Transportation Research Procedia
Volume 15, 2016, Pages 594–606
ISEHP 2016. International Symposium on Enhancing Highway Performance

A local non-restrictive Ramp Metering strategy based on stochasticity of capacity

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Abstract
A local non-restrictive ramp metering strategy PRO is introduced. It is based on the stochasticity of capacity. The ramp metering algorithm shows innovative features:
- upstream time shifted measurements for anticipation
- measurements are actuated every second
- up to three vehicles per green are allowed

Details of the theory of this strategy are described in the first part. At freeway B27 three ramp meters with the PRO algorithm were installed. In the second part, based on extensive detailed traffic and accident data the effects on traffic flow and safety are described. The impact is positive regarding vehicle speed, queue duration and length as well as capacity and traffic safety. The improvements of speeds, travel times and capacities are statistically significant. The ramp metering systems are highly cost effective.

Keywords: freeway operation, traffic control, ramp metering, stochastic capacity

1 Introduction

Freeway B27 passes through the center of Stuttgart and is an important commuter route from north and south to the state capital. The B27 south of Stuttgart is grade separated with two lanes per direction up to interstate A8. The AAWT is >80,000 veh/24h. In 1995 a corridor traffic management system (CTMS) was installed over a distance of 18 km to improve safety and harmonize traffic flow.

Three freeway junctions upstream of the airport junction are the starting point of disturbances caused by high entering volumes. Congestion caused by these bottlenecks has lengths of 8 km and lasts 2 hours.

A feasibility study by the Baden-Württemberg state authority for Road Technology (LST) suggests ramp metering as a cost-effective means to improve traffic flow. Therefore, in August 2012 three ramp metering systems in northbound direction were installed and operated in trial at junctions (Figure 1)

- Leinfelden-Echterdingen-South (Stetten),
- Filderstadt-West (Plattenhardt) and
- Filderstadt-East (Bonlanden)

Selection and peer-review under responsibility of the Scientific Programme Committee of ISEHP 2016

doi:10.1016/j.trpro.2016.06.050

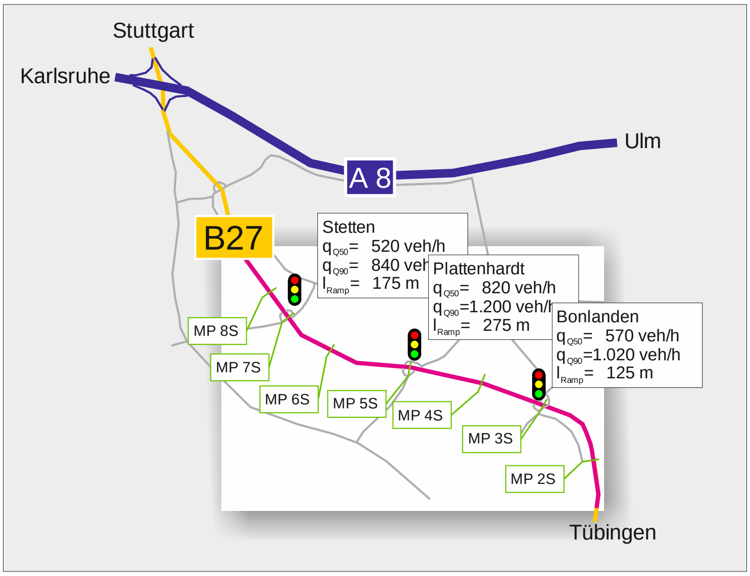


Figure 1: Study area of northbound B27 and junctions with ramp metering and measurement points „MP 2S“ to „MP 8S“

As volumes frequently reach values of ~1,000 veh/h (see Figure 1, 90th quantiles) and ramp lengths are normal or short a special focus had to be set on queue management.

These ramp metering systems (RMS) may be described innovative in various ways:

- It anticipates oncoming mainline volumes in order to harmonize merging volumes.
- The RMS are operated autonomously by the controller cabinet instead of a control by the distant traffic management center (which is German standard).
- The RMS act on basis of dynamic traffic data intervals that are actuated every second as opposed to the 60 second discrete intervals (German standard).
- Finally, these RMS are the first that provide green light for up to three vehicles per cycle. Currently (in Germany), only a few cases are operated with a maximum of two vehicles per green.

This report will first discuss the traffic engineering behind the algorithm PRO in comparison to another local strategy - ALINEA (most common in Germany). Finally, the effects of the three RMS are evaluated.

2 Theory

Ramp metering is the control of the entering traffic by a traffic signal at an on-ramp shortly before the merge area to a freeway. Ramp metering is based on the two principles

- Controlling the entering traffic volume and
- Simplifying merging maneuvers by dissolving large entering vehicle platoons in individual vehicles or small groups.

RMS may be fixed time or traffic responsive. Furthermore, local or area-wide strategies are available (Jacobson, Stribiak, & Nelson, 2006). Ramp metering basically is the control and optimization of a compromise between the traffic of the mainline and the entering traffic.

Uncontrolled access to a freeway often results in oversaturated freeways as alternative routes are even less attractive to the entering drivers if available at all. The question is, how restrictively entering traffic is hindered by the signal in terms of time delay in order to help mainline traffic.

The sphere of influence by RMS is rather big if traffic demand deviation and excessive queues are accepted. However, if critical ramp queues (that is vehicles blocking the adjacent network) are to be avoided RMS activity may not be restrictive at all. For example, if a permitted entering flow rate is reduced by 480 veh/h for a period of 2 minutes the queue will have grown by 16 vehicles. These vehicles will need about 250 m of space in a single lane ramp. As the queue is constantly moving no higher density was observed.

Framework conditions for German ramp metering are restrictive. Critical (excessive) queues or traffic relocation are not accepted. The first of the two principles stated above, adjusting the traffic volume, can therefore only be very short-termed and only applied as local RMS. Coordinated area-wide ramp metering is not used.

In Germany the ALINEA algorithm (Papageorgiou, Hadj-Salem, & Blosseville, 1991) is widespread. ALINEA as well as the majority of RMS algorithms target an optimal level of operation for the mainline. This is achieved by aiming at a volume close to mainline capacity (Wattleworth, 1965) (Taale & Middelham, 2000) or in the case of ALINEA an optimal occupancy (Papageorgiou, 1991). According to ALINEA the permitted flow rate q_{RMS} for the time interval n is calculated as follows (see also Figure 3)

$$q_{RMS,n} = q_{E,n-1} + k \times \left(o_{opt} - o_{n-1}\right) \quad \text{[veh/h]} \qquad \text{Eq. 1}$$

With:

$q_{E,n-1}$	= measured entering volume <u>downstream</u> of the RMS signal in the preceding interval n-1	[veh/h]
k	= adjustment factor of sensitivity	[veh/h]
b_{opt}	= optimal occupancy rate (configurable)	[%]
b_{n-1}	= measured occupancy rate on the mainline downstream of the merge in the previous interval n-1	[%]

This type of ramp metering can be very restrictive for the entering vehicles when the freeway is highly saturated and thus high occupancy values are measured continuously. A restrictive control will then constantly reduce the permitted flow rate below the on-ramp demand which leads to queues on the ramp into the subordinate network and possibly to traffic relocation. The latter effect may be welcome in transportation management although it is accompanied by significant loss of travel time and with decreased road safety. This can be healed by adding control rules to manage the ramp queue. Ramp queues are usually detected by measuring the occupancy on the ramp. When excessive queues are forming, the actual control algorithm is adjusted by increasing the originally permitted flow rate q_{RMS} (i.e. ALINEA/Q - (Smaragdis & Papageorgiou, 2003)). An even higher entering volume can oftentimes only be achieved by overruling the algorithm and turning off the signal or signaling green until the queue has dissolved. This way vehicles waiting at the ramp will push onto the main carriageway as one large platoon.

The result of this secondary consideration of entering vehicles may be a permanent oscillation between queue forming and spilling (Jiang, Chung, & Lee, 2012) (Gordon, 1996). This alternation is very counterproductive and can be observed at many sites with high entering volumes or little ramp queue space. Another observation at German ramp metering sites is a rather long time lag between initial traffic condition measurement and the control resulting from it. This is due to the aggregation of traffic data to intervals of 1 min as well as the transmission of data to and control action from the traffic management center. Traffic that has caused a certain control action is kilometers away at the moment an entering vehicle that has passed this very control action is finally entering the merge area.

These drawbacks were starting point for the algorithm development explained below.

Harmonizing merging volumes reduces the overall probability of a breakdown (Figure 2, left). In this simplistic example axis values are arbitrarily picked, no real values underlie. Even the curve is fictitious, many different mathematical descriptions for it exist in literature. However, the progressively increasing (convex) form of the curve of breakdown probability over volume is widely accepted (Athol & Bullen, 1973) (Elefteriadou, Roess, & McShane, 1995) (Brilon & Zurlinden, 2003). If "natural", uncontrolled merge volumes in one interval was 4,500 veh/h and 2,500 veh/h in the next traffic flow is subject to two probabilities of breakdown: 20 % and 2 %. If it was possible to control merge volume and harmonize it perfectly two intervals with 3,500 veh/h each would be optimal, if enough queuing space was left to store 1,000 veh/h until the next interval. This would result in two intervals with ~5 % chance of breakdown. In this simplistic example breakdown probability of the two intervals could be more than halved from 22 % to 10 %. Therefore a more narrow distribution of merge volumes bears less speed breakdowns.

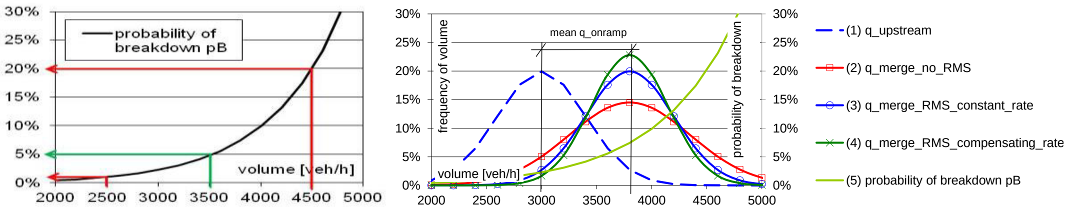


Figure 2: Effect of harmonized volumes on breakdown probability (left) and distribution of volumes with different ramp metering strategies (right) (Trapp, 2008) (Trapp, 2006)

However, only the entering volume can be controlled, mainline volume is stochastic looking at one point. Without anticipation (by an upstream time shifted measurement) of oncoming mainline volumes peaks at best a constant value is added to the stochastically varying mainline volume (Figure 2, right, (3)). Resulting variance will be reduced this way compared to no ramp meter (2), it is equal to the variance of mainline volumes (1). If it was possible to dampen freeway volume peaks by adding low ramp volumes (and fill "valleys" with a high ramp volumes), an additional reduction of merge volume variance could be achieved (4) and overall breakdown probability would be minimized.

Minimizing breakdown probability and anticipating oncoming traffic are goals of the proactive ramp optimization (PRO) (Trapp, 2006).

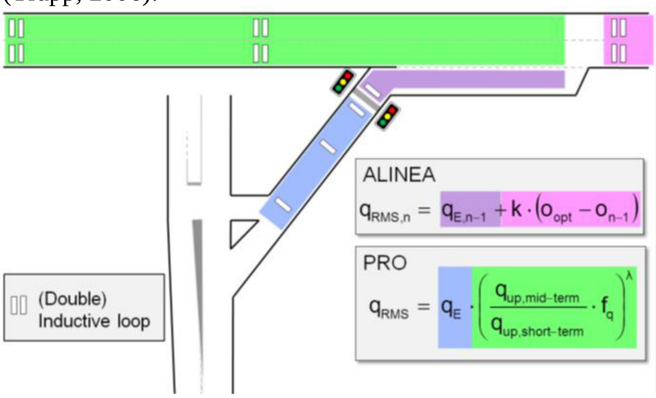


Figure 3: Comparison of algorithms ALINEA and PRO and its data measurement

Another goal of the algorithm PRO is to avoid this oscillation by directly and equally taking into account ramp and mainline volumes (Trapp, 2006):

$$q_{RMS,n} = q_E \times \left(\frac{q_{up,mid-term}}{q_{up,short-term}} \times f_q\right)^\lambda \qquad [veh/h] \qquad \text{Eq. 2}$$

with

q_E = On-ramp traffic demand. Measured every second as a moving average (here: 300 s interval) [veh/h]

$q_{up,mac}$ = "mid-term" mainline traffic demand. Measured upstream of the merge area every second as a floating interval (here: 60-75 s interval 1525-1775 m upstream) [veh/h]
$q_{up,mic}$ = "short-term" mainline traffic demand. . Measured upstream of the merge area every second as a floating interval (here: 20-25 s interval 775 m upstream) [veh/h]
f_Q = factor for balancing the traffic volume measurements (configurable) [-]
λ = sensitivity parameter (parameterized) [-]

Of course, time-shifted upstream measurements are subject to many blurring influences. Predictability of flow rates by upstream measurements is prerequisite to the idea. However, sufficient predictability of upstream measured flow rates is given even for distances of ~2 km and intervals lengths of 20 s or 70 s as used here (Trapp, 2006). Also, upstream measurements may be taken on both lanes or the right (slow) lane only. The slow lane volume obviously describes the merge process. On the other side, lane changing has a blurring effect on single lane measurement which is eliminated when all lanes are measured. For a two lane mainline it has been shown that both methods show comparable results (Trapp, 2006). The author is aware the some of the first tests with ramp access control were not successful as single vehicle gaps in the mainline stream could not be matched with a single entering vehicle (Buhr, 1969). However, the difference lies in the length of the interval that the entering vehicle is supposed to meet with. A 15 s or 20 s interval that is moving toward the merge area contains ~ 5 up to 10 vehicles and gaps. Here, not a single gap in the slow lane is targeted but a short-term merge-friendly environment as expressed by $q_{up,short-term}$ as measured on both lanes. The other upstream flow rate measured $q_{up,mid-term}$ represents the conditions that are to be expected beyond that short-term anticipation. If that is lower than the denominator then a better opportunity to release vehicles is soon expected and the flow rate (now) is lower. If short-term measurement shows little volume, then the situation is rather opportune for a higher release rate. The term in fraction thus represents the opportunity to release more or fewer vehicles at the RMS. However this term is without dimension as two volumes are divided, it varies around the mean value of ~1. Therefore it is multiplied with a volume, which is the ramp demand measured at the beginning of the ramp with a rather long interval to dampen peaks (as created by traffic lights in the adjacent network).

If prediction of oncoming volume peaks is possible a more precise control action is allowed for instead of unnecessary restrictive action in order not to miss out on the peak. However, once breakdown has occurred prediction of oncoming volumes is impossible. As metering effects of non-restrictive algorithms generally are small in congested conditions this doesn´t affect the algorithm´s effectiveness.

In short, the algorithm PRO is supposed to achieve three goals

- Anticipate traffic volume and thus control in a more tailored and sensitive manner,
- Equally consider ramp and mainline volumes for an optimized compromise and less restrictive control with minimum critical queues
- Reduce Breakdown probability by harmonizing merge volumes

Speaking in categories the algorithm PRO is a local, open loop (enhanced) metering at demand strategy.

The PRO algorithm needs data measurements and control actuation on an every second basis. This can only be provided if the control cabinet contains the complete control circuit. A transfer of data to the traffic management center or the sub center, as required by the German guidelines TLS (BASt, 2012), and transmission of the resulting control action back to the junction had been a potential time delay and carried additional risk of component failure.

Since the three questionable junctions had high (~840 veh/h) or very high (~1,200 veh/h) entering volumes (90th quantiles, Figure 1) and the ramp at junction Bonlanden hat only 120 m (8 vehicles) queuing space, there was a high risk of frequent critical queues, which would have resulted in considerable traffic flow and traffic safety problems. This was a main argument for using the PRO algorithm because of its less restrictive approach. Additionally a microsimulation feasibility study stated advantages in overall travel times of PRO over ALINEA and RWS (Taale & Middelham, 2000). For these reasons, the algorithm PRO was chosen as control algorithm at the B27.

High entering volumes and short to medium ramp lengths were reasons, to dynamically admit up to three vehicles per green phase, which allows flow rates of up to 1,200 veh/h. In Germany a minimum duration of red of 2 s is used combined with one second of amber each before and after and finally green. This results in minimum cycle times of ~6 s. The maximum metering rate with one vehicle per green is just over 600 veh/h (2 veh/green: ~900 veh/h 3 veh/green: 1,100 veh/h). Three vehicles per green allows continuous control at very high ramp volumes as well as a quick and yet controlled reduction of ramp queues without having to turn off the control in order to flush queues to the merge area.

3 Effectiveness

3.1 Data basis

Since the end of 2012 the three RMS run without further software or parameter adjustment. At that time the RMS were in continuous operation for several months, an adjustment of driver behavior could be expected as well as the possible although not wanted balancing of traffic demand. Therefore, the following months in 2013 were compared to the same months of 2012 prior to implementation of the RMS for assessment of their effectiveness.

Extensive data in 1-min intervals of the corridor traffic management system (CTMS) of the B27 could be used. This system has remained unchanged for many years in software and parameters and provides adequate data for assessment of the effects of the RMS. Data of the inductive loops "MP 2S" to "MP 8S" was used. They each lie within a distances of ~1,000 m. The entire study area is just over 7 km long (Figure 1).

An interaction between RMS and the CTMS cannot be excluded. However, the implementation of the RMS is the only systematic change in both periods compared. Whether the effect of the RMS is amplified or dampened by the existing CTMS cannot be determined based on the available data.

The investigation period is limited, as construction works would have impaired data by traffic relocation later on. The CTMS protocols, environmental and short-term traffic data of two months before (2012) and after (2013) implementation of the RMS were evaluated. Biases by weather, accidents, road works, weekends and public holidays / vacation were excluded. Further influences from changing traffic volumes and composition ("annual trend") or other congestion causes were considered and ruled out. Only "traffic on an average working day" was expected to remain in the datasets.

After exclusion of these biases the traffic volumes, speeds, travel times, queue lengths and accidents and finally economic benefits were evaluated.

Furthermore, for the assessment of the impact of the RMS on road safety accident data of the study area for the years 2009-2011 and 2013 / 2014 were used. Since the RMS were introduced in 2012, this period is excluded from the safety evaluation.

3.2 Road safety

The accident data were related to changes in the AADT and AAWT to obtain a better comparability of the annual accident risk.

When looking at the total number of accidents the year 2009 stands out (Table 1, line 1a). However, there were no known obvious reasons for this outlier such as construction sites or changing traffic volumes or control conditions of the CMTS. An analysis and comparison of the months of this year with and without differentiation of types of accidents also didn´t show evidence of a specific cause for this difference. Hence the accidents of 2009 are integrated into the following analysis.

The evaluation of all accidents (line 1b) shows an overall decreasing trend of the number of accidents by 14% over 3.5 years (difference between the averages of the annual figures of the compared periods), of which a large portion is attributed to the high accident value of 2009.

As the RMS are exclusively active on weekdays from 6.30 to 9:30 am, a comparison of the periods

- working days without the hours from 6:30 until 9:30 am (no RMS activity) and
- working days from 6:30 until 9:30 am (with RMS activity)

is suitable to examine the impact of RMS on road safety with respect to overall traffic safety development on the B27.

This evaluation shows a change in accidents

- working days without RMS of -4% (line 2b)
- working days with RMS of -16% (line 3b)

Based on this, an improvement of road safety of about 12% on working day morning peaks or ~2 accidents p. a. on the B27 caused by RMS can be stated.

			without RMS			with RMS	
			2009	2010	2011	2013	2014
1a	Accidents, AADT-adjusted	[1/a]	108,2	83,7	84,5	80,2	82,0
1b	Annual Accidents	[1/a]	92,1			81,1 (-14 %)	
2a	Accidents, AAWT-adjusted	[1/a]	52,1	34,1	46,9	49,6	36,0
2b	Annual accidents (working day without 6:30 to 9:30 am)	[1/a]	44,3			42,8 (-4 %)	
3a	Accidents, AAWT-adjusted	[1/a]	24,0	20,6	13,0	15,2	18,0
3b	Annual accidents (working day, 6:30 to 9:30 am)	[1/a]	19,2			16,6 (-16 %)	

Table 1: Analysis of accidents with and without RMS

3.3 Traffic relocation

Traffic relocation is often suspected by neighboring communities prior of the realization of RMS. Due to the topology of the study area along the B27 and the subordinate network relocations were evaluated as unlikely in the feasibility study. At most, they were expected from one freeway junction to the next.

However, on-ramp measurements should be regarded as unreliable as inductive loops are frequently queued in the case with RMS and thus are the count of vehicles is most likely defective to some degree. This degree is highly dependent on the specific location of the measurement (distance to the stop line) and the queue length variation.

With respect to this, based on available data it can be said that the three RMS do not relocate noteworthy traffic into the subordinate network.

3.4 Volumes

The idea of the introduced control law is the reduction of the probability of breakdowns by harmonizing volumes (by a more narrow distribution) in the merge area. Unfortunately, only data in 1-min intervals were available to examine whether the algorithm does affect the distribution of volume measurements. As the PRO-algorithm is designed to harmonize volumes on a higher resolution of ~15-20 seconds it is assumed that most of the harmonizing effect can´t be verified (if existing). Another reason that blurs measurability of this expected effect is that the measure points are located ~500-600 m downstream of the merge area. In a microsimulation study, however, the distribution of merge volumes was narrowed (as measured by standard deviation) by ramp metering. The PRO control yields the narrowest distribution of merge volumes (Figure 4 – left) and yet the broadest distribution of entering volumes (measured downstream of the ramp meter, Figure 4 - right). The explanation to this seeming contradiction is that the distributions of entering volume and 1st lane volume are not stochastically independent in case of PRO as this is its very idea.

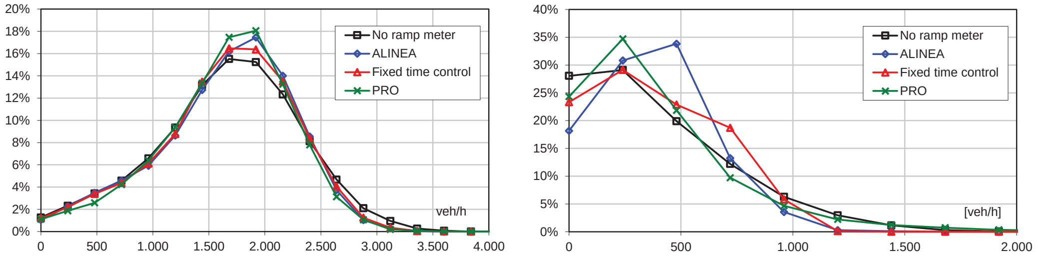


Figure 4: **Density function of merge area volumes (onramp + 1st lane) (left)**
Density function of entering volumes downstream of RMS (right) (Trapp, 2006)

3.5 Speeds

Table 2 shows the effect of the RMS on the speed level for the period from 6:30 to 8:30 am in which the RMS are most likely active. Overall, speeds are increased by 7 km/h (+9 %) due to the ramp metering systems. At the upstream end of the study area (MP 2S) this effect is most explicit with 14 km/h. At the downstream end of the study area at Stetten the benefit is less obvious with 2 to 4 km/h (MP 8S). At almost all measurement points average speeds increased statistically significant ($\alpha = 1\%$).

Speed improvement is observed equally on both lanes on all measurement points, there is no specific benefit for either lane.

The smallest speed advantage in the downstream RMS at junction Stetten should not be interpreted with a lower effectiveness of the RMS as compared to the other two sites. Improvement of traffic conditions necessarily have upstream effects on the queue length and duration. Therefore, the indicator speed is likely to change most clearly at the upstream end of the queues where average speeds drop sharply. In addition there are positive effects of each further upstream RMS that cumulate to increasingly positive effects.

Measurement Point	v_{Car} [km/h] **Without** RMS	v_{Car} [km/h] **With** RMS	v_{Car} Change	Significance level
MP 8S	76	78	+3%	1%
MP 7S – Stetten	75	77	+2%	10%
MP 6S	71	75	+5%	1%
MP 5S – Plattenhardt	64	69	+7%	1%
MP 4S	70	78	+11%	1%
MP 3S – Bonlanden	67	79	+17%	1%
MP 2S	83	97	+17%	1%
Mean	72	79	+9%	

Table 2: **Change of passenger car speed [km/h] without / with RMS and significance level for the period 6:30 until 8:30 am**

3.6 Capacity

A breakdown of passenger car speeds on the 1st lane were analyzed in 1 min intervals. Speed drops under a value v_{limit} with the size of Δv were defined as capacity event (Elefteriadou, Roess, & McShane, 1995) (Brilon & Zurlinden, 2003). The average of five 1-minute intervals of traffic volumes (mainline + entrance) prior to the interval with a speed drop were considered a capacity value of the merge area. A capacity increase by 3-7 % was measured under the influence of RMS. The increases are partly significant (Table 3).

Junction	v_{limit} [km/h]	Δv [km/h]	Capacity without RMS [veh/h]	Capacity change [%]	Capacity with RMS [veh/h]
Stetten	60	0	4.306 (n=92)	+2,9 significance: α =10 %	4.430 (n=41)
		10	4.293 (n=54)	+3,9	4.460 (n=21)
Plattenhardt	60	0	4.183 (n=50)	+5,0 significance: α =5 %	4.392 (n=33)
		10	4.148 (n=29)	+5,7	4.383 (n=14)
Bonlanden	70	0	3.850 (n=18)	+4,2	4.013 (n=9)
		10	3.717 (n=9)	+6,8	3.969 (n=7)

Table 3: Change of capacity due to RMS with PRO algorithm

In the phase of speed breakdown, the speed level with RMS remained the same as without. However, the capacity of the merge area is increased and thus breakdown probability is reduced. However, a higher capacity during this phase would slow down the development of congestion. Corresponding results on congestion probability and extent can be found in the section 3.7.

3.7 Congestion

Congestion is defined here on the basis of the average speeds measured on the measurement points. Congestion was defined for average speeds below 60 km/h.

The probability of congestion is the percentage of time with speeds below 60 km/h calculated for the period 6:30 until 8:30 clock for each measurement point. It turns out that the entire distance of the studied road section is less probable congested with RMS (Figure 5).

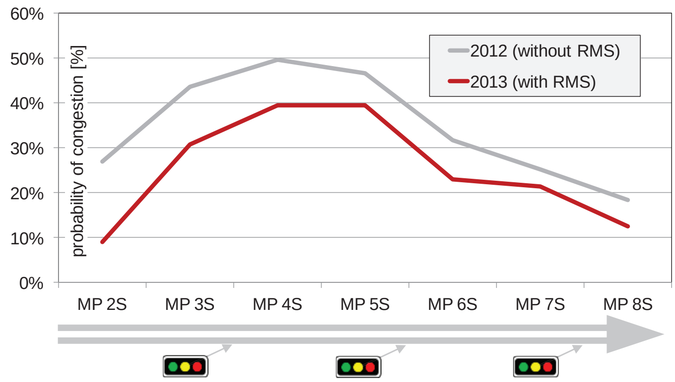


Figure 5: Change of congestion probability between 6:30 and 8:30 am by RMS

A closer look at the period of the initial speed breakdown at about 6:30 until 6:45 am revealed that onset of congestion has remained unchanged by RMS. This corresponds to the findings about speed drops in the chapter 3.4. The initial speed drop takes place unaffected by RMS. However, the volumes at which this happens are higher and thus breakdown probability is reduced.

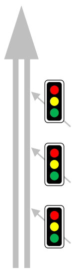
3.8 Critical queues

Critical queues on on-ramps are detected by the RMS in time and effectively reduced. This was confirmed based on own visual observations and road user feedback.

3.9 Travel times

Travel times are determined by assigning each measurement point to a section of the B27. This inference of travel time estimation from local measurements is permitted even in these unstable flow conditions as road sections are rather short with <1,000 m as well as 1-min data was used and thus the different traffic conditions could be well differentiated. The travel times were calculated from the section related speeds (Table 4). Maximum time savings are obtained by vehicles that transit through the entire distance of just over 7 km. These are about 130 s at about 7:30 am.

The reduction of section travel times is biggest at the beginning of the study area at measure point "2S" in Table 4 - analog to the mean local speeds in (Table 2). Vehicles that enter at the end of the study area at the intersection Stetten (measure point "7S"), will benefit only marginally.

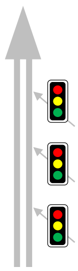


Section \ time	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30
8S	0	0	-1	0	2	4	2	4	1	0	0	0
7S	0	0	0	0	0	2	4	5	1	0	0	1
6S	0	0	0	2	1	4	6	6	1	0	0	1
5S	0	0	-2	7	5	11	16	9	0	0	0	0
4S	0	0	-2	5	6	17	19	6	0	0	0	0
3S	0	0	-3	24	33	40	24	5	0	0	0	0
2S	-1	0	-1	21	54	48	17	-1	0	0	0	0
Sum 2S ⇒ 8S	-1	0	-9	59	101	127	88	33	4	1	1	3

Table 4: Section-related change in the travel time through RMS [s]

These travel time changes in Table 5 are now multiplied with average traffic volume of the respective time intervals and sections in order to generate total travel times for all vehicles. It turns out that in the time before 6:00 am and after 9:00 am no benefit is generated because the three RMS are not or only sporadically active in these times.

On a normal working day during the period from 5 to 11 am the three RMS produce a total benefit from reduced travel time of ~152 h is created by RMS.



Section \ time	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	Sum	Sum cumulated
8S	0,0	0,0	-0,5	-0,2	1,1	2,1	1,2	2,0	0,3	0,0	0,0	0,1	6,3	6,3
7S	0,0	0,0	0,1	0,2	-0,1	1,1	1,9	2,0	0,3	0,1	0,1	0,2	5,9	12,1
6S	0,0	0,0	-0,1	0,8	0,7	2,0	3,0	2,8	0,3	0,0	0,0	0,2	9,7	21,9
5S	0,0	0,0	-0,7	3,1	1,9	4,1	6,3	3,5	0,1	0,0	0,1	0,1	18,6	40,5
4S	0,0	0,0	-0,8	2,3	2,4	6,5	7,7	2,2	0,0	0,0	0,0	0,0	20,4	60,8
3S	0,0	0,0	-1,2	9,1	10,0	11,8	7,7	1,5	0,1	0,1	0,1	0,0	39,3	100,1
2S	-0,1	-0,1	-0,6	9,8	19,8	17,3	6,4	-0,4	0,2	0,0	0,1	0,1	52,4	152,5
Sum 2S ⇒ 8S	-0,1	0,0	-3,6	25,1	35,7	44,9	34,3	13,5	1,4	0,3	0,3	0,7	152,5	152,5

Table 5: Change in total travel time by RMS [veh·h]

The downside of ramp metering success for the mainline always is delay in the queue at RMS signals, which must not be neglected. For these, no measured data is available, since the velocity measurement in the ramp is very unreliable.

Alternatively, the travel time increase is calculated as follows. According to local observations (see chapter 3.8) no excessive queues form. Based on this it is assumed that on average the RMS signal is controlling in a manner that the last vehicle of the queue has been released with the arrival of the first vehicle of the next cycle time of the adjacent traffic signals. The average time loss per vehicle t_l for the period is

$$t_l = \left(\frac{t_C}{n} - t_G\right) \times \frac{(n-1)}{2} \qquad [s] \qquad \text{Eq. 3}$$

With:

t_c = cycle time of adjacent traffic lights [s]

n = number of vehicles per cycle that arrive at the RMS [-]

t_G = time gap of following vehicles at the adjacent traffic lights (assumption: 2s) [s]

It is assumed that the first vehicle of a platoon will pass the RMS without losing time (hence "n-1").

In an adjacent traffic signal with t_{cycle} = 75 s and 800 veh/h traffic flow onto the on-ramp 40 cycles per hour result and thus n = 20 vehicles per cycle each experience a travel time loss t_l of ~17 s.

For the conditions at the B27 generally a travel time loss of t_l = 20 s is assumed what should be a moderate overestimation of the travel time disadvantage for entering vehicles. By multiplying the estimated travel time loss time of 20 s per vehicle with the average traffic flow travel time loss per peak hour is calculated [veh·h]. Overall on normal working day morning peak travel time losses of ~21.7 veh·h are provoked.

The total travel time record of three RMS is thus an improvement of 152 veh·h - 22 = 130 veh·h for each working day. These travel time savings result from the statistically significant improvement in mean speeds and can thus be considered significant.

3.10 Monetary benefits

For an assessment of the success of the investment, travel time savings per morning peak of three RMS can be multiplied by 150 working days per year and result in annual time savings of ~19,500 veh·h/a. With an average value of avoided car travel time of € 8.50/ Veh·h an economic benefit of more than € 165,000 per year is calculated. This means that the investment of €~500,000 for three has paid off after a few years.

Benefits from reduced accidents could to be added to the travel time benefits. During times of RMS activity at high traffic volume and low speeds less severe accidents are potentially avoided by RMS. ~12% of these less severe accidents (~2 accidents per year) can be reduced by ramp metering, therefore a few thousand EURO could be added to the value of € 165,000 per year. It should be noted that this safety improvement is complementary to the benefit of the constantly active CTMS.

4 Conclusion

The B27 is a major commuter inlet to the BAB A8 and Stuttgart with very high traffic volumes during the morning peak. Regular traffic jams are caused by high entering volumes at three junctions upstream of the airport junction. Therefore only an additional lane can be a complete solution to the congestion problems. Nevertheless, three ramp metering systems have been set up in the northbound direction for interim relief of congestion.

These three ramp metering systems were innovative for these reasons:

- They are the first with the PRO algorithm that has so far only be tested in the laboratory

- PRO is a proactive control method taking into account stochasticity of volumes and capacity
- They are the first traffic control systems, that are completely based on second by second data acquisition and processing,
- They are the first ramp metering systems with dynamically up to three vehicles per green time

An evaluation of extensive and detailed traffic and accident data showed for the morning peak hour that the three RMS

- do not relocate traffic to the adjacent network,
- do not generate critical queues into the adjacent network,
- statistically significantly raise the speed level by 2 to 14 km/h,
- reduce travel times for the main carriageway significantly,
- raise the capacity by 3 to 7%,
- generate a total travel time benefit of 130 veh·h per day,
- reduce congestion probability, length and duration,
- reduce accidents by ~12%.

Despite or because of the new features of these RMS, it turned out that the three RMS are highly effective in relation to their investment and running costs. Even without accident benefits the investment will pay after three to four years.

Another positive lesson learned is the fact that the effects of the ramp metering systems have been predicted in quality and quantity by microsimulation, and the micro-simulation study had delivered appropriate output parameters for the trial operation.

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