METERING WITH TRAFFIC SIGNAL CONTROL – DEVELOPMENT AND EVALUATION OF AN ALGORITHM

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ABSTRACT

For some on-ramps, which cause congestion on the motorway, it is not possible to install a ramp metering system for geometric or other reasons. But sometimes it is still possible to meter traffic with the traffic lights of nearby intersections in such a way that the situation on the motorway improves and on the urban network the situation does not get worse. The research described in this paper investigates the use of the traffic lights as metering lights if a ramp metering system is not available on the on-ramp. For this an algorithm was developed and tested in a simulation environment for a virtual network. The results showed that it is possible and effective, but the effectiveness is less than with regular ramp metering.

1. INTRODUCTION

In The Netherlands ramp metering is a common traffic management measure to decrease traffic jams on motorways and to improve throughput. Evaluation studies showed that it can be a very effective measure: the capacity of the motorway increased with 0% - 5%, speed on the motorway with up to 20 km/h and delay decreased with 8% - 30%, on average with 11% (Middelham & Taale, 2006). But on some locations, where it would be profitable to implement, ramp metering is not possible, because of the geometry of the on-ramp. For example, the on-ramp is too short to buffer traffic on it and blocking back would lead to queues on the urban network or it could be too expensive to implement ramp-metering on that location. Therefore, in the research described in this paper we look at the use the traffic signal controllers of nearby intersection to meter traffic heading for the motorway and we test this option with simulation for a theoretical network. The research is part of a development to come to a further integration of traffic management for motorways and urban traffic control. A development which is stimulated in The Netherlands with a field operational test around Amsterdam. Part of this test is to coordinate the operation of ramp metering systems with traffic signal control and to investigate the effects.

The Praktijkproef Amsterdam (Field Operational Test Integrated Network Management Amsterdam) aims at gaining practical experience with applying integrated network management in a large-scale regional (urban and motorway) network. It aims to improve the effectiveness of deploying traffic management measures in an integrated and coordinated way (Rijkswaterstaat, 2009). Within this project, the cooperating road authorities have opted for a stepwise implementation of the network control approach. In the first phase of the project the focus is on a motorway stretch (the A10-West, part of the A10 ring road) and its on- and off-ramps and connecting intersections, and one connecting urban arterial with its intersection controllers. All on-ramps to the motorway are equipped with ramp metering systems. In the subsequent phases, larger areas of the Amsterdam network will be considered (Hoogendoorn *et al*., 2014.)

One of the mean goals of the integrated control strategy is to use the spare capacity (buffer space) in the network. If there is ramp-metering traffic queues on the on-ramp, but normally the on-ramp has a limited space to store traffic. Using other parts of the network to store queues could improve the situation, because then on-ramp space for queues is virtually extended and ramp-metering can operate in the preferred mode for a longer time. These so-called buffers are predefined locations where vehicles can be ‘stored’ for a little while, without causing problems for the rest of the network. The usage of buffers in the network depends on the level-of-service in the network: if traffic conditions worsen, more buffer space can be added to alleviate the problems.

To use this buffer space in an effective way for the combination of a ramp metering system and a connecting intersection a supervisor module was developed. This supervisor (named ST1-Light or ST1L for short) essentially controls the inflow from intersection controllers adjacent to the ramp meter into the on-ramp, in order to prevent the queue on the on-ramp from spilling back onto the urban arterial. In doing so, it extends the storage space for the ramp-meter substantially. In particular for the Dutch situation, since the storage space on the on-ramps in many cases is very limited.

And that brings us to the situation in which the on-ramp has not enough storage capacity to implement an effective ramp metering system. The question then arises if it is possible to use the intersection controller to meter traffic to the motorway directly. This paper deals with this topic. First, it describes the original algorithm if a ramp metering system is available and then the adjustments for a situation without ramp metering. After that the simulation setup is given and the results of the runs to test the algorithm. Finally, some conclusions are drawn and directions for further research are given.

2. CONTROL PRINCIPLES

For this research we look at the situation where a bottleneck occurs downstream of the on-ramp. Normally, the ramp meter will restrict the inflow to the motorway to improve the situation there, at the expense of a queue on the on-ramp itself. If the queue grows the urban network can get blocked. To prevent that, the supervisor ST1L is asked to buffer traffic on the available locations in the network to decrease the flow to the on-ramp. In that way the ramp metering system can do its job and the queue on the on-ramp will stay within the limits.

An important issue then is how to distribute the surplus of vehicles between the available buffer locations, taking into account the limits these buffers have. The ST1-Light deals with this issue if there is ramp metering available and the control strategy for that is described in the next paragraph.

2.1. Control strategy with ramp metering

The ST1-Light realises the coordination between the traffic control goals which are set for the motorway and the local controllers on the urban arterials, using the available buffers. Every on-ramp has a feeding urban arterial. For this arterial a set of buffers is defined, which can be used to keep the on-ramp free of congestion, or at least as long as possible. The module determines which buffers can be used at a certain moment, because that depends on the current situation, both on the motorway and the urban network. The ST1L uses this information to determine boundary conditions for the local controllers on the arterial. The local controllers are responsible to handle the traffic on the intersections itself.

For the current implementation the ST1L only deals with restricting the inflow from the urban network to the on-ramp. For this an algorithm was developed, consisting of 7 steps:

1. Determine the buffers which are allowed to be used under the current traffic conditions, based on external information.

2. Determine the available effective buffer space for an on-ramp.

3. Determine if the use of buffers is needed, based on the (estimated) queue length on the on-ramp.

4. Determine how much traffic has to be stored in the buffers, defined as the difference between the estimated demand for the on-ramp and the actual metering rate. The ST1L will try to limit the flow to the on-ramp to the metering rate; otherwise the queue on the on-ramp will increase and eventually will block the surface streets.

5. Distribute the surplus of traffic among the available buffers, using the simple rule that all available buffers are filled equally. The formula for this is

$$b_j(t) = b_j(t-1) + b_r(t)\frac{s_j^{eff}(t)}{\sum_j s_j^{eff}(t)} \quad (1)$$

where b_j is the number of vehicles that is has to be stored in buffer *j*, b_r is the total number of vehicles for ramp *r* that needs to be stored somewhere else and s_j^{eff} is the effective buffer space for buffer *j*.

6. Calculate the adjustment for the green time g_m^n of signal *m* of intersection *n* that controls the buffer with

$$\Delta g_m^n(t) = \frac{b_j(t)C^n(t)}{u_m^n(t)} \quad (2)$$

where C^n is the cycle time and u_m^n is the saturation flow of the movement which is controlled by signal *m*.

7. Communicate the green time adjustments to the local controllers and start the next cycle.

These seven steps form the core of the algorithm. The complete specification (Taale, 2014) contains all kinds of details which contribute to an effective operation of the algorithm.

In the following paragraph the algorithm is adjusted for the situation that no ramp metering system is implemented on the on ramp and the traffic signal controller is used for that purpose.

2.2. Control strategy without ramp metering

If there is no ramp metering system available, a normal traffic signal control system could take over the metering functionality and the functionality to distribute a surplus of traffic over the available buffer locations. We call this dummy ramp metering. Differences between normal ramp metering system and dummy ramp metering are:

- Normally, for ramp metering only one car per green phase is allowed to pass the stop line. A traffic signal controller allows several vehicles to pass, in which case platoons of vehicles enter the motorway, instead of one by one.
- The distance to the motorway is larger for the traffic signal controller, which could lead to slower reactions in relation with the conditions on the motorway.
- For an intersection several movements could connect with the on-ramp, which means that the traffic signal controller should meter all those movements and not only one.

Dummy ramp metering also means that the system should determine the metering rate for the movements to the on-ramp and should also determine the effect of this metering rate on the use of the buffers. The control strategy is designed in such a way that these aspects and the differences mentioned are taken into account as much as possible. The following steps define the strategy (Legius, 2014):

1. Determine the buffers which are allowed to be used under the current traffic conditions, based on external information.

2. Determine the available effective buffer space for an on-ramp.

3. Determine if metering traffic is necessary and if so calculate the metering rate.

4. Determine if the use of buffers is needed, based on the (estimated) queue length on the on-ramp.

5. Determine how much traffic has to be stored in the buffers, defined as the difference between the estimated demand for the on-ramp and the actual metering rate. The ST1L will try to limit the flow to the on-ramp to the metering rate; otherwise the queue on the on-ramp will increase and eventually will block the surface streets.

6. Distribute the surplus of traffic among the available buffers, using the simple rule that all available buffers are filled equally.

7. Calculate the adjustment for the green times.

8. Communicate the green time adjustments to the local controllers and start the next cycle.

For determining the metering rate in step 3 the AD-ALINEA algorithm is used. AD-ALINEA is based on the original ALINEA metering algorithm (Papageorgiou *et al.*, 1991) and it adapts the control parameter critical occupancy to the current situation (Kosmatoupoulos *et al.*, 2006). Steps 6 and 7 are equal to steps 5 and 6 of the control strategy with ramp metering.

To test and compare the different control strategies a simulation environment was used. This environment and the simulated scenarios are described in the next section.

3. SIMULATION SETUP AND SCENARIOS

The control strategies in the previous section were tested in a simulation environment. For this the microscopic simulation tool VISSIM was used, because of the signal control possibilities and the connection with the MATLAB programming environment in which the control strategies were developed. In the following aspect some simulation aspects are discussed as well as the network and the scenarios.

3.1. Simulation aspects

An important goal of metering is the prevention of the capacity drop. To determine the influence of metering with a traffic signal controller on this phenomenon, the model should be able to simulate that. For microscopic simulation models that is not always possible. For VISSIM vehicle acceleration and deceleration values were adjusted to be able to simulate the capacity drop to an acceptable extent. In the simulated case the capacity drop was about 20%

Also most micro-simulation models have difficulties to simulate the merging process accurately. For this study this was important, because of the difference in metering strategies and the amount of vehicles allowed to enter the motorway at the same time (one-by-one or in platoons). To get satisfactory merging behaviour in VISSIM lane change parameters, such as the accepted and maximum deceleration, had to be adjusted.

3.2. Network and demand

To be able to show the effects of the different control strategies clearly and to be able to control as much as variables as possible, a virtual network was used. It consists of a 2-lane motorway of 4 kilometres, with 2 on-ramps. These on-ramps are connected with two intersections, each with 6 movements, of which 2 are leading to the on-ramp and which have a buffer space. A sketch of the network is shown in figure 1. The on-ramp has a length of 400 meter and the buffer space for the intersections is 200 meters for every movement.

The demand used in the simulation is given in figure 2. It shows a peak in the demand after 20 minutes, both for the motorway and for the on-ramps. The demand for on-ramp 1 is about twice as high as for on-ramp 2. This demand profile (demand profile 1) leads to congestion on the motorway, somewhat downstream of on-ramp 1 and the congestion lasts about an hour. The speed contour plot, which shows this clearly, is presented in figure 3. Another demand profile was also simulated (demand profile 2). For this profile the demand for on-ramp 2 is the same as for on-ramp 1.

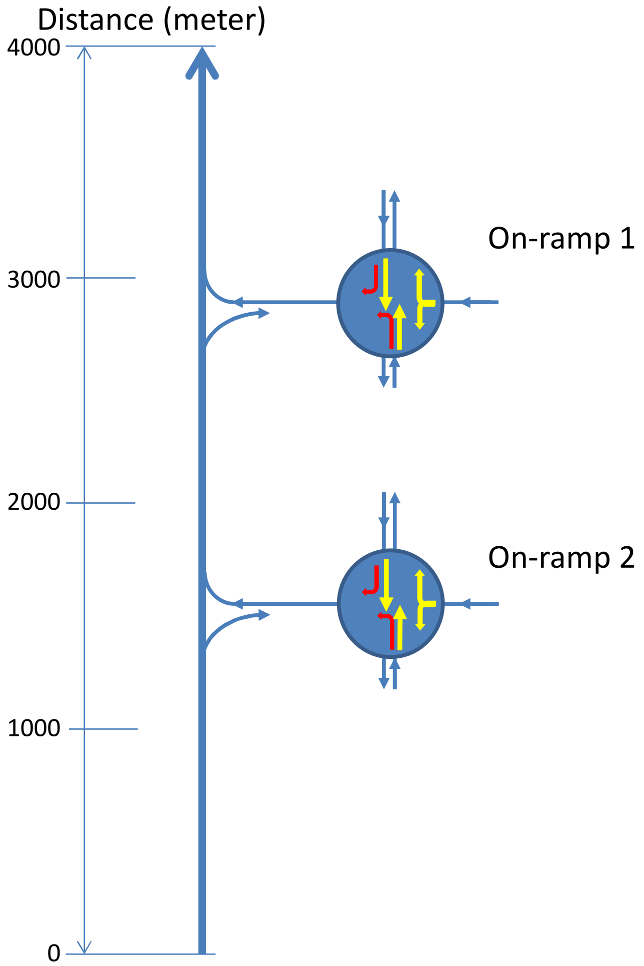

Figure 1: Virtual network used for the simulations

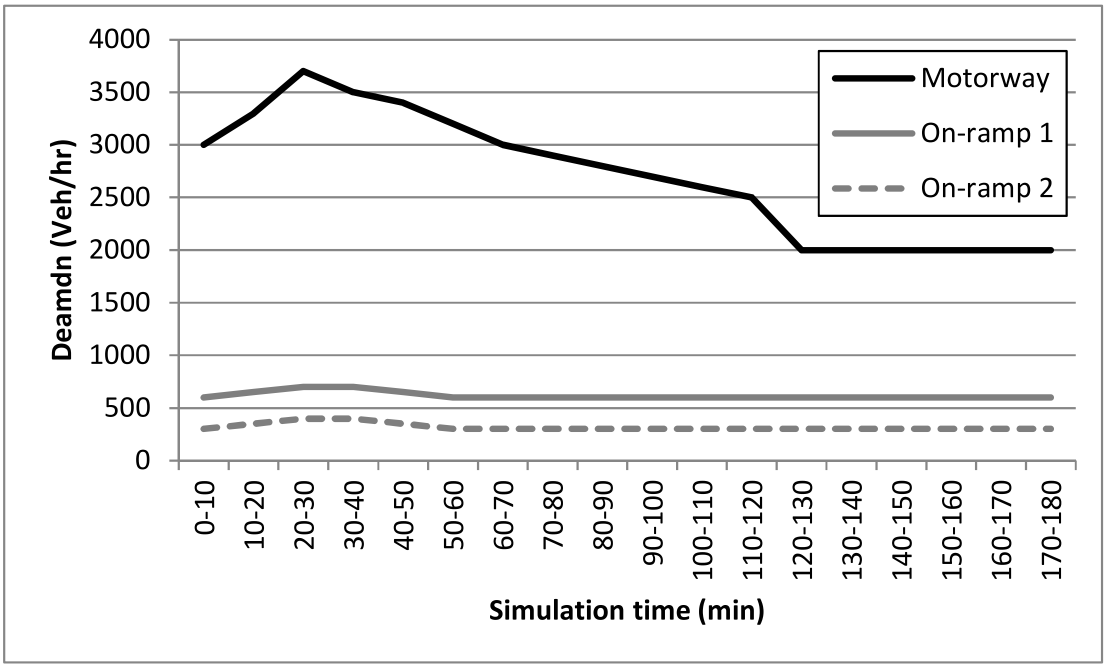

Figure 2: Demand profile for the simulations

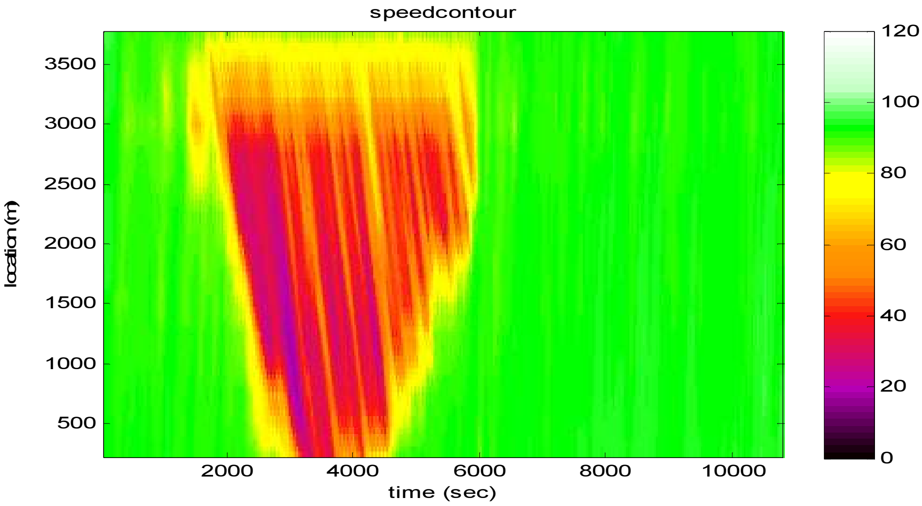

Figure 3: Speed contour plot for the base situation

3.3. Scenarios

The goal of this research was to see whether or not normal traffic signal controllers could be used to meter traffic and to improve the situation in the network, just like normal ramp metering. To this end three scenarios were simulated:

1. Base: situation without ramp metering, but with local (fixed-time) signal control for the intersections.

2. Local ramp metering: situation with ramp metering on the on-ramps and local signal control. Ramp metering is done with the AD-ALINEA algorithm, using the following parameters:
   - Default critical density: 33 veh/km/lane.
   - Density threshold for switching ramp metering on: 24 veh/km/lane.
   - Density threshold for switching ramp metering off: 17 veh/km/lane.
   - Minimum cycle time ramp metering: 3.75 seconds.
   - Maximum cycle time ramp metering: 15.0 seconds.
   - Gain parameter K: 70.

3. Dummy ramp metering: situation in which the traffic signal controllers are used to meter traffic towards the on-ramp. The algorithm for this is described in paragraph 2.2.

These three scenarios were simulated with 6 different random seeds to account for the stochastic nature of the simulation. The results of these 6 simulations are averaged and assessed for the indicators total distance travelled (veh.km), total time spent (veh.hrs), average delay (sec/veh) and total delay (veh.hrs).

4. RESULTS AND DISCUSSION

4.1. Network results

Figure 4 shows the total distance travelled for the three scenarios and two demand profiles. For all scenarios the results are nearly the same (differences with the base situation are smaller than 0.02%), which means that the same amount of traffic was simulated and that the differences for the other indicators can be contributed to the control strategy used.

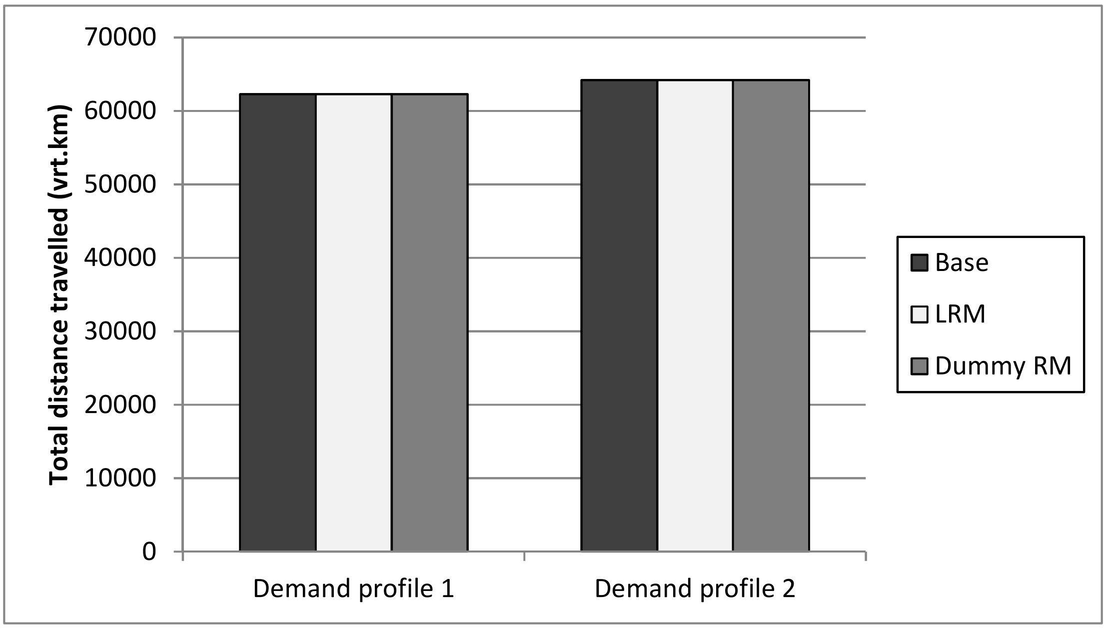

Figure 4: Results for the total distance travelled

The results for the total time spent in the network and the average delay per vehicle are shown in the figures 5 and 6.

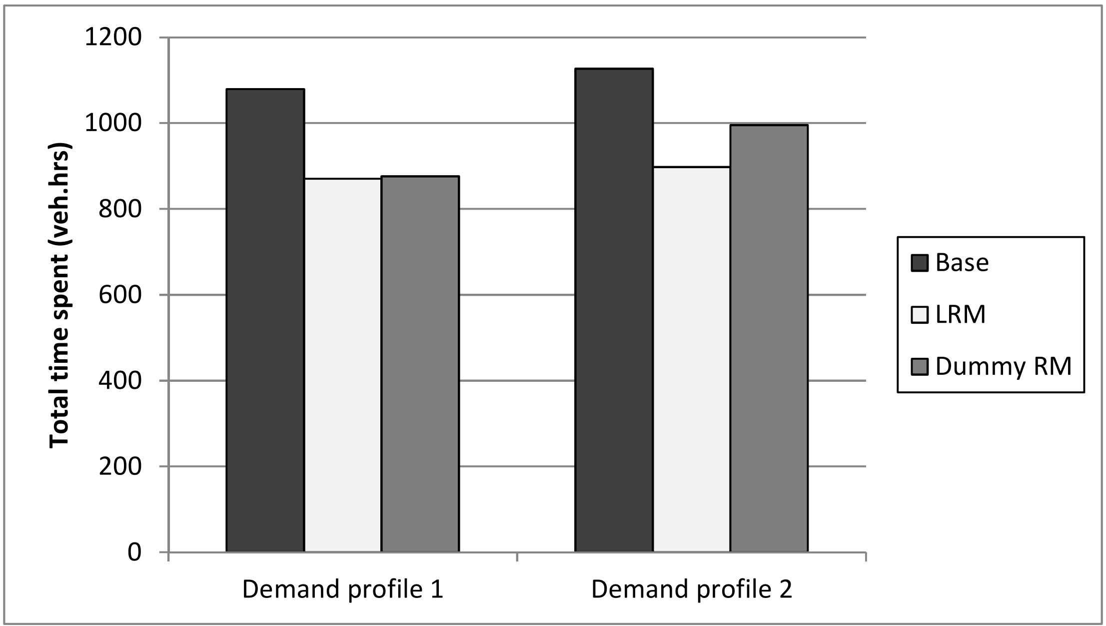

Figure 5: Results for the total time spent in the network

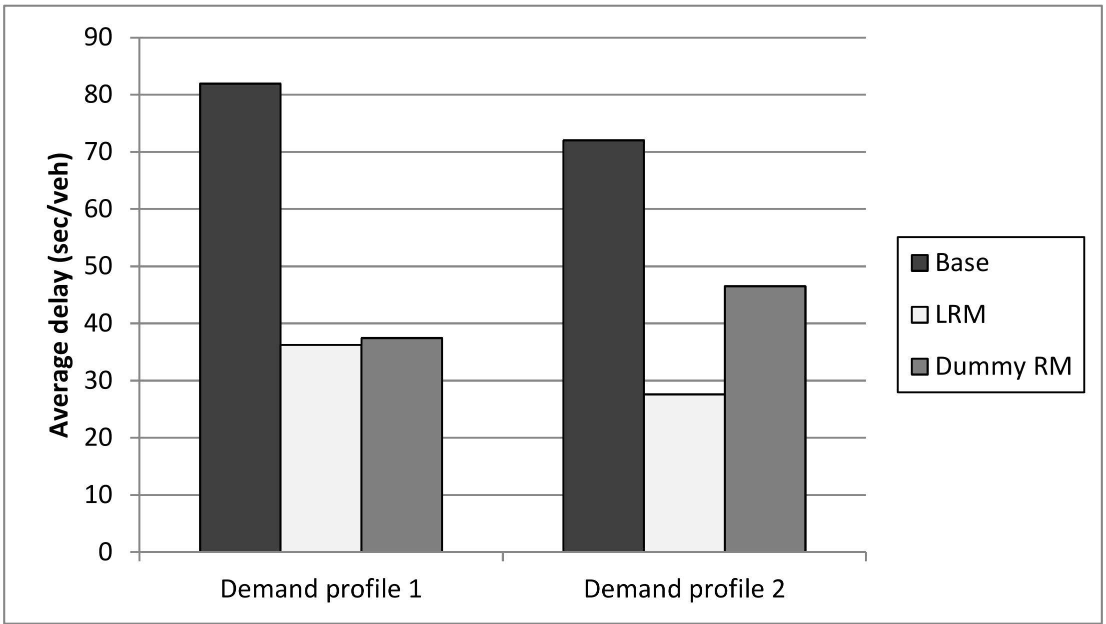

Figure 6: Results for the average delay per vehicle

From these graphs it is clear that metering itself is beneficial for this network. Local ramp metering decreases the total time spent with 19.3% for demand profile 1 and 20.3% for demand profile 2. Metering with traffic signal control (dummy ramp metering) obtains almost the same effect for demand profile 1 (decrease of 18.8%), but for demand profile 2 the effectiveness is less (decrease of 11.7%), but still considerable.

The same pattern emerge from the results for the average delay per vehicle: ramp metering decreases the delay with 55.8% (demand profile 1) and 61.7%

(demand profile 2) and metering with traffic signal control decreases the delay with 54.3% (demand profile 1) and 35.4% (demand profile 2).

4.2. Other results

To take a more detailed look into the results, the slanted cumulative curve is used. This curve displays the cumulative flow downstream on-ramp 1, where the congestion starts. It is slanted, because a certain threshold (an estimate of the capacity in this case) is extracted from the values, which gives the possibility to visualise the capacity drop. In figure 7 the slanted cumulative curve for one of the six simulations for demand profile 2 is given. A capacity drop is visible in this graph as a decrease for the cumulative flow while the demand still increases. The graph shows that for the base situation the capacity drop occurs earlier (red dashed vertical bar at minute 27) than for the situation with dummy ramp metering (green dashed vertical bar at minute 40). That means that for this situation the capacity drop is postponed, but not prevented, as in the case with ramp metering. At the moment the capacity drop occurs in the base situation, the capacity for the RM situation is higher than for dummy RM. This is shown by the dashed black slope lines. This explains that the results for RM are better than for dummy RM, which in turn are better than the results for the base situation.

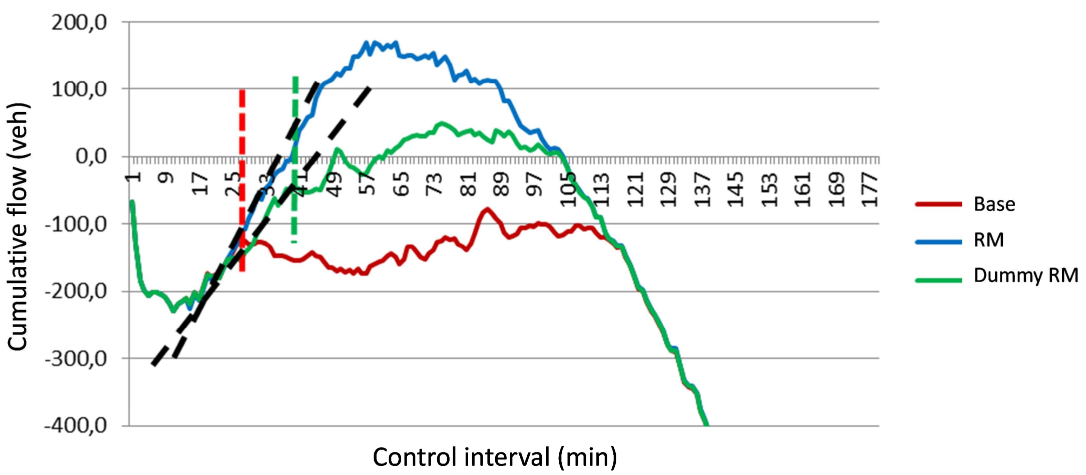

Figure 7: Slanted cumulative curve, demand profile 2, simulation 5

A final result concerns the delay in different parts of the network. For demand profile 2 a distinction is made in delay for the motorway and delay for the urban network. The results are shown in figure 8.

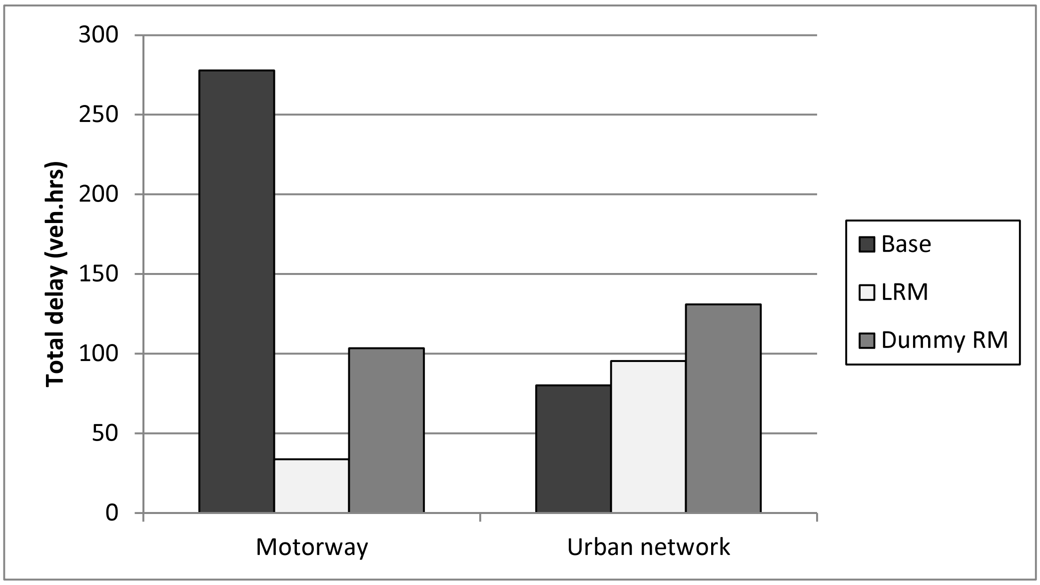

Figure 8: Delay for different parts of the network

It is clear that metering causes a shift in delay from the motorway to the urban network, which is of course to be expected. However the net effect is positive. For local ramp metering there is a decrease in delay of 64%, for metering with traffic signal control this is 35%, which is still considerable.

5. CONCLUSIONS AND FURTHER RESEARCH

The goal of the research described in this paper was to investigate if normal traffic signal control can be used to meter traffic heading for the motorway. We can conclude from the results in this paper that metering with traffic signal control is a promising control strategy. The simulations showed that sometimes the same effect as normal ramp metering can be obtained, but normally it is less effective. Still, it is much better than no metering at all. So, for real-life cases it is certainly an option to consider if ramp metering is not possible.

It can also be concluded that metering with a traffic signal controller can also postpone a capacity drop on the motorway, but to a lesser extent than normal ramp metering, which can be expected due to the disadvantages (metering further away from the motorway and platoons). The influence of these disadvantages has not been investigated, but it is expected these are important aspects for the effectiveness of the control strategy.

Another assumption in this research is the use of fixed-time control for the intersections. Advanced control strategies, such as vehicle actuated control, agent-based control (Van Katwijk, 2008) or anticipatory controls (Taale, 2008) behave different and thus have different impacts on the effectiveness of the metering strategy. But how this works and what impacts that are, is not clear and is left for further research.

Other issues for further research are the use of the AD-ALINEA metering algorithm and its parameters, the network configuration and demand profiles of this simulation approach and the possibility for coordination between the on-ramps. For ramp metering coordination strategies have been developed, such as HERO (Papamichail & Papageorgiou, 2008), but for metering with traffic signal controllers, this is still a topic for research.

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BIBLIOGRAPHY

Hoogendoorn, S., Landman, R., Van Kooten, J., Taale, H. and Schreuder, M. (2014) Integrated Network Management Amsterdam: Towards a Field Operational Test, Proceedings of the *93rd Annual Meeting of the Transportation Research Board*, Washington D.C., January 2014.

Kosmatopoulos, E., Papageorgiou, M., Manolis, D., Hayden, J., Higginson, R., McCabe, K. and Rayman, N. (2006) Real-Time Estimation of Critical Occupancy for Maximum Motorway Throughput, *Transportation Research Record*, Volume 1959, pp. 65-76, 2006.

Legius, P. (2014) Metering with Traffic Signal Control, MSc Thesis, Delft University of Technology, January 2014 (in Dutch).

Middelham, F. and Taale, H. (2006) Ramp Metering in The Netherlands: An Overview, Preprints of the *11th IFAC Symposium on Control in Transportation Systems*, Delft, The Netherlands, August 29-31, 2006, pp. 267-272.

Papageorgiou, M., Hadj-Salem, H. and Blosseville, J.-M. (1991) ALINEA: A Local Feedback Control Law for On-Ramp Metering, *Transportation Research Record*, Volume 1320, pp. 58-64, 1991.

Papamichail, I and Papageorgiou, M. (2008) Traffic-Responsive Linked Ramp-Metering Control, *IEEE Transactions on Intelligent Transportation Systems*, Volume 9, Issue 1, pp. 111-121.

Rijkswaterstaat (2009) Field Operational Test Traffic Management Amsterdam – Proof of Concept, Report for the Dutch Ministry of Infrastructure and the Environment, October 2009 (in Dutch).

Taale, H. (2008) Integrated Anticipatory Control of Road Networks – A game theoretical approach, PhD thesis, TRAIL nr. 2008/15, Delft University of Technology, Delft, December 2008.

Taale, H. (2014) Technical Specification Supervisor T1-Light (without network control system), version 2.8, February 11th, 2014 (in Dutch).

Van Katwijk (2008) Multi-Agent Look-Ahead Traffic-Adaptive Control. PhD thesis, TRAIL nr. 2008/03, Delft University of Technology, Delft, January 2008.