5 – Flowchart of virtual stop line strategy

TRUCK PRIORITY STRATEGY

The second strategy aims to discriminate between vehicles based on their classification. For example priority for heavy vehicles to minimize their fuel waste as they consume more fuel than others. On a single-lane on-ramp this may be done by decreasing the green intervals or increasing the number of vehicles per green. When a dual-lane on-ramp is concerned the lane with the particular vehicle may be favored over the other, releasing more vehicles till the heavy vehicle has passed. This same principle of lane discrimination could also be applied at dual-branch on-ramps where two traffic flows come together. Based on the composition of the traffic flow (e.g. share of heavy vehicle) or upstream influences of the traffic flows they may be treated differently.

In this study the TP strategy was integrated using two control plans in Aimsun. Similar to the VSL strategy, the first control plan regulates on-ramp flow based on the ALINEA algorithm, i.e. without truck priority. Under the condition that a truck is present on the onramp, control plan two is activated. Again triggers are used for evaluation, this time using the occupancy measurements of the detectors on the on-ramp. Truck priority is only realized if the truck is the fourth vehicle in the queue. Preliminary simulations showed that giving priority to trucks at a bigger distance from the stop line disrupts the flow on the motorway disproportionally. The flow chart of the TP strategy is shown in Figure 6.

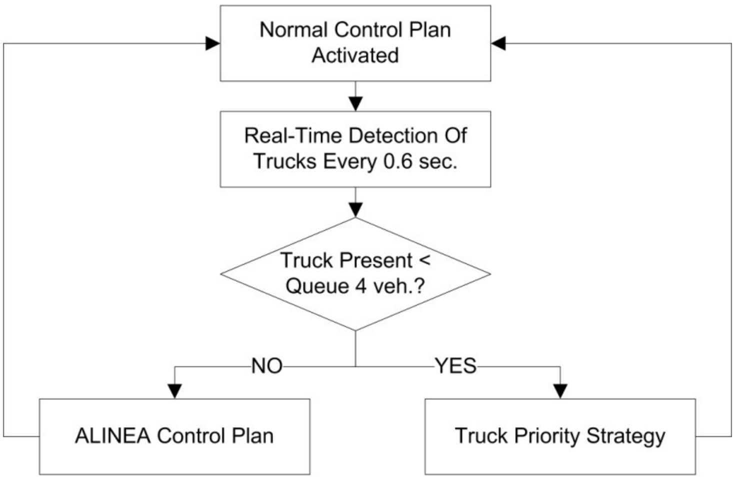

Figure 6 – Flowchart of truck priority strategy

EVALUATION

In an emission study, the development and calibration of the traffic models plays a crucial role. Model calibration is the process whereby parameters in the model are adjusted to accurately reproduce local traffic conditions and driver behavior; it is one of the most difficult issues in traffic simulation. It is a critical factor in evaluation studies as it determines the accuracy and reliability of results. Preliminary simulations using the default parameter settings of Aimsun caused major problems with regard to queuing and merging behavior of vehicles. This resulted in long queues on the on-ramp and overspill to the adjacent network (see also Figure 7).

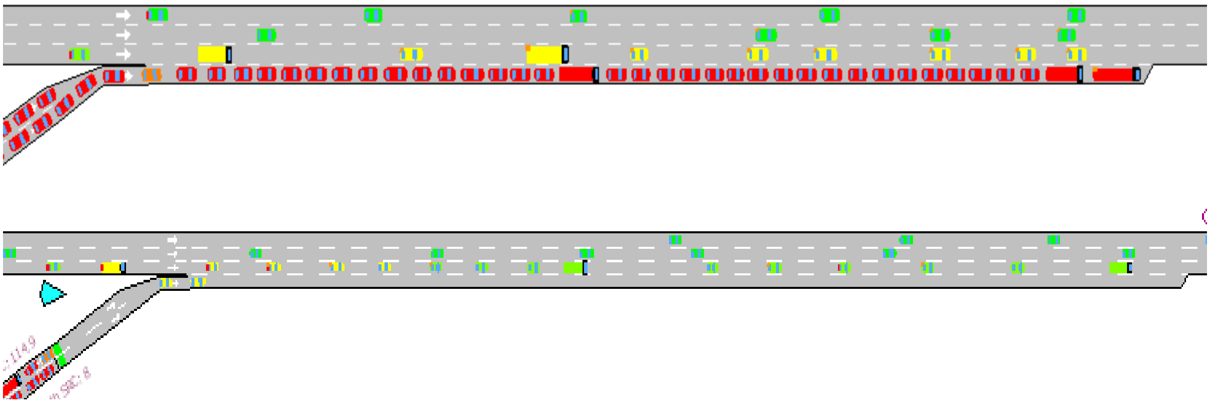

Figure 7 – Merging behavior before (above) and after (below) model calibration

To overcome these problems one can alter the parameters for: driver reaction time, reaction time at stop, car following behavior, lane change behavior and gap acceptance. It is beyond the scope of this paper to discuss the details of calibration undertaken for this study. For reference only, Table 1 summarizes the parameters that changed after calibration.

Table 1 – Calibrated parameters

Model parameter	**Default value**	**Calibrated value**
Drivers reaction time	0.75	0.68
Reaction time at stop	1.35	1.00
Lane Changing Model		
Percent overtake (%)	90	99
Percent recover (%)	95	100
Queuing up speed (m/s)	1	1
Queue leaving speed (m/s)	4	8
Look Ahead Model		
Maximum number of turnings	2	3

For evaluation purposes, then network under study is divided in two sections: one covering the motorway and another covering the on-ramp. Using the detailed vehicle data output of Aimsun four measures of effectiveness have been selected to evaluate accessibility and environmental impacts:

- Traffic emission values (CO_2, NO_x, and PM)
- Total travel time
- Average number of stops
- Volume of vehicles simulated

Carbon dioxide has an immediate link with fuel consumption. It is known that 1 kg CO_2 corresponds, on average, to 0.4 liter of fuel, although there is a small difference between the types of fuel (8). For statistically sound results, 10 runs with different seeds were averaged for all scenarios to compensate for the stochastic nature of traffic. The simulation period ran from 7:50 AM to 9:00 AM, which is representative for the morning commuter peak. For the VSL strategy a traffic flow of 1400 vehicles/hour was used for the on-ramp and 5400 vehicles/hour for the motorway. The TP strategy was evaluated for a single lane on-ramp with a traffic flow of 700 vehicles/hour, while the motorway traffic flow was 5400 vehicles/hour. In all cases the throughput of the network (i.e. vehicles entering the simulation) was evaluated to be sure that the travel time and emission estimation were based on similar traffic volumes. In all cases, negligible differences were found which means that comparisons can be made safely. In the following sections the results for each of the strategies are presented.

VIRTUAL STOP LINE STRATEGY

For the on-ramp, activation of the VSL strategy resulted in an overall reduction of CO_2 of 15%, a 23% reduction in NO_x emission, and a 14% reduction in PM. These substantial results were achieved mainly due to the reduction of the stop and go's, for the total network this reduction was 18%.

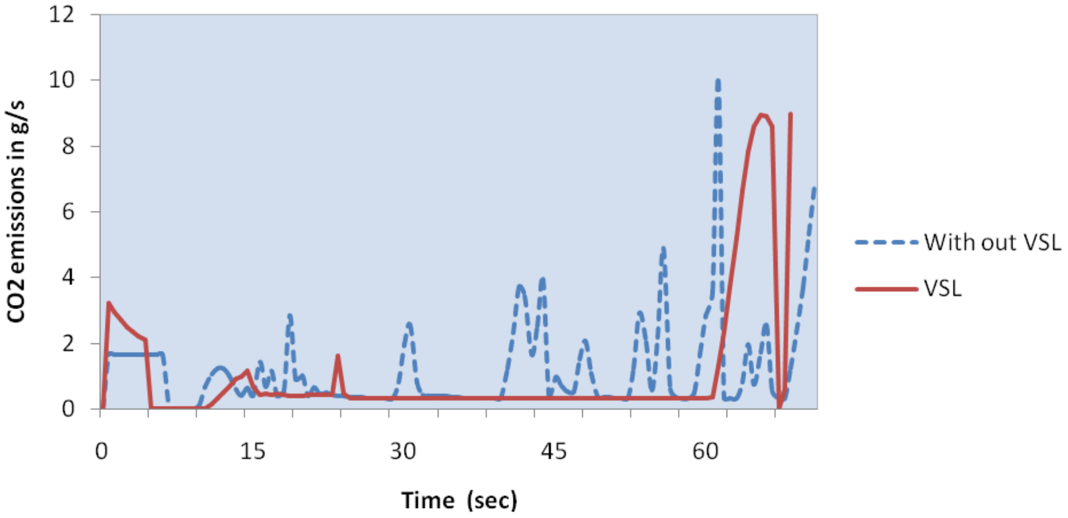

Figure 8 – comparison of typical vehicles on on-ramp without and with VSL activated

Figure 8 shows the typical trajectory of a vehicle on an on-ramp with and without activation of the virtual stop line strategy. Clearly, trajectories are much smoother with the strategy activated. The peaks in the curve around 60 seconds mark the moment the VSL strategy is deactivated and the vehicles move on to the actual stop line of the ramp metering strategy. On the entire network a reduction of 4% in CO2, 4% in NOx and 5% was observed. See also Table 2.

Table 2 – Results for virtual stop line strategy

	Aggregation Level	**Without VSL Strategy**	**With VSL Strategy**	**Difference**	**Impact**
CO_2 emissions (kg)	On-Ramp	253	214	38	-15%
	Motorway	874	871	33	Nihil
	Network	1127	1085	42	-4%
NO_x emissions (kg)	On-Ramp	0.963	0.739	0.224	-23%
	Motorway	4.640	4.630	0.010	Nihil
	Network	5.604	5.369	0.234	-4%
PM (kg)	On-Ramp	0.0559	0.0479	0.008	-14%
	Motorway	0.0655	0.0672	-0.0017	+2.67%
	Network	0.1214	0.1151	0.0063	-5%
Traffic Volume (vehicles in simulation)	Network	6805	6827	-23	Nihil
Total Travel Time (veh-sec)	Network	278046	280587	2541	+1%
Number of Stops	Network	0.393864	0.321962	0.0719013	-18%

TURN OFF ENGINE

Evaluation of the turn off engine strategy shows that the benefits are marginal. The strategy to advice motorists to turn off their engine was examined for compliance rates of 20%, 40% and 100%. For the analysis, vehicle modes (i.e. idling, accelerating and cruising) and emission rates were taken from the simulation using Matlab and assessed in combination with the compliance rates. Results are shown in Table 3. Even for compliance rate of 100% the impact on the total CO_2 emission in the network is less than 1 %.

Table 3 – Impact of turn off engine strategy

Compliance Rate (%)	Amount of CO_2 saved (gram)	Impact total network emission (%)
20	300	0.14
40	600	0.28
100	1500	0.70

TRUCK PRIORITY STRATEGY

For the on-ramp, activation of the TP strategy resulted in an overall reduction of CO_2 of 29.6%, a 37% reduction in NO_x emission, and a 34% reduction in PM. Although, the emission of motorway traffic slightly increases, the effect on the on-ramp is large enough to achieve an overall improvement. Compared with the virtual stop line strategy the benefits are higher as a result of targeting the most polluting vehicles with the TP strategy. This might be explained by the share of trucks of 10%, which is relatively high compared to other studies. Unexpectedly, the motorway hardly suffers from the truck priority strategy.

Table 4 – results for truck priority strategy

	Aggregation Level	Without Truck Priority	With Truck Priority	Difference	Impact
CO_2 emissions (kg)	On-Ramp	247	174	73	-29.6%
	Motorway	1.062	1.076	-1.398	+1.3%
	Network	1.333	1.250	239	-17%
NO_x emissions (kg)	On-Ramp	1.43	0.89	0.54	-37%
	Motorway	5.75	5.78	-0.03	+0.4%
	Network	7.18	6.66	0.52	-7%
PM (kg)	On-Ramp	0.05	0.04	0.02	-34%
	Motorway	0.087	0.084	0.003	-3%
	Network	0.14	0.12	0.02	-15%
Traffic Volume (vehicles in simulation)	Network	7095	7154	-59	Nihil
Total Travel Time (veh-sec)	Network	276	285	-9.8	+3.5%
Number of Stops	Network	0.1528	0.1335	0.0118	-88.6%

CONCLUSION

Fuel consumption at metered on-ramps can significantly be reduced by applying strategies which target inefficient stop-and-go movements of (heavy) vehicles. Benefits may increase up to 30 percent on on-ramps and 17 percent including the motorway section. The strategies and simulation results discussed in this paper serve as input for the development of the eCoMove application ‘ecoRamp Metering and Merging’. In simulation and at test sites this application will be evaluated in combination with other measures to reduce fuel consumption in traffic.

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