EVALUATION OF IMPACTS OF THE MOTORWAY CONTROL SYSTEM (MCS) IN STOCKHOLM

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ABSTRACT

Stockholm as many other major urban areas suffers from road traffic congestion due to difficulties to provide much needed capacity expansion of its road networks to cope with the increasing demand. Major arterials operate close to or over capacity during morning and afternoon rush hours, which results in recurring congestion and serious disturbances even by relatively minor incidents. A Motorway Control System (called MCS) has been implemented on the E4 motorway through Stockholm with recommended speed signalling triggered by automatic incident detection alarms for downstream queues. A major research study was undertaken in cooperation with national and regional road authorities to assess the impacts of MCS on traffic performance and traffic safety. The project included extensive field studies with stationary as well as mobile data collection techniques aimed at capturing individual driver behaviour (speed adaptation, deceleration process) as well as traffic characteristics (flow, speed, lane distribution, headways). The impacts of MCS were analysed by comparison of survey results for time periods with high, middle and low traffic flows without and with the system in operation. The study concluded that the main MCS impact consisted of a sharp decrease of the standard deviation of speed, which would indicate an improvement in homogeneity and traffic safety. Furthermore MCS reduced the frequency of very short headways as well as the frequency of lane changes between the middle and the left lane.

Driver behaviour impacts were difficult to assess due to the difficulties to perform controlled experiments with or without active MCS for comparable situations. Most drivers seemed to ignore the recommended speed signs since they were not mandatory. However, there was an indication that recommended speed signalling warning for downstream queuing influenced the deceleration process to become more stable.
1. INTRODUCTION

1.1 Background
Stockholm as many other major urban areas suffers from road traffic congestion due to difficulties to provide much needed capacity expansion of its road networks to cope with the increasing demand. Many arterial roads operate close or over capacity during morning and afternoon rush hours, which causes serious recurring traffic congestion as well as incident impacts. The Swedish Road Authority (SRA) in cooperation with the Stockholm government have therefore implemented a Motorway Control System (called MCS) based on the Dutch MTM system on the E4 motorway through Stockholm. Although MCS has been in operation since the late nineties and is currently being expanded, there is yet no comprehensive knowledge regarding the impacts of this system on traffic performance and traffic safety. This paper is based on a major research project undertaken at KTH in cooperation with national and regional road authorities in Stockholm aimed at filling this knowledge gap.

Figure 1, Route E4 approaching Stockholm during morning rush hour.
1.2 The Stockholm Motorway Control System (MCS)
The northern part of the E4 motorway (8 km) was equipped with MCS in 1996, and the southern part (12 km) in 2004. The latter section has an AADT around 150 000 vehicles, and flows around 5000-6000 veh/h per direction of travel (3 lanes 3.5 m wide). MCS is essentially a main-line link control system, although some ramp metering has also been implemented in 2005 to avoid excessive overloading of critical road segments. The basic function of the system is to detect incidents in the form of slow moving traffic, and to reduce the risk for collisions by display of recommended speed limits using Variable Message Signs (VMS) on gantries upstream of the incident. This involves the following process as shown in Figure 2:

1. **Traffic surveillance for recording of the actual traffic situation and automatic incident detection.**
   Microwave detectors collect information of vehicle passages in each lane as a basis for calculation of flow, speed, occupancy and headway, which is, aggregated as one-minute averages. Smoothed averages of speed are also calculated as a basis for Automatic Incident Detection alarms (AID), which can be verified using closed circuit television (CCVT).

2. **Lane signalling using VMS for communication with the drivers.**
   AID-alarms based on detection of speed using two threshold levels (35 and 50km/h). If one of the values subsides its threshold, an AID legend-request results which triggers pre-determined lane-signalling plans aimed at reducing the speed of traffic approaching the location of the detected incident. These signals are displayed by VMS panels mounted on gantries above each lane every 500 m which can show recommended speed levels (70, 60, 50, 30 km/h) or lane closure.

3. **Driver response to the lane signalling and surrounding traffic situation.**
   Drivers approaching a gantry with activated lane signals can react in different ways; ignore the signal message or change their speed and/or selected lane in response to the signal. The purpose of MCS is that the drivers will change their behaviour in such ways that it will improve traffic safety and traffic performance on the controlled road link.
1.3 Objectives and Scope

The main purpose of the project was to gain improved knowledge of MCS implementation for link control, especially focusing on its impact on traffic safety and traffic performance, two important objectives of transport policy.

1.4 Research Methodology

On congested motorways shockwaves are normally frequent causing “stop-and-go” waves, in which vehicles can only travel with reduced speed or come to a complete standstill for periods of time.

Furthermore congestion increases the amount of interaction between vehicles and leads to a high amount of lane changes in very short gaps. In order to capture these characteristics as well as individual driver behaviour in general, the data collection has to be very detailed. The selected research strategy for the project described in this paper was therefore “microscopic” assessing traffic performance and safety impacts based on studies of driver response to the displayed MCS lane signals.

The project included the following main stages:

A) Study of driver behaviour in response to MCS variable speed sign messages, and related local traffic performance and safety effects.

B) Study of impacts of MCS on traffic process along the road.

C) Coding of MCS- functionality and driver behaviour characteristics in a microscopic simulator.

D) Calibration, validation and application of the simulation model for the usage of MCS impact assessment.
This paper covers results obtained in stage A and B above. Stage C is planned to be completed in 2007 and results from the empirical study regarding driver behaviour related to MCS operation will be incorporated in a microscopic simulation model (e.g. VISSIM). In addition, the Automatic Incident Detection (AID) algorithm will be implemented in the simulator for further analyses of different strategies and improvement of the MCS functionality.

This will enable “controlled experiments” in Stage D for evaluation of system impacts and alternative strategies for application of the system and its operation in the traffic management centre (called TRAFIK STOCKHOLM).

1.5 International Literature Review

Motorway link control using advisory or enforced variable speed signs to warn drivers of incidents blocking the driveway such as queues downstream have been applied in many countries since the early seventies (Kühne, R.D., 1991; Smulders, S., 1990, 1992, 1996; Smulders, S.Helleman, D.E., 1998; Zackor, H., 1979). Similar techniques can also be used to warn for adverse weather conditions such as fog (Cooper, B.R.Sawyer, H., 1993; Hogema, J.H.Van der Horst, R., 1997), slippery road (Rämä, Pirkko., 2001) and work zones (Lin, P. W. et al., 2004; Ober-Sudermeier, A. Zackor, H., 2001).

In an overview of speed limit systems (Hegyi, A., 2004) a distinction is made between 1) approaches that aim at homogenization, and 2) resolution of shockwaves or jams. Most applications of link control emphasize homogenization or stabilization effects i.e., (Rämä, Pirkko., 2001; Smulders, S., 1990, 1992, 1996; Zackor, H., 1979). For proper operation of such systems real-time information of traffic flow, speed, occupancy and for some type of systems also weather, visibility or road surface condition are required to determine the appropriate speed at which drivers should be travelling. Several authors report that enforced speed limits lead to higher driver compliance which is necessary to ensure efficient system operation (Harbord, B., 1997; Rämä, Pirkko., 2001; Smulders, S., 1990, 1992, 1996; Van den Hoogen, E.Smulders, S., 1994; Wilkie, J. K., 1997).

Homogenization measures such as speed control aim to reduce the flow and speed variance between or within lanes. It also aims at decreasing the fraction of small headways in order to reduce the risk for shock waves, thereby minimizing accident risks and upstream congestion. (Remeijn, H., 1982) shows that variable speed signs for driver warning have been successfully applied on many Dutch motorways. Other studies, e.g. (Garber, N.J. Gadiraju, R., 1989), show that accident rates do not necessarily increase with an increase in average speed, but rather with increased speed variance. The aim of homogenization should therefore not be reduction of the mean speed but reduction of the speed differences (Cremer, M., 1978), (Smulders, S., 1990).
Experiments reported by Van den Hoogen (1994) indicate that Variable Speed Limit (VSL) control does not eliminate congestion at bottlenecks since the capacity of the roadway is not increased, however the effects of the bottlenecks on upstream traffic can be lessened. Other studies use variable speed limits with the aim to reduce the occurrence of shock waves on motorways, (Hegyi, A., 2004; Hegyi, A. et al., 2003, 2003).

An attempt was made by Hegyi (2004) to outline the difference between homogenization and breakdown prevention in terms of when to apply speed limits. The homogenization approach uses limits that are above the critical speed (i.e., the speed that corresponds to the maximal flow), while the breakdown preventing approach allows speed limits that are lower than the critical speed in order to limit the inflow to bottleneck areas.

Although link control using variable speed signs has been applied on a wide scale in several countries since the seventies, there is a lack of research studies evaluating the impact of these systems. Most of the developed models are not validated with any empirical data (Alessandri, A. et al., 1997; Hegyi, A. et al., 2002). Kostsialos et al. (2002), and Papageorgiou et. al (2003) state that “very few systematic studies have been conducted to quantify the impact of link control measures. One important component in the control loop in variable speed control management is driver behaviour, which is difficult to detect and forecast adding uncertainty to the problem of traffic management.

2. DATA COLLECTION

The study included a pilot study on a stretch of motorway on the northern part of the E4 motorway, where MCS had been active since 1996. The main study was carried out on the southern part of the same motorway where MCS was implemented in 2004. During the “before” surveys in May 2004 MCS was functioning with AID and VMS message selection without displaying any messages to the drivers. The “after” study was performed in September 2004 with fully activated MCS.

Both the “before” and the “after” studies included stationary as well as mobile data collection. The following traffic characteristics were observed for each lane:

- Traffic flow distribution and composition.
- Headway and headway distribution (headway defined as the time between passage of the front axel of the leading vehicle and the front axel of the following vehicle).
- Spot speed and speed distribution.
- Travel time and delay.
- Lane change frequency.
2.1 Stationary Studies

Two methods of data collection were used for the stationary studies:

A: MCS data collection
B: Video recording

**A: MCS data collection**

Data provided by the MCS detectors is aggregated by outstations in the field before it is transmitted to the traffic control centre. The resulting information includes total traffic flow and the average speed for all lanes per minute. Furthermore the system records AID alarms and the time for activation and deactivation of the recommended speed signs and lane closure signals. The studied segment for MCS data collection included ten gantries. Figure 3 below illustrates an example of the plotted data.

![Average speed (km/h) and the displayes (VMS) recommended speed in gantry nr. (649)](image)

Figure 3. Average speed and displayed recommended speed for a selected gantry (plotting of MCS data)

**B: Video recording from elevated positions**

To gain more insight into the behaviour of drivers during congested traffic conditions a very detailed data collection is required. For this purpose video recording from elevated positions was selected as described below.

Four bridges were used as vantage points for video camcorders covering the movements of each vehicle in both directions of travel. From the Tram Bridge the road section was observed by two remote controlled video cameras mounted on a 15 m high mast. Four additional cameras were mounted on the other bridges as shown in Figure 4.

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Figure 4. Studied segment of E4 equipped with MCS detectors in each lane and four gantries (location in meters) with VMS showing the positions of the video recorders used for research data collection.

To capture traffic behaviour on individual vehicle level the collected data and the videotapes were processed using the SAVA video analyzer program developed at KTH (Archer, J., 2003). The SAVA program has been designed to interpret the information from digital films recorded in Digital Audio Video Interleaved (*.avi) format as illustrated in Figure 5. The collected data consists of vehicle passage times, traffic flow, vehicle speed, headway, vehicle type, and lane changes for each vehicle in each lane.

Figure 5. Analysis of video film recorded from the Tram Bridge in the northbound direction towards Stockholm
2.2 Mobile studies

A comprehensive car-following study was undertaken during two weeks in the morning and afternoon peak traffic period 07:00 to 09:00 and 15:00-17:00. The mobile study was carried out using an instrumented vehicle (Volvo V70) equipped with a computer for automatic recording of trip data, which was logged on a laptop. The collected data included travel distance (m), velocity (m/sec), longitudinal acceleration (m/s²), latitudinal acceleration (m/s²), GPS-based information, film recording of the view ahead and behind the vehicle, etc. The mobile data collection was performed using different drivers, male and female, chosen randomly. The purpose of the study was to capture detailed driver behaviour data focusing on the driver response to the recommended speeds displayed on the panels. Figure 6, shows an example of plotted results of vehicle speed and displayed recommended speed.

Figure 6, Floating car measurement with KTH instrumented vehicle.

3. DESCRIPTIVE RESULTS

Selected results from data reduction of the “before” and “after” surveys are documented below.

3.1 Traffic Flow and Composition

Table 1 records traffic flow, speed and headway data for each of the three lanes during time periods representing a range of traffic flow conditions: High traffic 07:00-09:00, Low traffic 11:00-13:00, and Middle traffic 15:00-16:00.
During the morning peak traffic period (north bound) the left lane carries considerably more traffic than the other two lanes as can be seen from the table. The lane distribution becomes more balanced after the implementation of MCS as shown for the southbound direction for the same time period. During periods with lower traffic the middle lane carries the highest traffic load before as well as after implementation of MCS.

### 3.2 Lane Changes

Lane changes were observed through video recordings over a stretch of 200 m length. Table 2 shows results for the two hour morning peak traffic period 07:00 – 09:00 regarding frequency of lane changes and their distribution.

<table>
<thead>
<tr>
<th>Lane Changing</th>
<th>Without MCS</th>
<th>Share</th>
<th>With MCS</th>
<th>Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL-ML</td>
<td>110</td>
<td>15%</td>
<td>100</td>
<td>30%</td>
</tr>
<tr>
<td>ML-LL</td>
<td>221</td>
<td>31%</td>
<td>18</td>
<td>5%</td>
</tr>
<tr>
<td>ML-RL</td>
<td>162</td>
<td>22%</td>
<td>67</td>
<td>20%</td>
</tr>
<tr>
<td>RL-ML</td>
<td>180</td>
<td>25%</td>
<td>125</td>
<td>38%</td>
</tr>
<tr>
<td>LL-ML-RL</td>
<td>20</td>
<td>3%</td>
<td>8</td>
<td>2%</td>
</tr>
<tr>
<td>RL-ML-LL</td>
<td>30</td>
<td>4%</td>
<td>15</td>
<td>5%</td>
</tr>
<tr>
<td>Total</td>
<td>723</td>
<td>100%</td>
<td>333</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 2, Frequency and ratio of lane changes per two hours and 200 m between different pairs of lanes during the morning peak period without and with MCS operation.

The number of observed lane changes was more than twice as high without as with MCS in operation. Most lane changes without MCS occurred from the middle lane to the left lane, with MCS in operation this occurred from the right to the middle lane.
3.3 Speed Characteristics

Speed characteristics for different lanes and time periods with and without MCS in operation periods were studied. Figure 7 illustrates individual vehicle speeds between 15:30 and 17:30 in the outbound direction towards Stockholm before and after MCS implementation.

The figure shows that drivers in left lane maintained much higher speed than those in the middle and right lanes, and drove faster than the speed limit (90 km/h) during the whole period. This was also evident from the speed distribution chart shown for each lane for low traffic conditions in Figure 8 below.

![Figure 7](image)

Figure 7, Individual vehicle speed observations (km/h) for three lanes during the afternoon period “before” (upper figure) and “after” (lower figure) after MCS implementation.
Speed and headway distributions for each lane during middle traffic flow conditions different periods are exemplified in Figure 8. From this figure it can be seen that the drivers in the left lane maintained higher speed and shorter headways than those in the other lanes.

Figure 8. Example of speed and headway distribution in different lanes during middle traffic flow conditions “before” MCS

When the traffic demand increased shockwaves and congestion occurred as shown in Figure 9 for “before” and Figure 10 for “after” conditions (without and with MCS in operation). The speed dropped considerably and the traffic discharge occurred in a queuing mode with shock waves of different severity at the tail of the queue. MCS was implemented to warn the oncoming traffic for such queuing conditions downstream through display of lower recommended speed as shown in Figure 10.
Figure 9. Vehicle speed (km/h) during morning peak traffic “before” implementation of MCS.

Figure 10. Vehicle speed (km/h) during morning peak traffic “after” implementation of MCS.
Figure 11 shows headway distribution and Figure 12 speed distributions during periods “before” and “after” MCS operation with data from the same survey periods as the data in figures 9 and 10.

Figure 11, Headway distribution for three lanes before and after implementation of MCS.

Figure 12, Speed distribution for three lanes before and after implementation of MCS.

From Figure 11 it can be seen that the frequency of very short headways was considerably higher in all lanes before implementation of MCS than after. This phenomenon is closely related to the instability of the traffic stream, particularly for the left lane where congestion usually set in first when MCS is not in operation (Smulders, S. 1990).
3.4 Driver behaviour

The mobile data collection for study of driver behaviour focused on the impact of MCS recommended speed signalling triggered by downstream queues. The deceleration process and speed adaptation when approaching a slow-moving queue was studied using three different methods:

1. Study from the moment the driver noticed the end of the queue (controlled from video recording from instrumented vehicle).
2. Study from the moment the driver started braking (automatically registered by the instrumented vehicle).
3. Study from the moment when the driver noticed the first MCS sign until he/she slowed down to approach the end of the queue.

All three methods considered deceleration while the third method also considered speed adaptation before the drivers approached the queue. The data reduction process included segmentation of the observations as follows:
- based on whether the MCS had or had not been activated;
- based on if the traffic situation was free-flowing or congested;
- based on the initial speed in of the vehicles in three groups, under 50 km/h, between 50-70 km/h and over 70 km/h.

Most drivers approached a congested road section exceeding the speed limit, irrespective of whether the MCS displayed a lower recommended speed or not. As the driver approaches the end of the queue, traffic grows denser which makes it difficult to maintain a high speed. By the time the end of the queue has been noticed, the speed has decreased to a level, which is between the speed limit and the speed recommended by MCS.

Figure 13 illustrates a commonly recurring deceleration processes for drivers in restrained traffic conditions with a lower speed than the recommended by MCS.

Figure 13. Illustration of typical deceleration process during restrained traffic conditions when the MCS recommended speed signs are active
Speed adaptation during free-flow conditions
The driver behaviour during free-flow conditions was similar as during restrained traffic flow considering speed levels higher than the speed limit before approaching the end of the queue, even though MCS displayed lower recommend speed.

Figure 14 shows a typical deceleration pattern during free-flow conditions from the point where the driver first spots the MCS recommended speed until the completion of the deceleration.

Figure 14. Illustration of deceleration process during free-flow conditions with active MCS speed signs.

4. ANALYSIS OF MCS IMPACTS

4.1 Impacts on Traffic Conditions

The impacts of MCS can be looked at statistically with analysis of variance methodology, particularly for speed and headway distributions during different traffic flow conditions (Rämä, Pirkko., 2001). The purpose was to test whether observed differences in means speeds and headways could be explained by the natural sampling variability, or whether it could be attributed to the impact of MCS speed signalling. Results of this analysis are exemplified in Table 3 below for time periods with or without MCS with similar traffic flow.
Table 3, Comparison of average speed and headway before and after activation of MCS.

The hypothesis that MCS had no effect on speed was tested. The same test was made for the impacts of MCS on headways. Each analysis was undertaken for high as well as low traffic conditions. The standard deviation of speed was also studied as suggested as an indicator for traffic safety and traffic condition homogeneity by Solomon (1994) and Baruya (1998).

The results can be summarized as follows:

**Impacts of MCS during periods of high traffic flow:**
*(upper part of Table 3)*

- The average speed increased significantly in the left and right lanes.
- The standard deviation for speed in each lane was reduced (30-40%).
- The average headway increased significantly in the right lane.
- The standard deviation for the headway decreased only in the left lane.

**Impacts of MCS during periods of low traffic flow:**
*(lower part of Table 3)*

- The results show small differences for speed and headway averages and standard deviations with or without MCS in operation. The most likely reason for this is that there were very few time periods with activated recommended speed signs during low traffic conditions.

### 4.2 Impacts on Driver Behaviour

In general analysis of MCS impacts on individual driver behaviour is complex due to the difficulty to find comparable traffic conditions during periods with or without active MCS. There is normally more congestion in the former case. However, the following observations could be made based on the study.
**Speed adaptation during free-flow conditions**

Most drivers did not follow the recommended speed signalled by MCS, normally they would drive much faster. Slightly lower speeds were observed with active MCS signals, but it could not be established whether this was caused by denser traffic downstream or by the speed signals themselves. Speed reduction occurred when the traffic became so dense that this became a necessity.

**Deceleration process when approaching a queue**

More in-depth studies of MCS impacts on driver behaviour in this regard are needed. However from the present study it was observed that MCS speed signs seemed to make drivers more cautious with regard to the possibility that there would be a queue ahead. Drivers who had been warned by active MCS had a significantly higher but more even deceleration, which increased closer to the queue. Drivers approaching a queue without pre-warning from active MCS speed signs both accelerated and decelerated before they arrived at the end of the queue, see Figure 15.

![Influence of MCS on deceleration](image)

Figure 15. Deceleration process in retrained traffic conditions with and without active MCS recommended speed signs, (Szabo, J. 2006, unpublished KTH M.Sc. thesis)

The braking distance was also longer in the “before” MCS case with a range between 50-450m as compared to 50-250 m for the “after” MCS case.

A questionnaire regarding the car following, showed that 45% of the drivers adapted their speed to the MCS recommended speed-whilst the speed choice of the other 47% was influenced by the vehicle in front (Ax and Werner, 2004).
5. CONCLUSIONS

Traffic flow characteristics for comparable time periods were analysed before and after implementation of MCS with recommended speed sign control. The main MCS impact consisted of a sharp decrease of the standard deviation of speed, which would indicate an improvement in homogeneity and traffic safety. Furthermore MCS reduced the frequency of lane changes between the middle and the left lane.

Driver behaviour impacts were difficult to assess due to the inability to perform controlled experiments with or without active MCS for comparable situations. Most drivers seemed to ignore the recommended speed signs, which often did not correspond to what could be maintained during the actual traffic situation. However, there was an indication that active speed signs warning for a queue downstream influenced the deceleration process to become more stable.

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