KTH Architecture and the Built Environment

Improved traffic management for Swedish motorways using efficient ramp metering strategies: A case study for the Södra Länken tunnel

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Abstract

Motorway traffic management is becoming more and more crucial due to the increase of mobility in urban and motorway networks. The continuous development of intelligent traffic management strategies enables the deployment of advanced motorway control strategies without the need of infrastructure intervention. The project investigates and evaluates the potential of using adequate ramp metering strategies to mitigate traffic congestion on the Swedish motorways. In particular, the Södra Länken motorway tunnel in Stockholm is studied, which is prone to temporary closures due to congestion. The research involves, a data-driven analysis to understand the network traffic dynamics and to identify critical bottleneck locations and appropriate ramps where metering can be feasible (e.g. with sufficient storage capacity) and beneficial. Traffic simulation is used in order to assess the performance of the ramp metering strategies under different congestion patterns. The analysis evaluates and compares the feasibility as well as the impacts of the various ramp metering strategies in terms of their efficiency in reducing traffic congestion in the network. Recommendations and insights for the most promising metering strategies and their implementation requirements are provided to the traffic authorities as the basis for decisions on potential field deployments.

1 Introduction

1.1 Background and earlier studies

Motorway traffic management is becoming more and more crucial due to the increase of mobility in urban and motorway networks. The continuous development of intelligent traffic management strategies enables the deployment of advanced motorway control strategies without the need of infrastructure intervention. Thus, investigation of the methodological and implementation details for such advanced traffic management systems paves the way for research in the field.

In particular, tunnel traffic management is a challenging problem due to the anatomy of tunnels and the necessity to ensure safety in addition to throughput maximization. This work addresses the case of the Södra Länken motorway segment in Stockholm, Sweden, as a continuation of a previous study (Tympakianaki et al., 2019) on the Södra Länken tunnel. Due to high demand that often exceeds its capacity, congestion often occurs in the tunnel. Furthermore, queues that often occur on a highly congested segment downstream of the tunnel tend to spill back into the tunnel. In order to prevent traffic jams from forming inside the tunnel and impede or block evacuation in the case of fire, the local traffic authorities have adopted a strategy of temporarily closing some of the tunnel entrances to allow the queues to dissipate. Before any tunnel closure takes place, warning messages are sent out to the drivers informing them about the existence of congestion in the tunnel. Furthermore, tunnel warnings and closures have significant impacts for travellers as they experience delays either due to congestion or their attempt to find alternative routes through the urban network. In a previous study (Tympakianaki et al., 2018) the authors identified and measured the impacts of the current tunnel closure policy in the surrounding network using heterogeneous traffic information from a set of historical days. The analysis showed that during closures vehicles take alternative paths to their destination or reenter the tunnel at other entrances. It was hence observed that the current policy of temporarily closing some of the tunnel entrances may resolve congestion; however, only locally and temporarily.

In Tympakianaki et al. (2019) the authors proposed an approach to identify the underlying causes of recurrent congestion in tunnels and tests the hypothesis that the cause may vary from day to day. It was also suggested that the appropriate tunnel management strategy to deploy depends on the cause. The methodology was demonstrated for the Södra Länken tunnel revealing two different spatiotemporal congestion patterns. Simulation analyses were conducted in order implement and evaluate thoroughly alternative tunnel operation strategies, including the current closure policy, ramp metering and a combination of both ramp metering and closure of tunnel entrances. Based on the results, ramp metering was found to be a very promising strategy for regulating the traffic congestion inside the tunnel, especially since it reduces the impacts on the surrounding network.

The findings of the aforementioned analyses (Tympakianaki et al., 2018; 2019) motivated the proposal of the current project, in order to explore the most adequate metering strategies for the Södra Länken segment as well as for other crucial parts of the motorway, where adequate control strategies are needed.

1.2 Objective

The aim of this project is to investigate the potential of using different ramp metering strategies to mitigate traffic congestion on the Swedish motorways. In particular, the Södra Länken motorway tunnel in Stockholm is studied. The findings of the analysis could be applied elsewhere where similar challenges are faced. Recommendations for the most adequate control strategies and their implementation requirements are provided as the basis for decisions for Trafik Stockholm/ Trafik Göteborg on potential field implementations.

In particular, a few ramp metering strategies are implemented and analysed in a simulation environment in order to investigate the potential of implementing this policy for the tunnel problem. The main advantages of the ramp metering policy for this case are the following:

- Manage throughput capacity more effectively compared to the temporal closure policy.
- Mitigate/avoid closure impacts on the network (e.g. detouring).
- Flexible metering scheme (time of day, duration, etc.) can be deployed for different demand patterns.
- Improved traffic conditions for the entire tunnel stretch.
- Alignment with Trafikverket's Urban Mobility Program for Stockholm Region

1.3 Scope and limitations

Thorough investigation of the potentials and requirements for the implementation of ramp metering strategies is conducted. In particular, the project objectives involve:

- Identification of critical bottlenecks[1] along the network, given available traffic information.
- Identification of critical on-ramps where metering would be feasible and beneficial.
- Investigation of the most adequate metering strategies, existing in the literature, and their requirements in terms of traffic information, etc.
- Evaluation of the selected strategies through traffic simulation.

The methodological approach in earlier studies is generic and similar analysis can be conducted to other networks on the Swedish motorways. In particular, existing metering strategies that have been proposed in the literature, with few of them also implemented in the field, are investigated. The key inputs for most of the metering strategies are traffic measurements. The motorway network in Sweden is well instrumented with sensors. Thus, existing sensors' infrastructure is used in order to obtain appropriate traffic measurements to be given as inputs for the analysis.

In order to evaluate the effectiveness of different control measures it is important to specify relevant indicators. In particular, the impact of ramp metering should be evaluated with respect to the total travel time or travel delays for the entire network in order to account for the delays due to formed queues on the metered on-ramps as well as potential redistribution of traffic. Nevertheless, no specific indicators were provided for this study. For future studies, traffic as well as socioeconomic and safety indicators should be taken into consideration for the recommendation of adequate traffic management strategies.

The focus of this study is on identifying the most promising ramp metering strategies to improve the traffic conditions in the Södra Länken tunnel. However, the potential impacts of ramp metering in the surrounding network are not examined.

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[1] In this study, critical bottlenecks are considered major bottlenecks that trigger the formation of congestion and require intervention in order to improve the network efficiency.

1.4 Structure

The report is organized as follows. Section 2 presents an overview of freeway metering strategies that have been proposed in the literature, with focus on tunnel traffic management strategies. Section 3 introduces the proposed methodology, which consists of a data-driven analysis for identifying distinct traffic patterns as well as of a simulation analysis in order to evaluate adequate metering strategies. Section 4 presents a case study involving a congested tunnel in Stockholm, Sweden. Section 5 presents the results and analysis. Section 5 summarizes the conclusions. Section 8 presents future directions.

2 Literature review

Motorway traffic management is becoming increasingly important as travel demand grows in many urban areas. Tunnel traffic management, in particular, is a challenging problem due to the need for safe conditions in addition to high throughput. Queueing inside tunnels is associated with risks such as exposure to carbon monoxide (CO) and slow evacuation in case of fire or other incidents. Hence, the criteria for efficient tunnel traffic management strategies are typically more rigorous compared to freeway traffic management in general (FHWA, 2015).

The network efficiency can be evaluated by the total time spent by all drivers in the traffic network (Papageorgiou and Kotsialos, 2002) to reach their destination (exit the traffic network). Hence, the effectiveness of any control measure or strategy can be measured by the decrease of the total time spent.

Ramp metering has proven to be an effective method to mitigate the congestion covering on- and off-ramps, response to incidents, as well as ensure safer merging. Metering has been used extensively for freeway traffic control (Papageorgiou et al., 1991). It is applied on ramps, depending on the location of the bottlenecks and ramps' storage capacity.

Various positive effects are achievable if ramp metering is appropriately applied:

- Increase in mainline throughput due to avoidance or reduction of congestion;
- Efficient incident response;
- Improved traffic safety due to reduced congestion and safer merging.

The types of metering strategies can be categorized to local and coordinated strategies. Local strategies use fixed-times for the traffic cycles and apply a pre-specified metering rate or they can be responsive based on real-time traffic measurements. Coordinated metering can be effective in the presence of multiple bottlenecks or when the on-ramps storage space is limited.

In Papageorgiou and Kotsialos (2002), an overview of freeway ramp metering strategies is presented. Metering on the entrance ramps involves determination of the metering rate. Metering strategies are divided into two classes: *Fixed-Time strategies* and *Traffic-responsive strategies*.

Fixed-Time strategies, in which, metering rates are determined based on constant historical demands without use of real-time measurements. It is proven to be effective in eliminating recurrent congestion, provided severe incidents or sudden changes in demand do not occur. The main drawback of fixed-time strategies is that due to the absence of real-time measurements, overload of the mainstream flow or underutilization of the freeway may occur. Hence, it is important that the strategies are accurate.

Traffic-responsive ramp metering strategies use real-time measurements from sensors installed in the network to determine the control policy. According to the values of the real time traffic data, such as flow rate, density, and occupancy, the metering rate varies over time. Responsive strategies can be classified as local (or isolated) or coordinated. Local ramp-metering strategies make use of measurements from the vicinity of a single ramp to control each on-ramp independently of all other metered ramps in the network, such as the feedback-based ALINEA strategy (Papageorgiou et al., 1991). Coordinated ramp-metering strategies make use of the traffic conditions from an entire freeway network to control all metered ramps within the network rather than the local conditions around independent on-ramps. Coordinated strategies may be more efficient than local ramp-metering strategies due to the more comprehensive information provision and coordinated control actions, particularly in the frequent case of restricted ramp storage spaces (Faulkner et al., 2014). Finally, there are more sophisticated control systems that emerge, known as *integrated* systems. In (Kotsialos et al., 2002) an integrated system is defined as a control system with different types of control measures, such as ramp metering, signal timing, and route guidance via variable message signs (VMS).

Although ramp metering is a valuable tool for efficient freeway traffic control, it has negative impacts due to the temporary formation of queues at the metered on-ramps. In order to prevent the extension of ramp queue that may interfere with the local network, on-ramp queue control is usually implemented (Papageorgiou and Papamichail, 2008). One approach is to release the ramp metering or set the metering rate to a high value whenever the occupancy at ramp entrance exceeds a certain threshold (e.g. 50%). Another, more effective, measure of the on-ramp queue management is to directly control the ramp-queue.

In this project, ramp metering as well as metering of the mainline are implemented to control the inflow at different tunnel entrances and on-ramps that are expected to affect the tunnel traffic conditions. The focus of this work is to mitigate congestion due to known localized bottlenecks that are identified using historical traffic measurements. Ramp metering will of course lead to queue formation at the traffic lights, but the achieved outflow inside the tunnel is expected to be higher than the outflow under congestion, thus resulting in a corresponding reduction of the total time spent in the network. Traffic lights can be applied to all lanes simultaneously or to individual lanes separately.

There are several causes of tunnel traffic congestion. One example is increase in demand during peak hours exceeding the tunnel capacity. Moreover, weaving areas inside the tunnel may generate spontaneous/temporal bottlenecks. In more complex networks, traffic conditions affecting the tunnel may develop downstream the tunnel. Tunnel traffic conditions are also sensitive to drivers' behaviour (Calvi et al., 2012). Consequently, tunnel management policies should be robust with respect to the range of traffic patterns that may lead to congestion.

A strategy often deployed to deal with recurrent tunnel congestion, e.g. by the State Road Traffic Authority (VLB) in Berlin (Lange et al., 2010), is entrance closure (RABT, 2006). The TOB (Tunnel Ortskern Ortsteil Britz) tunnel is part of the Berlin urban freeway ring and is often congested during morning peak hours due to high demand exceeding the tunnel capacity. The closure times and durations are based on empirical analysis of flows and speeds from typical congested days.

Several studies in the literature focus on tunnel traffic management. Greenberg and Daou (1960) presented an operational study of traffic flow in the Holland Tunnel in New York. The target of the control strategy was to limit the number of entering vehicles using signals. Gazis and Foote (1969) proposed metering for the Lincoln tunnel to limit the tunnel inflow.

Cuneo et al. (1999) evaluated a dynamic traffic management system for the Central Artery/Tunnel network in Boston. Microscopic simulation was used to provide insights for effective integration of different strategies such as metering, lane control, etc. Liao et al. (2012) used simulation to evaluate different traffic management strategies for the congested Hsueh-Shan Tunnel in Taiwan under incident conditions. The strategies included combinations of ramp closure, ramp metering, route guidance, and lane control. Ramp metering provided the best performance. Xue et al. (2000) developed a real-time contraflow control method to reduce congestion in the George Massey Tunnel in Vancouver. A classification method was used to match the current traffic demand to the historical traffic patterns and predict the future demand. Tan and Gao (2015) utilized traffic control to mitigate congestion and improve the air quality within tunnels. A ramp metering and mainline traffic control scheme based on time-varying origin-destination rates was proposed to optimize air quality as well as maximize traffic throughput. Recently, Sun et al. (2018) investigated the mechanisms of congestion at the Xiangyin Tunnel in Shanghai due to the gradient changes along the tunnel, which is known as sag. Multiple bottlenecks are induced by the interaction between the tunnel sag and the upstream on-ramp. Three distinctive congestion stages were observed based on analysis of traffic flow features (volume, speed, occupancy). A feedback control strategy was proposed which cooperatively controls the freeway mainline and the on-ramp to improve the performance of the tunnel sag.

3 Methodology

The approach for identifying the causes of congestion in the tunnel and designing adequate ramp metering strategies includes the following steps:

1. Clustering of historical traffic data to identify distinct congestion evolution patterns and characterization of the underlying demand patterns and bottlenecks related to each pattern.
2. Simulation-based identification of the most effective metering strategies for each congestion scenario.

3.1 Data analysis

3.1.1 Data description

Data from the Motorway Control System (MCS) in Stockholm covering the study area are used for the analysis. The data contain information regarding vehicle speed and traffic counts per minute per lane. With 46 MCS portals along the mainline of the westbound tunnel and additional portals covering the on- and off ramps, the data obtained from the MCS portals manage to capture the real traffic conditions inside and downstream the tunnel very well. As a basis for the model calibration, traffic counts and weighted average speeds at different locations inside the tunnel, as well as at entrances and exits are analysed, both for regular days (without closures) and days with heavy congestion and tunnel closures.

3.1.2 Cluster analysis

With the proliferation of large data sets, clustering is increasingly used in transportation studies (Weijermars, 2007). Clustering requires a number of features that are characteristic of the traffic patterns, such as speed, density, speed propagation measurements, etc.

Clustering methods belong to two main groups: hierarchical and partitional. In hierarchical clustering, successive agglomerative or divisive steps are followed, i.e. by merging smaller clusters or splitting larger ones. Appropriate clusters can be determined by a dendrogram that shows the clustering stages and the variation within the clusters. In partitional clustering (e.g. the k-means algorithm), the number of clusters is specified in advance. The selection of the number of clusters is then based on the contribution of each additional cluster to some measure of performance (e.g. variability). For the purpose of this paper, Ward’s hierarchical clustering (Ward, 1963) is chosen. A practical advantage of hierarchical clustering is the visualization of the effect of the number of clusters. Moreover, a dendrogram can be helpful in identifying outliers, e.g. days with very different traffic patterns.

Each day is initially assigned to its own cluster and pairs of clusters are combined stepwise until one cluster remains. The number of clusters N is decided using the dendrogram. Let y_{dlt} be the traffic measurement at location l in time interval t on day d, L the total number of locations and T the total number of time intervals used in the analysis. The cluster membership is assessed by calculating the within-cluster variability for all potential clusters:

$$\sum_{d\in C_k}\sum_{l=1}^{L}\sum_{t=1}^{T}(y_{dlt}-\bar{y}_{klt})^2, \quad (1)$$

where C_k is the set of days in cluster k, and $\bar{y}_{klt}$ is the mean value across all days in cluster k. The criterion for merging different clusters is the minimization of the increase in the total within-cluster variability after two clusters are joined.

3.2 Simulation

The representative congestion patterns resulting from the cluster analysis are then given as input to the simulation analysis, which aims to replicate the different traffic patterns leading to tunnel congestion, and evaluate the effectiveness of various tunnel traffic management strategies under each demand pattern. Simulation models can realistically capture the interactions between supply and demand when assigned to a given network. For the purpose of the analysis in this study, microscopic traffic simulation is used to better reflect the traffic conditions in the tunnel. Microsimulation models can be used to analyse traffic phenomena through detailed representation of the behaviour of individual drivers with respect to the interactions with other vehicles, the road characteristics and their response to control measures. In particular, travel demand in microscopic simulation is usually represented by time-dependent Origin-Destination matrices. Travel behaviour is modelled by route choice models and the traffic dynamics result from a set of various driving behaviour models, including lane-change and car following models (Toledo et al., 2005). Calibration and validation of the models are very important in order for the models to reproduce the actual conditions.

3.2.1 Calibration

The current study initially considered data collected in 2014. Under the time the study was carried out, there were changes in other parts of the network that modified the congestion patterns in the city. Therefore, the demand had to be re-calibrated to correspond to the traffic conditions in 2017. The re-calibration was based on traffic flow data from the MCS portals. More details on the calibration process are presented in Section 5.

3.2.2 Validation

The validation process is performed afterwards in order to evaluate how well the model replicates reality. Toledo and Koutsopoulos (2004) suggests that there are two different approaches to model validation; visual and statistical.

Visual validation involves comparing visual representations of measures of performance (MOPs) from the simulated outputs and the outputs generated from the observed data. Space-time plots is an example of such a visual representation of an output, which means that visual validation played a part of the calibration process of this model.

Statistical validation is less subjective and more accurate compared to visual validation. Several different statistical methods and measures exist to quantitatively compare simulated- and observed outputs. Two aggregate measures of performance were used: the root-mean-square error (RMSE) and the mean absolute error (MAE) for OD flows, counts and speeds, relative to the true (observed) values:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}({y_n}^{est} - {y_n}^{obs})^2} \quad (2)$$

$$MAE = \frac{1}{N}\sum_{n=1}^{N}|({y_n}^{est} - {y_n}^{obs})| \quad (3)$$

Where, N is the number of measurements, ${y_n}^{est}$ are estimated measurements, and ${y_n}^{obs}$ are observed measurements.

Theil's inequality coefficient U was also used to measure both relative error and bias (Toledo and Koutsopoulos, 2004):

$$U = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left({y_n}^{est}-{y_n}^{obs}\right)^2}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}({y_n}^{est})^2}+\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left({y_n}^{obs}\right)^2}} \quad (4)$$

U assumes values between zero and one. $U = 0$ implies perfect fit between the estimated and observed measurements, while $U = 1$ indicates the worst possible fit. Theil's inequality coefficient is decomposed to three proportions of inequality: the bias (U^M), variance (U^M) and covariance (U^M) proportions:

$$U^M = \frac{(\bar{y}^{est}-\bar{y}^{obs})^2}{\frac{1}{N}\sum_{n=1}^{N}({y_n}^{est}-{y_n}^{obs})^2} \quad (5)$$

$$U^S = \frac{(S^{est}-S^{obs})^2}{\frac{1}{N}\sum_{n=1}^{N}({y_n}^{est}-{y_n}^{obs})^2} \quad (6)$$

$$U^C = \frac{2(1-\rho)S^{est}S^{obs}}{\frac{1}{N}\sum_{n=1}^{N}({y_n}^{est}-{y_n}^{obs})^2} \quad (7)$$

where $\bar{y}^{obs}$, $\bar{y}^{est}$, S^{obs} and S^{est} are the sample means and standard deviations of the observed and estimated measurements, respectively, and ρ is the correlation coefficient between the two sets of measurements.

The bias proportion is a measure of the systematic error of the identified solution and the variance proportion is an indication of how well the solution replicates the variability in the observed data. Values of less than 0.10 - 0.20 for these proportions indicate good performance. The covariance proportion measures the remaining error and should be close to one.

For further validation, time series was constructed comparing speed and flow measurements of simulated and observed outputs. This was done for several critical locations in the tunnel as well as for the most important on-ramps.

4 Case study

The approach presented in Section 3 is applied to a tunnel on the Södra Länken motorway section in Stockholm, Sweden (Fig. 1). The Södra Länken freeway is 6 km long, of which 4.7 km is in tunnels. It connects Essingeleden in Stockholm with Värmdöleden in the Nacka municipality (Fig. 1). The tunnel has in general two lanes in each direction and a speed limit of 70 km/h. There are six entry points and six exits (including the mainline entrance and exit). Södra Länken was designed to serve 60,000-70,000 vehicles per day when it opened in 2004. Today, however, the daily traffic demand is 90,000-100,000 vehicles per day. The network of interest is equipped with radar detectors every 200-500 meters as part of the MCS, which report counts and speeds per minute per lane (indicated by dots in Fig. 1).

In order to prevent queues forming inside the tunnel and ensure safety, the traffic authorities have adopted a preventive strategy of temporarily closing some of the tunnel entrances. The number of tunnel closures, due to recurrent congestion only (excluding incidents), has increased over the years with about 60 closures in 2015 (i.e., more than one closure per week). The average closure duration between 2005 and 2015 is about 45 minutes. The closures occur most commonly during the morning peak between 6:00 am and 8:00 am.

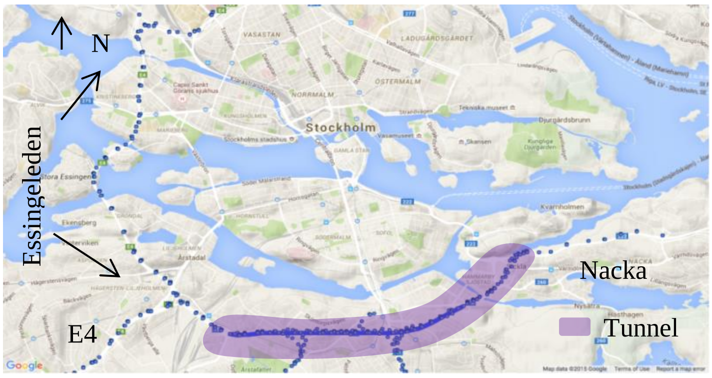


Fig. 1 Södra Länken freeway, Stockholm, Sweden (shaded area). Dots indicate sensor locations.

Before any tunnel closure takes place, warning messages are broadcast via radio, displayed on variable message signs (VMS), and posted on Stockholm's traffic information website. The messages inform drivers about the congestion in the tunnel, but provide no route guidance routes information.

Currently, tunnel closure decisions by the traffic authority are based on speed measurements at sensor locations within critical segments depicted as red rectangles in Fig. 2. Based on predefined speed thresholds and a time window of observing low speed values, a warning for queues inside the tunnel is first given; if low speeds persist, a closure decision is triggered. The speed thresholds are 25 km/h for locations in segments 1 and 4, and 20 km/h for locations in segments 2 and 3 (Fig. 2). A necessary condition for the tunnel to be closed is that speeds at any location within segment 4 drop below the corresponding threshold for a predefined time window (5 minutes). During a closure the evolution of congestion is observed and the tunnel remains closed until the queues dissipate i.e., speeds increase above a prespecified threshold.

During closures travellers experience long delays, either due to congestion or their attempts to find alternative routes through the surrounding urban network.

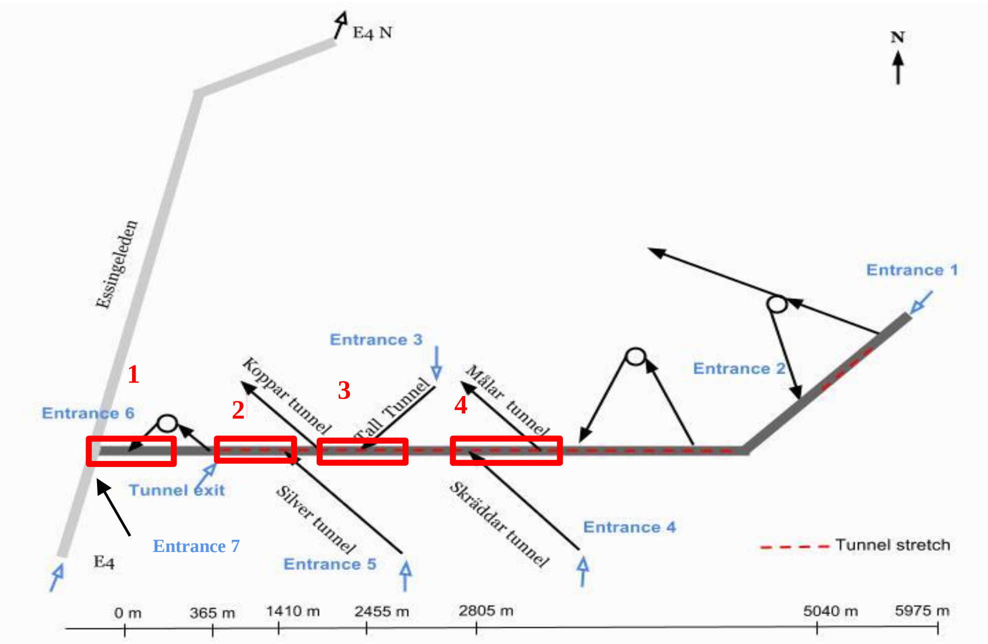


Fig. 2 Measurement locations for tunnel closure decisions under current practice.

5 Results and Analysis

Traffic data are collected per lane from the MCS. The westbound direction and the morning period are selected for the analysis. A set of 25 weekdays in April and October 2014 and 22 days in October 2017, including days with and without tunnel closures, is selected. No days with incidents or sensor failures are included in this data set.

As a basis for the model calibration, traffic counts and weighted average speeds at different locations inside the tunnel, as well as at entrances and exits are analysed, both for regular days and days with severe congestion and tunnel closures.

5.1 Data-driven congestion characterization

Cluster analysis for 2014

Clustering based on the metric in eq. (1) is used to distinguish the temporal and spatial variations among days in the data set and to potentially identify different causes of tunnel congestion. Speed and density measurements at the MCS sensor locations by time of day are used as features. During the morning period measurements from 25 MCS sensor locations inside and downstream the tunnel are aggregated over 5-minute intervals for a time period starting at 6:00 am up to the earliest tunnel closure (7:15 am) that is observed in the data set.

The sensor locations are selected such that they cover important segments and merging/diverging locations in the network, including locations used in the current tunnel closure decision-making process. Finally, locations sufficiently downstream the tunnel exit are used in order to capture the impact of downstream bottlenecks on the tunnel congestion.

Fig. 3 shows the dendrogram from the hierarchical clustering. The days in the data set are presented as leaf nodes and are assigned to specific clusters indicated by clades. Based on the similarity of the different days indicated by the reported distance between clusters (on y-axis), three main clusters are identified. Days belonging to the same cluster share similar spatiotemporal characteristics of the traffic patterns. Cluster 1 includes days without congestion inside the tunnel, while clusters 2 and 3 include days with congestion. For several days in these clusters, the congestion triggered warnings and/or closures.

The main difference between clusters 2 and 3 is with respect to the time and space evolution of congestion. The differences are highlighted by the speed contour diagrams along the westbound direction of the tunnel for two select days, 9th of April 2014 (cluster 3) and 1st of April 2014 (cluster 2) between 5:00-10:00 am, as shown in Fig. 4. The boundaries of the space-time plots are the tunnel entrance from the east (1) and the end of Södra Länken before the merging with E4 northbound (Fig. 1). The blank areas on the contour plots represent closure periods.

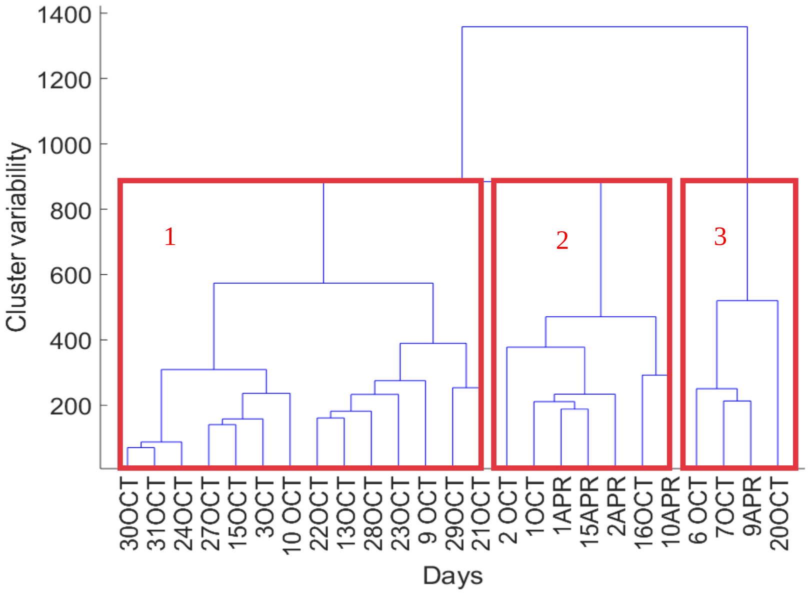


Fig. 3 Clustering dendrogram based on speed measurements downstream and inside the tunnel.

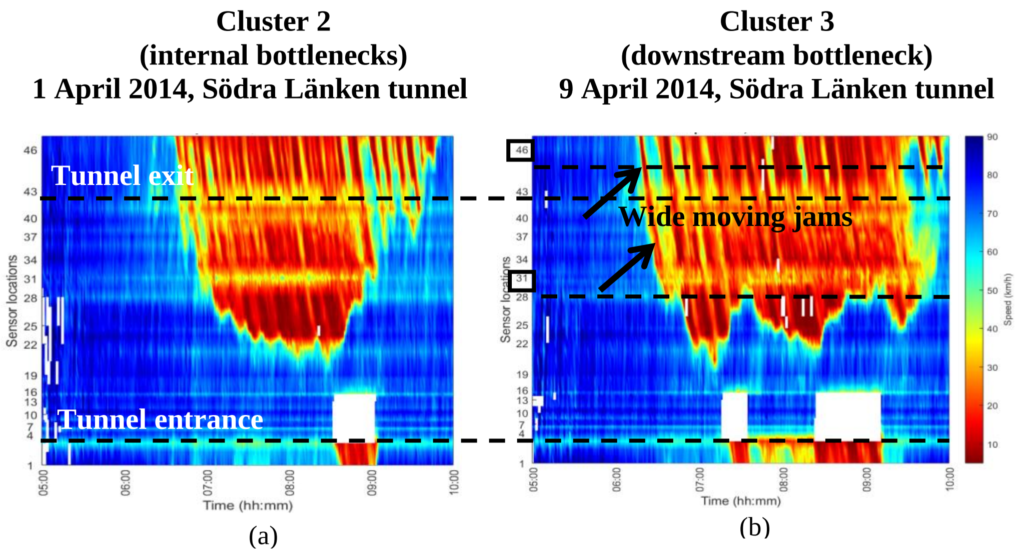


Fig. 4 Speed contours per minute interval for: (a) 1st and (b) 9th of April 2014.

The analysis of the different clusters reveals two distinct congestion patterns. April 9th and April 1st, are selected for further analysis as representatives of each cluster. The first pattern (April 9th) represents days when congestion is triggered by downstream bottlenecks and tends to propagate rapidly inside the tunnel. The second pattern (April 1st) includes days when the downstream congestion spills back slower, while congestion inside the tunnel is generated mainly at the weaving segments inside the tunnel.

Fig. 5 depicts three bottlenecks inside and downstream the tunnel, based on the speed contours analysis. In particular, “Bottleneck 1” is triggered by the downstream conditions on Essingeleden in conjunction with the merging of vehicles coming from E4 northbound. The second cause of congestion inside the tunnel is associated with “Bottleneck 2” and “Bottleneck 3”. The heads of those two bottlenecks are generated at critical segments where weaving phenomena are observed. Congestion at those segments may occur independently of the conditions downstream the tunnel exit.

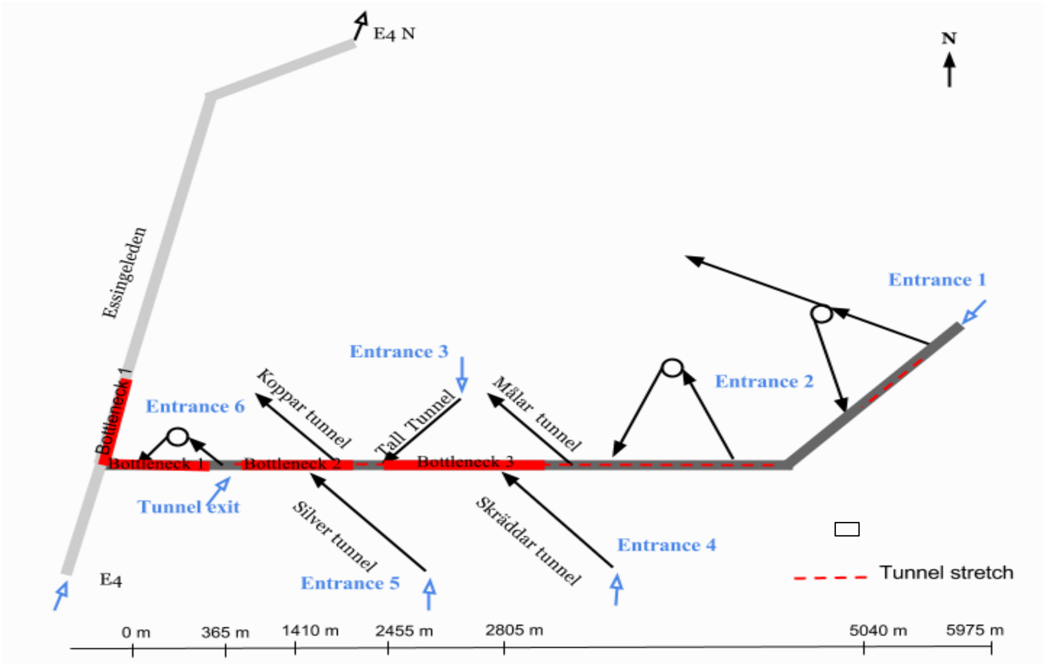


Fig. 5 Main bottlenecks in Södra Länken network.

The results are consistent with the hypothesis that congestion originates inside the tunnel for the type of days in cluster 2, while congestion on days of cluster 3 is a result of both downstream bottlenecks and weaving bottlenecks inside the tunnel.

The analysis presented above is based on measurements from 2014, when the previous work on tunnel congestion was first conducted. During the period 2014 to 2017, the population in Stockholm county has increased by 37 772 people (Statistics Sweden, 2018). The number of registered vehicles in the county has increased from 863 947 in 2014 (Transport Analysis, 2015) to 929 570 in 2017 (Transport Analysis, 2018), an addition of 65 623 vehicles. Additionally, changes in the traffic conditions are expected after the opening of the Norra länken tunnel in 2014-2015 as well as the introduction of congestion charges on Essingeleden in January 2016 (Fig. 6). Therefore, the clustering analysis is extended for the identification of congestion patterns based on measurements from 2017.

Fig. **6** Map of Stockholm showing Essingeleden, Södra- och Nörra länken.

Cluster analysis for 2017

Similar analysis is conducted for the days in October 2017 in order to reveal any differences in the congestion patterns compared to the year 2014. The results suggest that the data for all 22 weekdays of October 2017 can be divided into three clusters; two clusters with severe congestion and one cluster with less congestion. The three clusters are presented in the dendrogram shown in Fig. 7.

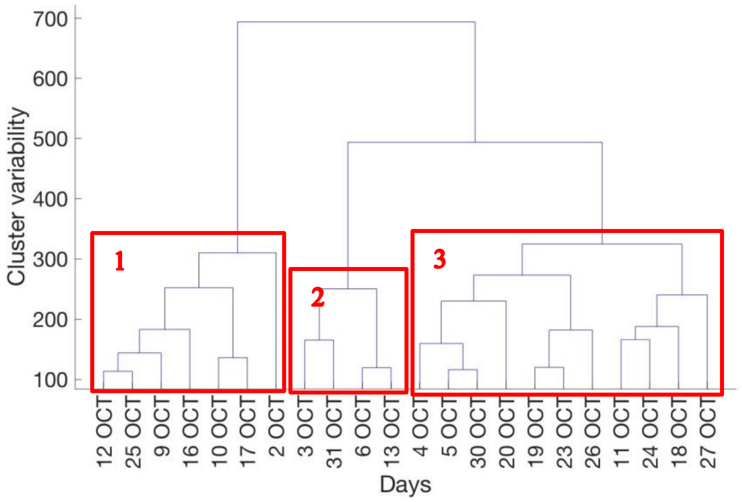


Fig. 7 Clustering dendrogram based on speed measurements downstream and inside the tunnel.

Three clusters are identified based on the similarities between different days. The difference between the clusters suggests that the development of congestion in the tunnel follows two distinct patterns. In cluster 1, congestion appears to originate from bottleneck 2 (Fig. 5), the weaving segment related to entrance 5 (Fig. 5) and develops upstream to bottleneck 3 (Fig. 5) located between the tunnel entrances 3 and 4. Congestion develops further upstream the tunnel on days included in cluster 1 compared to days that belong to cluster 3. In cluster 3, congestion is less at entrance 5. Instead, congestion seems to originate from entrance 3, however, it does not reach as far upstream as on days in cluster 1. Overall, the level of congestion is higher for days that belong to cluster 1 as opposed to cluster 3.

Speed contours for one representative day included in each of the three clusters are presented in Fig. 8 (contour plots for all days included in each cluster are presented in Appendix A). The main difference between days in clusters 1 and 3 relate to the propagation of congestion. In particular, it can be observed that the queues on days in cluster 1 propagate far upstream in the tunnel, at entrance 2. In cluster 3, however, the queues reach about 800 meters downstream entrance 2.

Cluster 2 contains days with minor congestion. On these days, congestion appears at bottleneck 3 right after entrance 3 and there are no spillback queues developing from downstream bottlenecks. The analysis of this study focuses on the most severe congestion patterns, hence, the patterns identified in clusters 1 and 3.

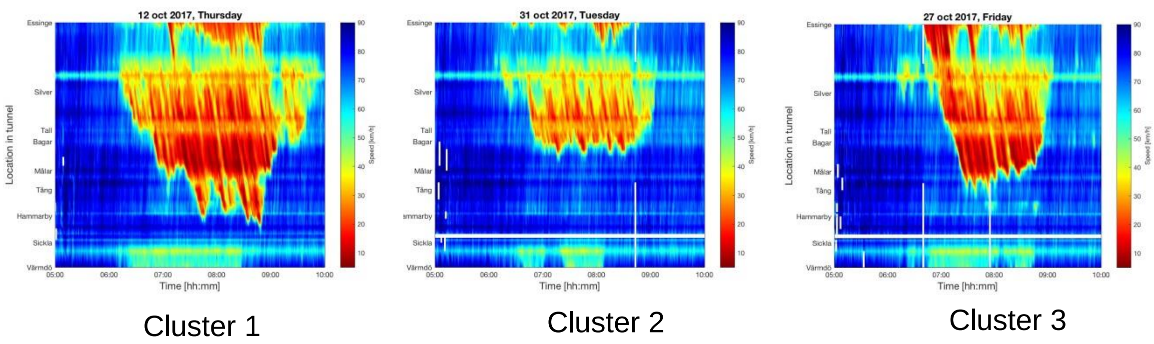


Fig. 8 Speed contours per minute interval for representative days from each cluster.

Comparison of traffic conditions in 2014 and 2017

Based on the results from cluster analyses for the years 2014 and 2017, the main difference observed with respect to their congestion patterns is that in 2017 congestion is mainly triggered due to internal bottlenecks, and not so often due to downstream bottlenecks as observed for 2014.

5.2 Simulation-based evaluation of metering strategies

Before conducting any simulation experiments, calibration of the network and demand is required. Based on the results of the cluster analyses for years 2014 and 2017, different demand scenarios corresponding to the demand patterns extracted are used for the evaluation of different metering strategies.

These demand scenarios are then used for the comparison and evaluation of the different simulation scenarios that followed. With respect to the network calibration, the default values for the different model parameters are used (i.e., driver behaviour parameters, vehicle fleet, etc.).

For the year 2014, two demand scenarios corresponding to the patterns extracted in clusters 2 and 3 were used for the evaluation of different metering strategies. Two closure days (1st and 9th of April 2014) are used as representatives for the two congestion patterns. Data from each day were used to calibrate an OD matrix to represent the demand patterns for the specific scenario. For the year 2017, the congestion pattern identified in cluster 1 is selected to be simulated, as congestion on those days is more severe.

Each of the demand scenarios is simulated under alternative metering scenarios. The microscopic traffic simulation model TransModeler 4.0 (Caliper, 2008) is used. The simulated network consists of the main motorway section, including the tunnel, the E4 motorway and all tunnel ramps (Fig. 5); in total 57 links and 77 OD pairs. The simulation period is 6-9 am.

The initial demand matrix is extracted from SAMPERS (Beser and Algers, 2002). The OD matrices for the typical days that are analysed are generated based on observed vehicle counts from the two days on certain locations. The OD matrices are adjusted to minimize the error between the observed and simulated counts and speeds at key sensor locations.

The analysis and results that are presented in the rest of the report are focused on the most recent congestion patterns, i.e. for year 2017.

5.2.1 Calibration

Fig. 9 shows the average inflow from the most critical tunnel entrances based on average count measurements from weekdays in October 2017. The highest inflow arrives from entrance 1 (Värmdövägen). Entrance 4 brings high inflow into the tunnel, however, due to congestion on the on-ramp the inflow reduces to only 800 veh/h during the peak.

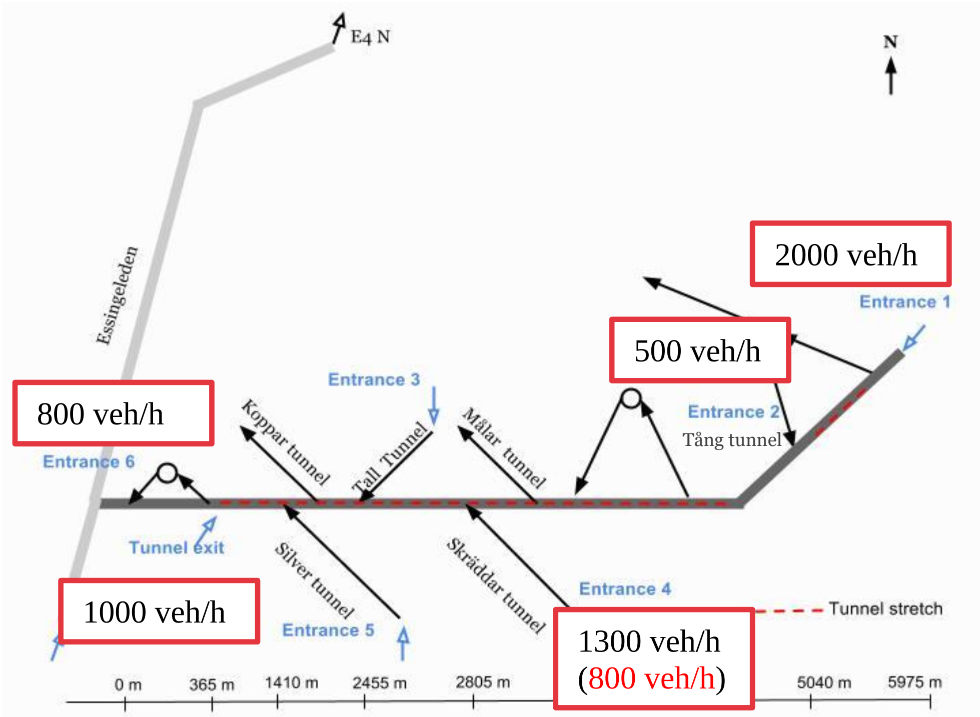


Fig. 9 Average inflow measurements at main tunnel entrances for October 2017.

A speed contour plot is constructed based on average speed data from all days included in cluster 1 (Fig. 10). The morning peak between 6:15 - 7:45 am is calibrated based on 23 MCS sensor locations along the mainline of the tunnel averaged across all days in cluster 1.

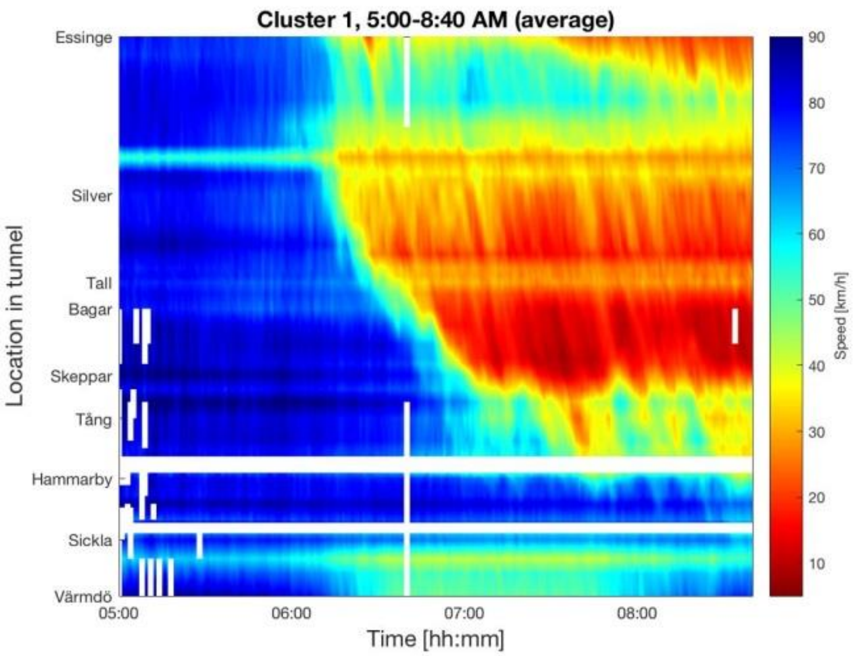


Fig 10 Average speed contour per minute interval of days in cluster 1.

Congestion in the observed measurements starts at approximately 6:15 am and propagates at upstream to the weaving segment between entrance 2 (Tång tunnel) and the Mälar tunnel exit (Fig. 9) at approximately 7:00 am. Congestion remains until the end of the peak. In Fig. 5 it is shown that two bottlenecks exist in the tunnel; the first at entrance 5 and the second at entrance

3, as it was also identified in the cluster analysis. Furthermore, as indicated on the average speed contour of cluster 1, there are no spillback queues downstream the tunnel from Essingeleden.

This type of congestion pattern will be used as the representative pattern to evaluate different ramp metering strategies.

5.2.2 Validation

Table 1 presents Theil's inequality statistics, the RMSE and MAE for counts and speeds as a goodness-of-fit-measure. For the validation, measurements of speeds and counts from 10 sensors along the mainline of the tunnel are used, different from the ones used for calibration. The calculated values indicate very good fit of the measurements.

Table 1 Goodness-of-fit statistics.

	U	**U^M**	**U^S**	**U^C**	**MAE**	**RMSE**
Counts (veh/h)	0.09	0.015	0.032	0.98	328	406
Speeds (km/h)	0.12	0.022	0.0007	0.96	9.7	13.2

Regarding the observed outputs, averaged measurements for all days included in cluster 1 are used. The measurements of the simulated output are averaged over 5 independent simulation runs. Both the observed- and the simulated measurements are also averaged over 15-minute time intervals between 6:00 - 8:30 am.

The Theil's U coefficient on Table 1 indicates a good overall fit on both counts and speeds. The bias proportions (U^M) indicate good performance. The low values of the variance proportion (U^S) for both speeds and counts, indicate that the model captures the variance between the observed and the simulated outputs very well. The covariance proportions (U^C), indicate very good fit of the measurements.

Both the MAE and the RMSE values are rather high regarding the count measurements. The MAE indicates that the mean absolute error is 328 vehicles per 15 minutes. Similarly, the RMSE value is high for counts.

5.3 Experimental design

Different ramp metering scenarios as well as scenarios that involve metering in the mainline are implemented and evaluated in the simulation. The term metering is used in the rest of the report to refer to both ramp metering and mainline metering. The examined scenarios differ with respect to the following factors:

- Metering location
- Metering rate
- Activation time
- Combination of metered on-ramps

The metering locations are depicted on Fig. 11 and involve the following on-ramps and mainline locations:

- Entrance 1(V222)
- Entrance 2 (Sicklavägen)
- Entrance 5 (Huddingevägen)
- Entrance 6 (Åbyvägen)

The traffic cycles for the metering scenarios are fixed and different for the various scenarios. In most of the cases *one-car-per-green* metering policy was used and the cycle length varies between 4 - 7 seconds. For some metered on-ramps, the ALINEA strategy is also implemented when feasible. For this purpose, adequate adjustment of the strategy parameters was conducted (see Appendix A for the description of ALINEA).

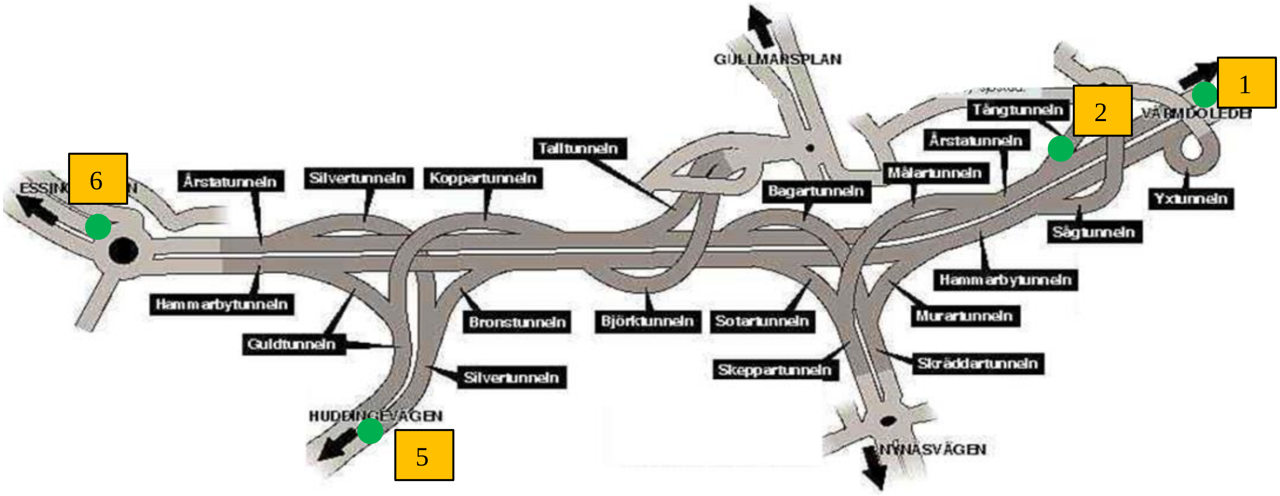


Fig 11 Metering locations on Södra Länken.

Table 2 summarizes the design of the most promising metering schemes that are evaluated. Different metering rates are examined based on a *one-car-per-gree*n policy. In particular the following traffic signal cycles and corresponding metering rates are implemented:

- *Metering scenario 1: Entrance 5: cycle 7 sec, rate: 500 veh/h*
- *Metering scenario 2: Entrance 5: cycle 6 sec, rate: 600 veh/h*
- *Metering scenario 3: Entrance 5: cycle 7 sec, rate: 533 veh/h, Entrance 1 (2 lanes): cycle 5 sec, rate: 1440 veh/h, Entrance 6: cycle 4 sec, rate 900 veh/h*
- *Metering scenario 4*: *Entrance 2: cycle 7 sec, rate: 457 veh/h, Entrance 5: cycle 6 sec, rate 533 veh/h, Entrance 6: cycle 5 sec, rate 640 veh/h*
- *Metering scenario 5*: *Entrance 1: cycle 7 sec, rate: 457 veh/h, Entrance 5: cycle 4 sec, rate 800 veh/h, Entrance 2: cycle 5 sec, rate 640 veh/h*

For the scenarios that involve metering of Entrance 1, metering is implemented in the mainline downstream entrance 1.

Table 2 Summary of main metering scenarios.

Metering scenarios	Entrance 1 (2 lanes)	Entrance 2 (1 lane)	Entrance 5 (1 lane)	Entrance 6 (1 lane)
1			06:00 - 08:00	
2			06:00 - 08:00	
3	07:00 – 07:30	07:30 – 08:30	06:00 - 08:00	
4		06:00 - 08:00	06:00 - 08:00	06:00 - 08:00
5	07:00 – 07:30	07:30 – 08:30	06:00 - 08:00	

5.4 Results

5.4.1 No metering scenario

In the base scenario, no congestion mitigation strategy is applied. Fig. 12 shows the speed contour plots for the base scenario representing the simulated speeds. The boundaries of the space-time plots are the tunnel entrance from the east (1) and the end of Södra Länken before the merging with E4 northbound (Fig. 12). The contour plot indicates the generation of an internal bottleneck downstream entrance 5 at 6:10 am, which propagates upstream and reaches the congested on-ramp at entrance 4. In this scenario, congestion lasts until the end of the simulation period, i.e. 9:00 am.

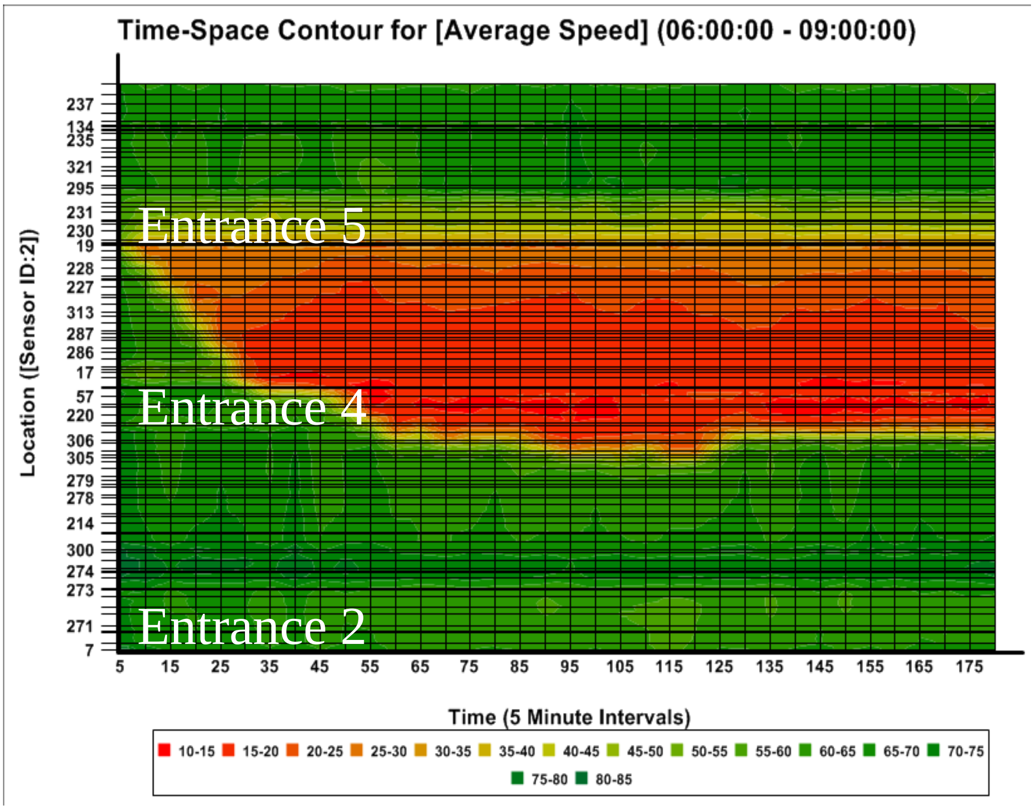


Fig. 12 Speed contours per 5-minute interval for base scenario 2017.

5.4.2 Metering scenario 1

Metering scenario 1 involves metering of entrance 5 (Silver tunnel) between 6:00 – 8:00 am. Fig. 13 depicts the speed contour plot for the most rigorous scenario with metering rate 500 veh/h. The plot indicates that with metering, congestion is reduced in time and space compared to the scenario without metering (Fig. 12). In particular, congestion is prevented early in the morning at the Silver (entrance 5) tunnel bottleneck. However, congestion starts developing later and propagates upstream towards Skräddar on-ramp (entrance 4). The potential reasons for that are investigated further by analysing the traffic measurements for specific sensor locations inside the tunnel.

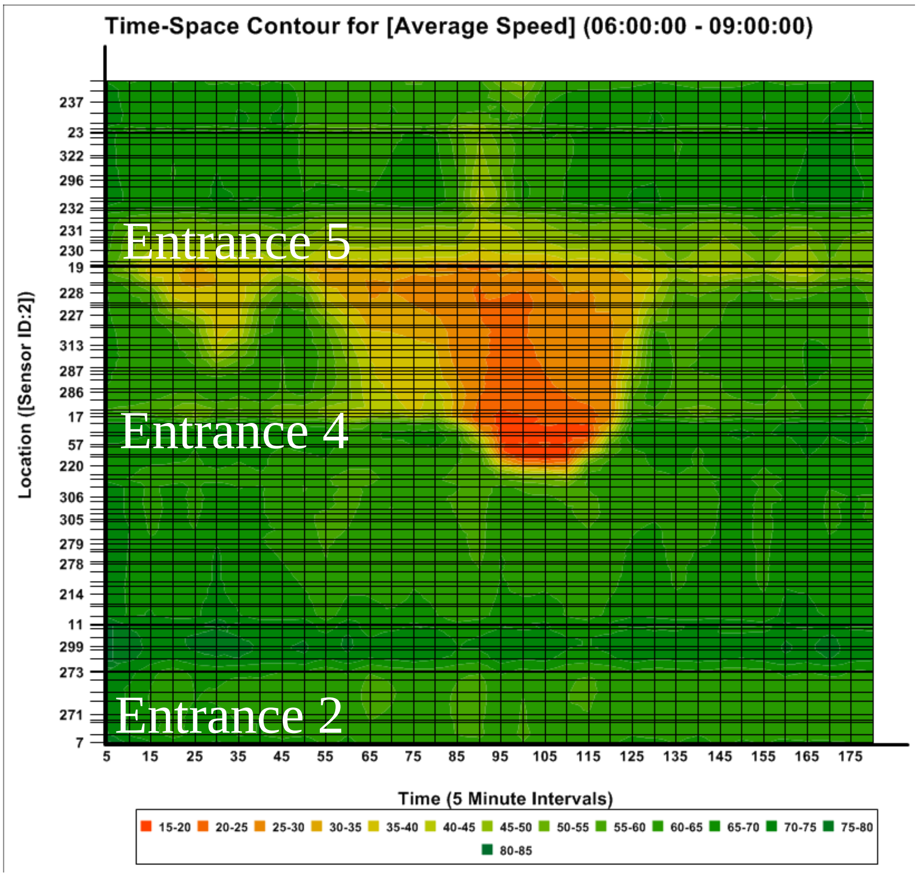


Fig. 13 Speed contours per 5-minute interval for metering scenario 1.

In particular, the location corresponding to the entrance of Skräddar tunnel is further analysed. Figs 14 a-b show the flow and speed measurements over time entrance 4 (Skräddar), for the base and metering scenario, respectively. It is noteworthy that in the no metering scenario the ramp inflow during 6:30 – 8:45 am is significantly low due to congestion, as indicated by the reduced speeds. However, when metering is applied at the downstream on-ramp (entrance 5), the throughput on entrance 4 increases significantly, which is consistent with the increase in the speeds. This indicates how the control of a downstream bottleneck through metering can help to mitigate or even prevent the formation of congestion at upstream on-ramps.

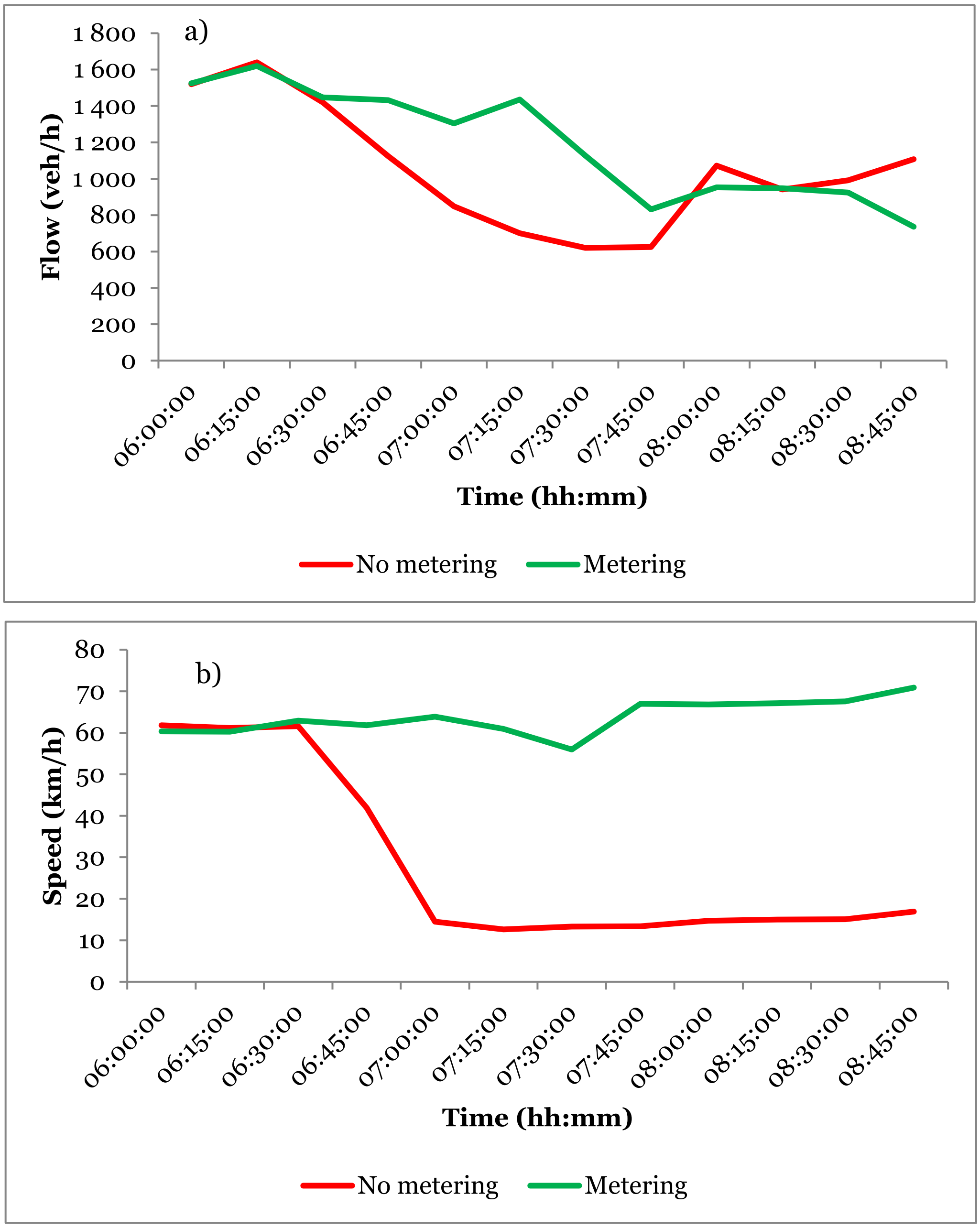
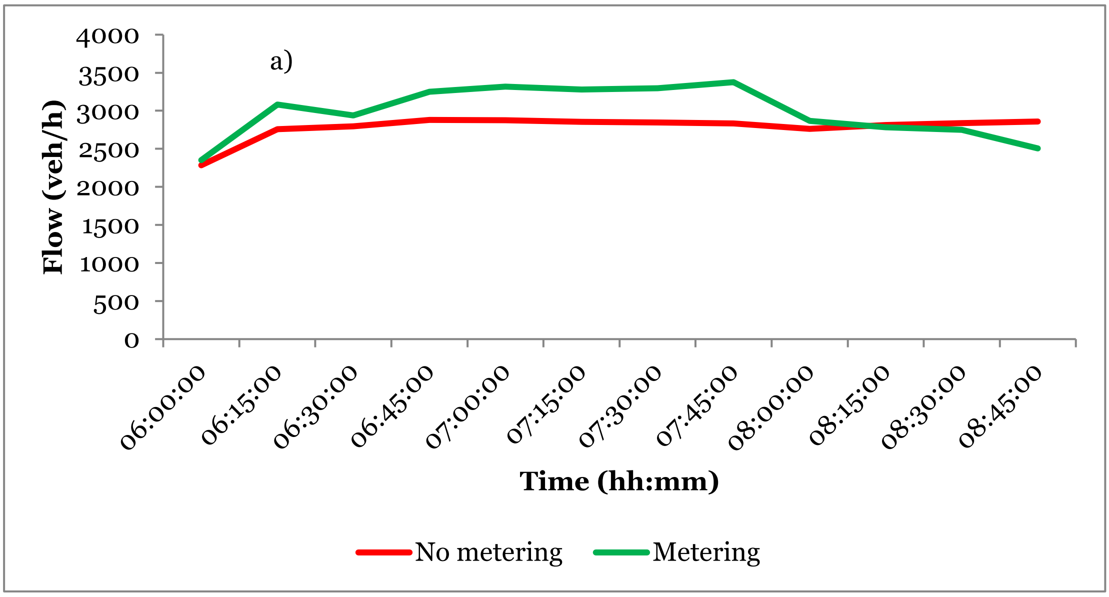


Fig. 14 Comparison of no metering and metering scenario 1 at entrance 4 for: a) Flows, and b) Speeds.

Figs 15 a-b depict the corresponding flow and speed time series at a sensor location inside the tunnel downstream entrance 3. It is observed that the tunnel throughput has been increased by 500 veh/h by controlling entrance 5. With respect to the speeds, higher values are observed during the metering period compared to the scenario without metering. Nevertheless, congestion is formed again between 7:00 – 7:45 am. This can be explained due to the higher inflow that is now released from entrance 4 (Fig 5) due to mitigation of congestion.



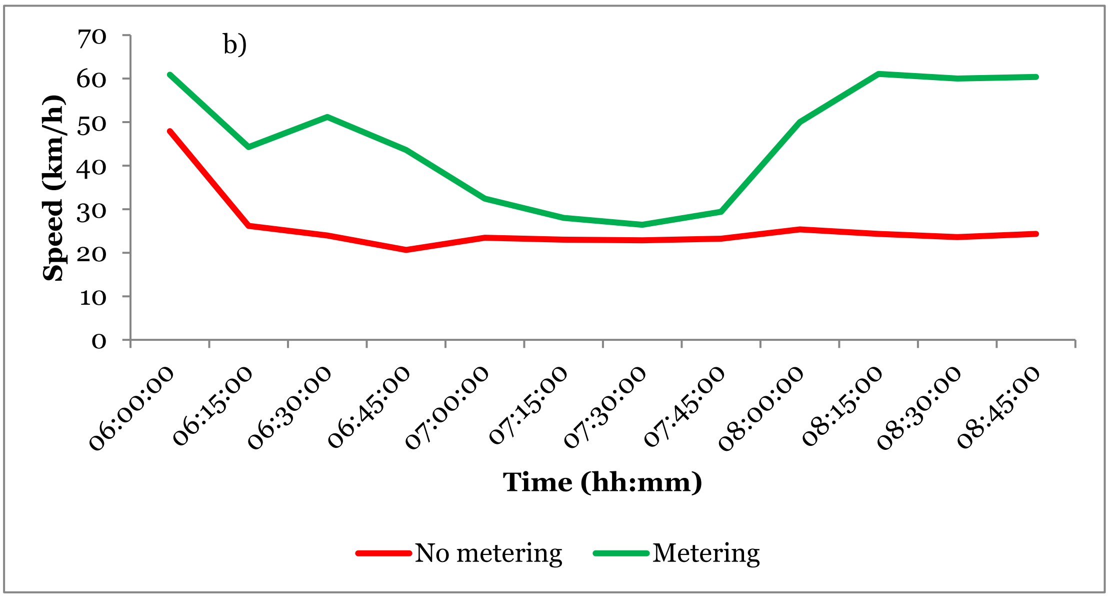


Fig. 15 Comparison of no metering and metering scenario 1 downstream entrance 3 for: a) flows, and b) speeds.

The inflow at the metered on-ramp (entrance 5) is also analysed. Figs 16 a-b present the flow and speed time series at the front of the on-ramp before merging with the mainline tunnel. As it can be seen the inflow from entrance 5 is consistent with the metering rate (500 veh/h) and is 45% lower than the inflow when no metering is applied. The corresponding speeds at the end of the metered on-ramp are low due to the merging, however, higher than in the no metering scenario.

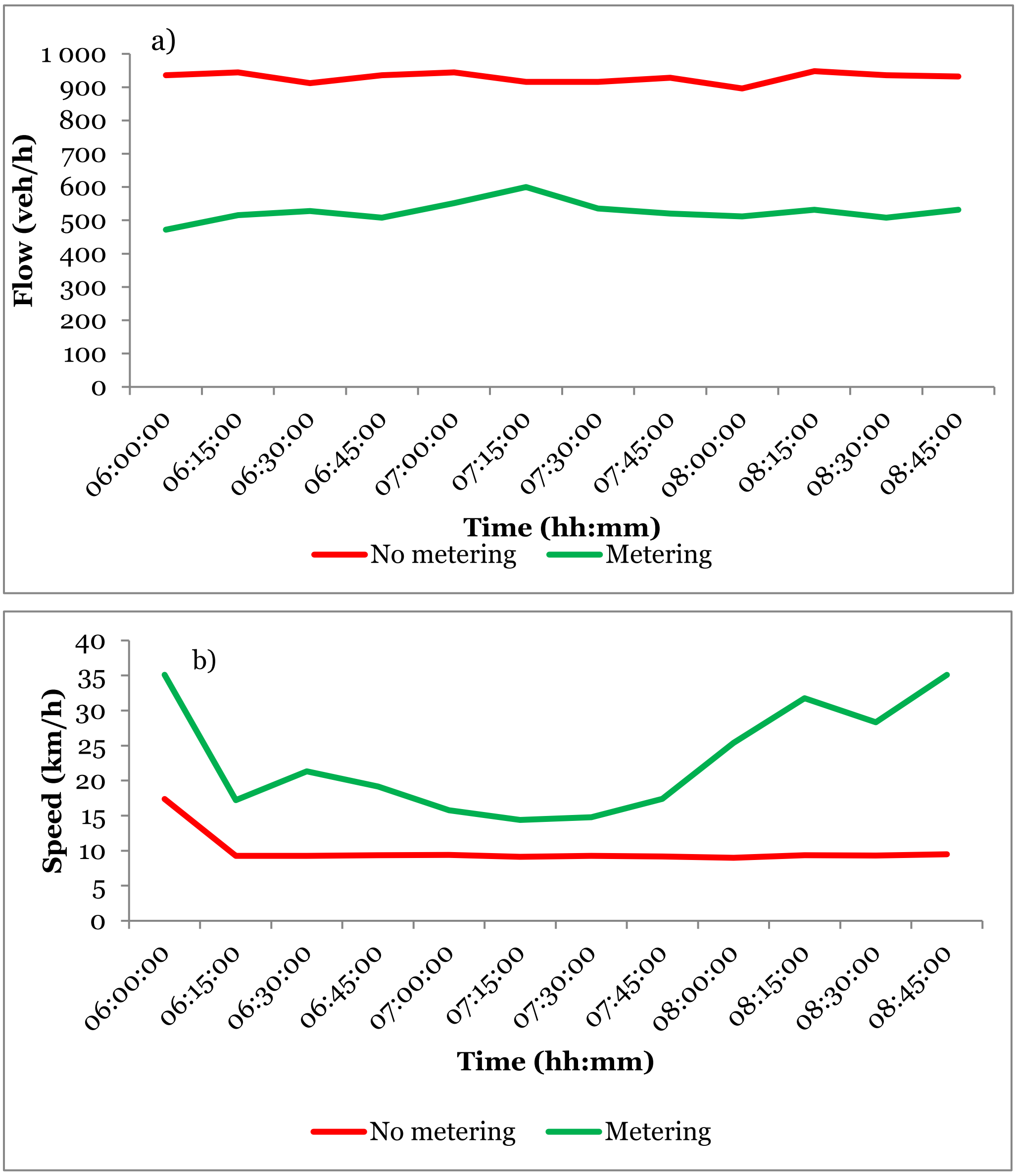


Fig. 16 Comparison of no metering and metering scenario 1 at the metered entrance 5 for: a) flows, and b) speeds.

5.4.3 Metering scenario 2

Metering scenario 2 involves metering of entrance 5 between 6:00 – 8:00 am with metering rate 600 veh/h. Similar results are obtained when the metering rate at entrance 5 is 600 veh/h, as it can be seen in Fig. 17. The results for the flow and speed measurements are similar to those for scenario 1 (Figs 14-16).

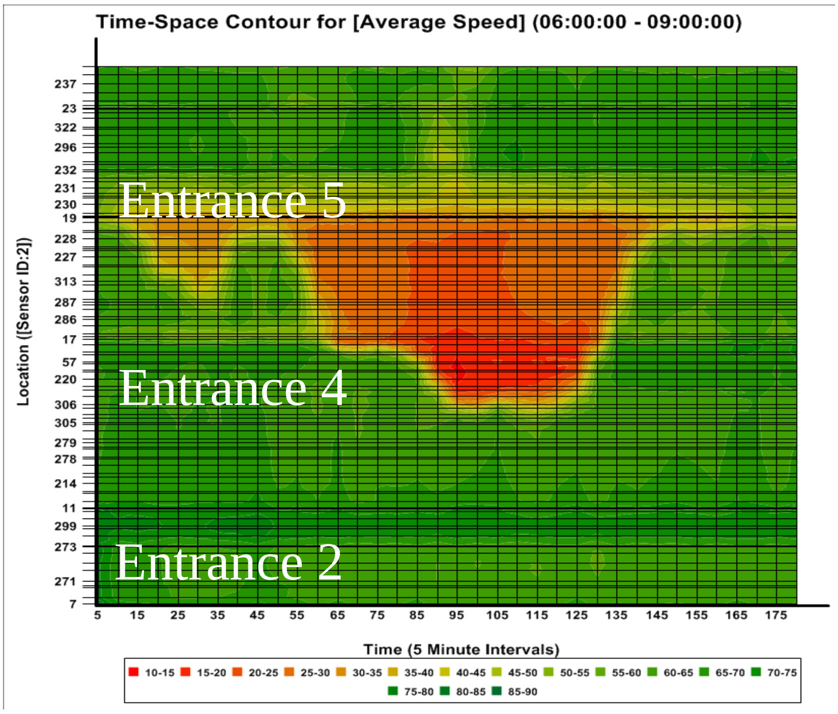


Fig. 17 Speed contours per 5-minute interval for metering scenario 2.

5.4.4 Metering scenario 3

Metering scenario 3 investigates metering on two lanes on the mainline downstream entrance 1 (7:00 – 7:30 am), which brings the highest inflow into the tunnel, as well as at entrances 5 and 6. The metering rates are 1440 veh/h for entrance 1 and 500 veh/h for entrance 5. Metering on entrance 1 is implemented for a short period, 30 minutes, in order to avoid queue build-up on the mainline. The contour plot on Fig. 18 clearly demonstrates the benefit of implementing metering at entrance 1.

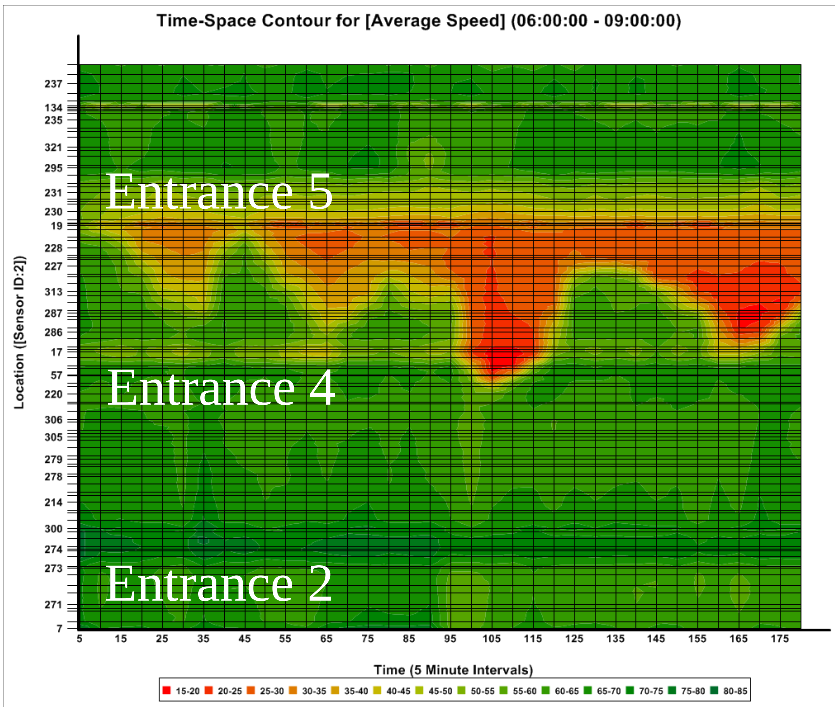


Fig. 18 Speed contours per 5-minute interval for metering scenario 3.

Figs 19 a-b compare the flow and speed time series between the scenarios with and without metering for entrance 4. The results are similar to those in scenario 1. The throughput is increased when entrances 1 and 5 are metered. Figs 20 a-b show the corresponding flows and speeds downstream entrance 3. Compared to the results obtained in scenario 1, the speeds remain high for almost the whole simulation period when both entrances 1 and 5 are metered. The measured flow during control is overall higher compared to the no metering case.

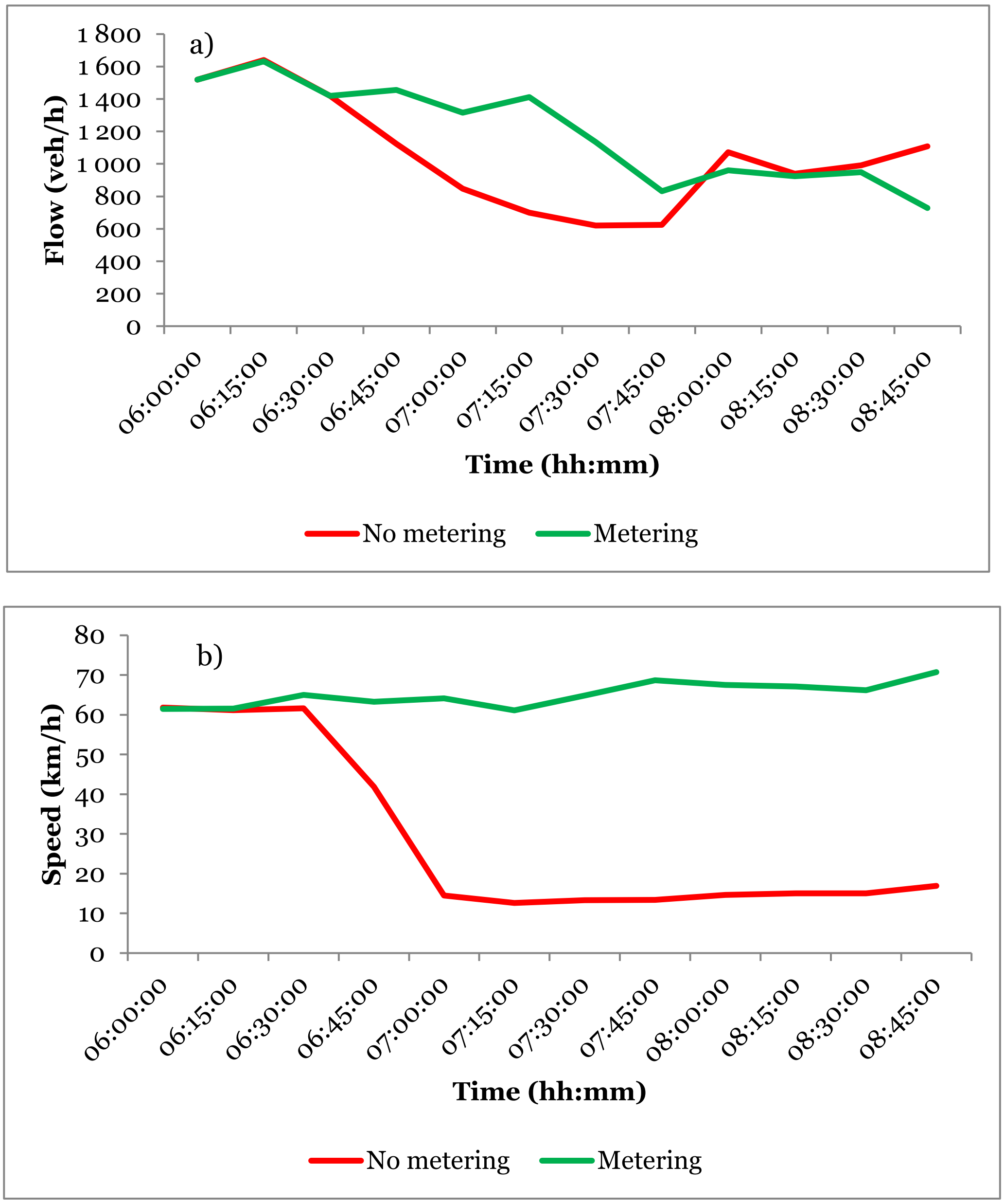


Fig. 19 Comparison of no metering and metering scenario 3 at entrance 4 for: a) flows, and b) speeds.

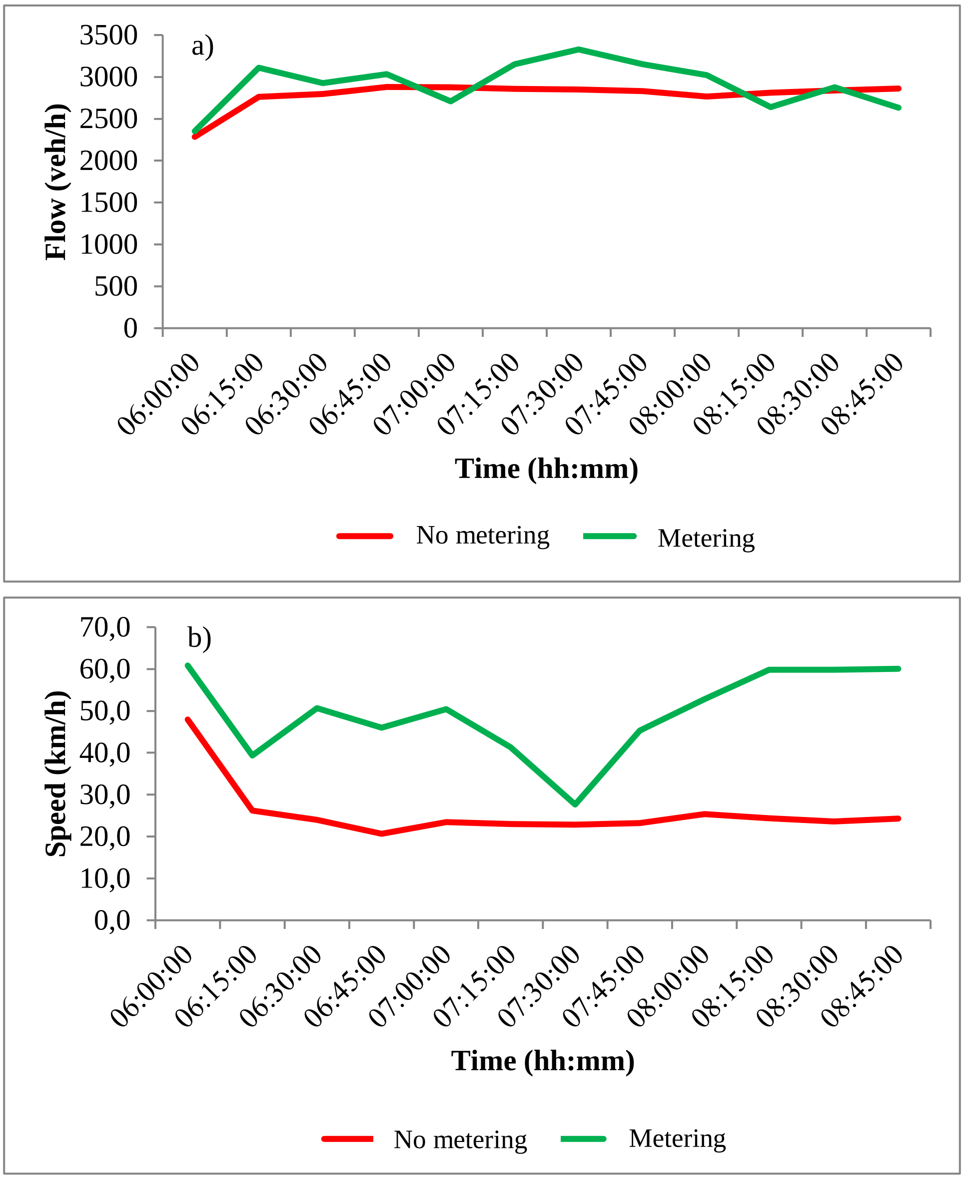


Fig. 20 Comparison of no metering and metering scenario 3 downstream entrance 3 for: a) flows, and b) speeds.

5.4.5 Metering scenario 4

Metering scenario 4 investigates metering on entrances 2, 5 and 6 with corresponding metering rates, 500 veh/h, 533 veh/h, and 640 veh/h, respectively. The metering time is 6:00-8:00 am for all ramps. The contour plot on Fig. 21 shows that congestion in the tunnel can be significantly reduced and similar results are obtained as in metering scenario 3. The main difference between metering scenarios 3 and 4, is that in scenario 3 the mainline upstream entrance 2 is controlled, while in scenario 4 ramp metering is applied at entrance 2. Entrance 2 brings less inflow into the tunnel compared to Entrance 1, hence the metering plan is not very restrictive.

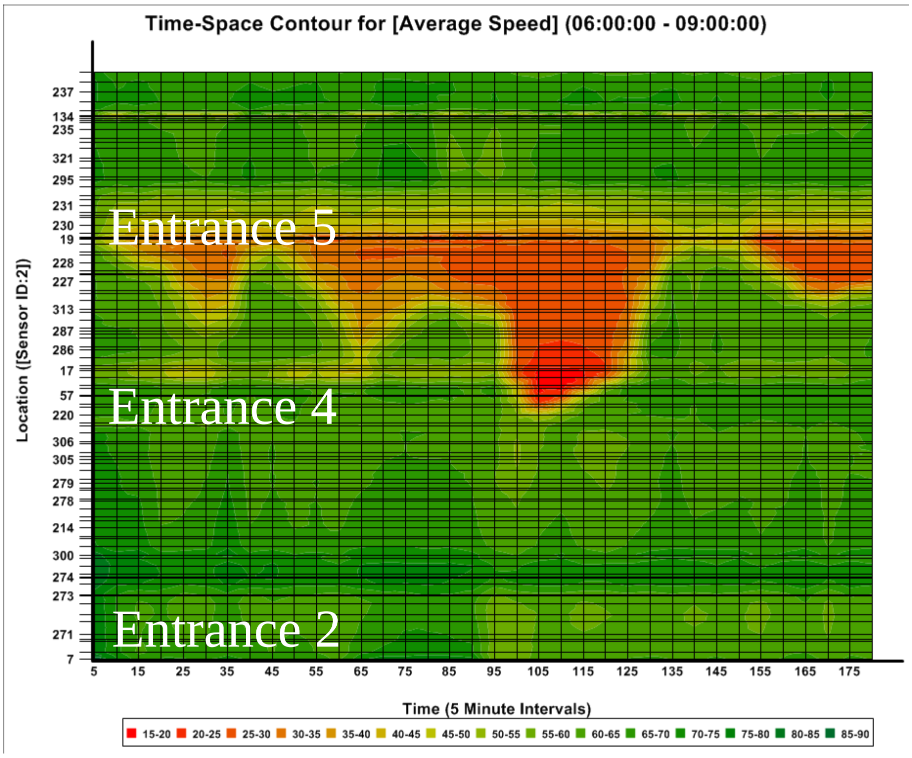
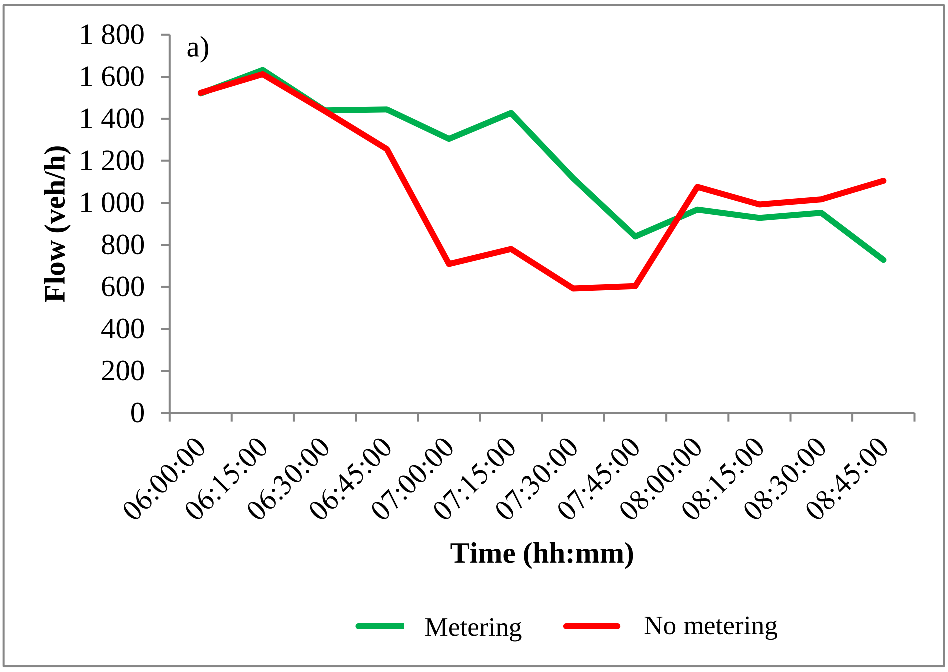


Fig. 21 Speed contours per 5-minute interval for metering scenario 4.

The flow and speed time series in Figs 22a-b indicate the effect of this metering scenario at entrance 4. Similar to the results obtained from Scenario 3 (Fig. 19), propagation of congestion from downstream bottlenecks is avoided at this on-ramp compared to the no metering scenario. Consequently, the inflow from this ramp is increased during the congestion peak (6:45 – 8:00).



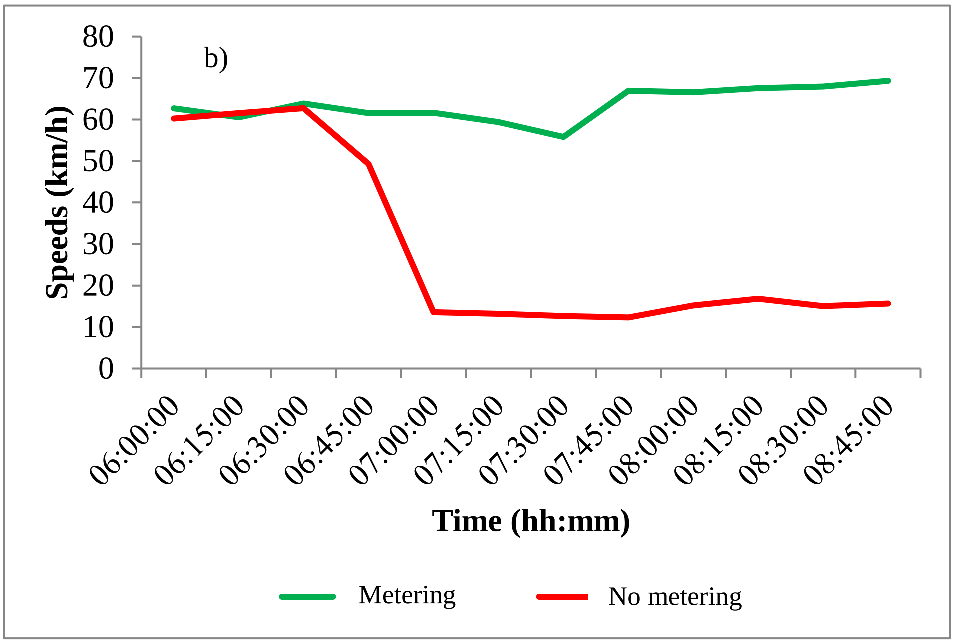


Fig. 22 Comparison of no metering and metering scenario 4 at entrance 4 for: a) flows, and b) speeds

The flow and speed measurements inside the tunnel downstream Entrance 3 are depicted on Figs 23a-b. With metering, the flow has increased on average by 11% during the metering period (6:00 – 8:00 am). Similarly,the speeds are enhanced, however, after a while they decrease again after 7:15 am compared to the corresponding values from metering scenarios 1 and 3. This is probably due to the fact the the metering rate is higher at entrance 5 compared to metering scenario 1 in order to mitigate the queues and delays on the metered on-ramp, as well as, that the mainline flow from entrance 1 is not metered in scenario 4 compared to scenario 3.

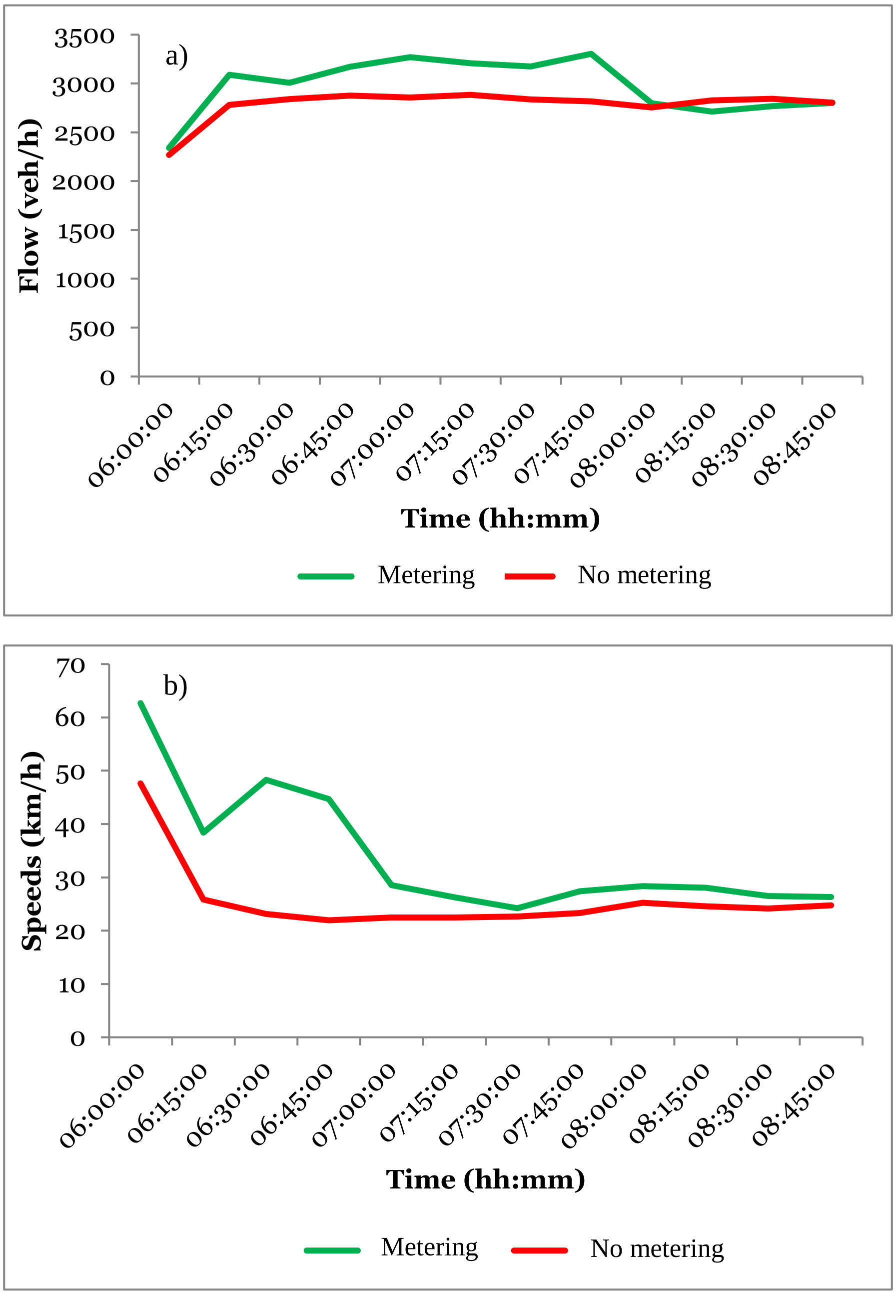


Fig. 23 Comparison of no metering and metering 4 downstream entrance 3 for: a) flows, and b) speeds.

5.4.6 Travel times

One important measure of performance is the travel time. In particular, O-D travel times are shown for four OD pairs and the main metering scenarios in Fig. 24. The corresponding travel times for the scenario without metering are also presented for comparison. The presented travel times are the average values derived from ten simulation replications.

The first OD pair covers most of the tunnel stretch. Its length is 6.24 km. The origin is at Sicklavägen (entrance 2, Fig. 5). Based on the OD travel times shown in Fig. 25, the traffic conditions are enhanced for scenario 1 where metering at Silver tunnel entrance (entrance 5) is deployed. The metering is implemented early in the morning (6:00 am) and for the whole simulation period. The resulting OD travel times are reduced for most of the metering scenarios, except for scenarios 4 and 5, where significant increase in travel times is observed. This is expected as metering is implemented at the on-ramp where the origin of this OD pair is.

OD travel times for scenario 3 show further improvement compared to scenario 1. This is expected as in this scenario both entrance 5 as well as the main tunnel entrance 1, which brings the highest flow into the tunnel, are metered.

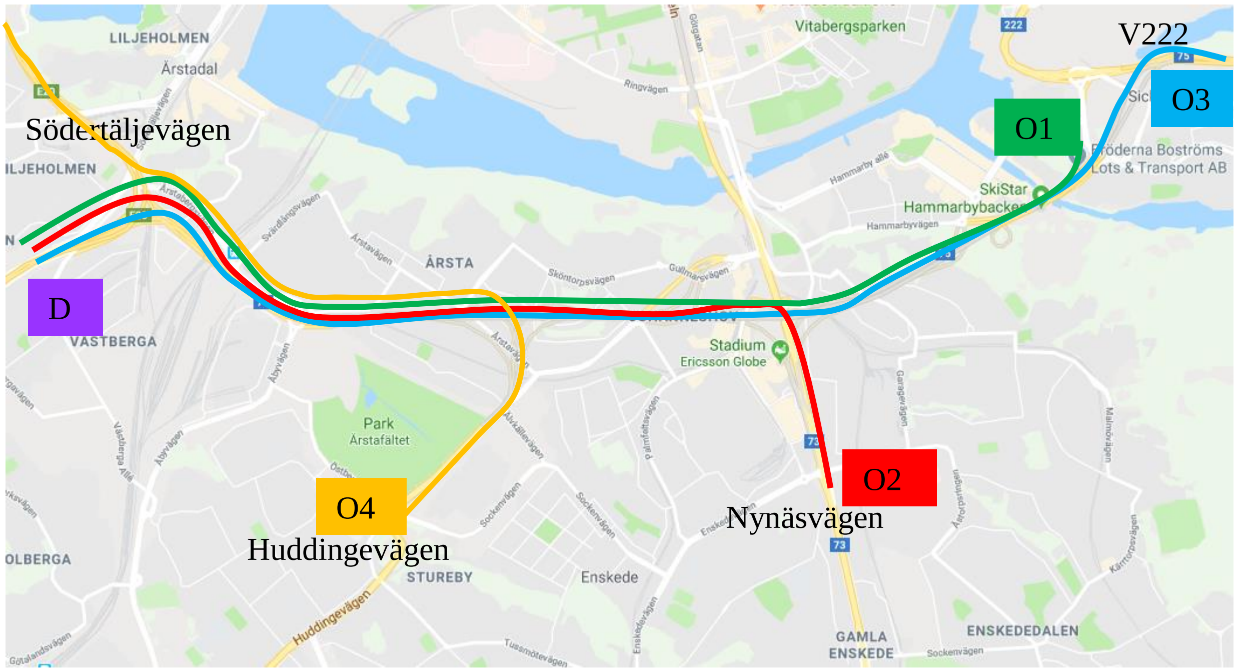


Fig. 24 Select OD paths.

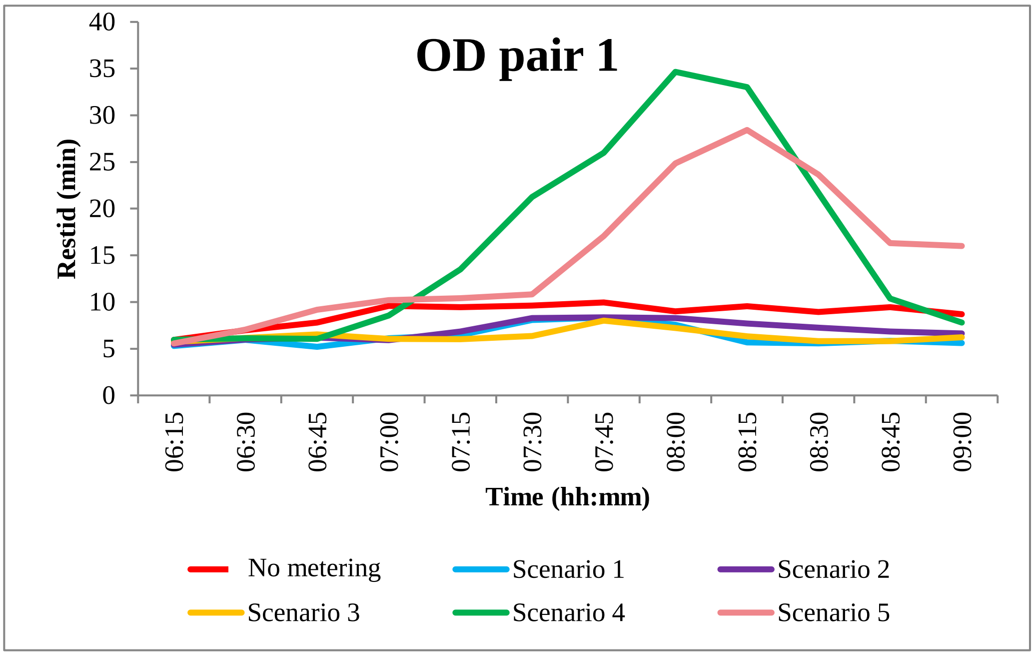


Fig. 25 Travel times.

The second OD pair originates at the congested entrance 4 (Fig. 5) and has the same destination as the first OD pair. Its length is 4.3 km. As shown on Fig. 26, in the no metering scenario travel times are very high due to congestion on entrance 4 and inside the tunnel. When the series indicates zero value for the no metering scenario, it represents that no vehicle was able to complete the segment in order to be sampled. When entrance 5 is metered in scenarios 1-2, travel times decrease significantly (77%). The travel time reduction for scenarios 3-4 is higher (85%). For these scenarios, three metering is applied at three on-ramps.

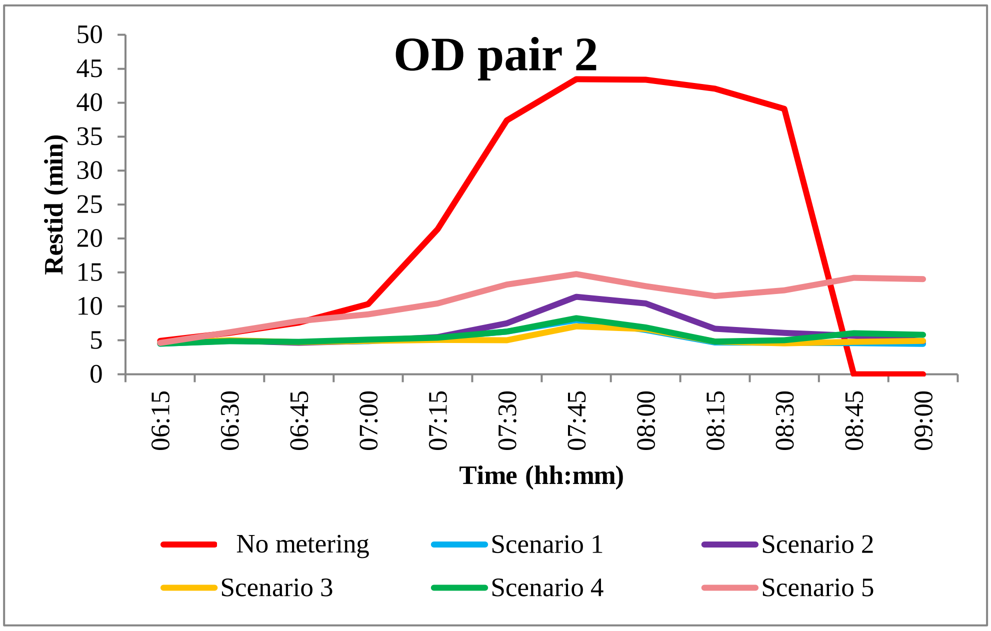


Fig. 26 Travel times.

In Fig. 27 the travel times for OD pair 3 are presented. This OD pair is about 14 km long with its origin east of the tunnel entrance and destination north on Essingeleden. For scenarios 1, 2, and 4, the travel times are slightly reduced compared to the no metering scenario. A higher reduction is observed for scenario 4, where three on-ramps are metered. Scenarios 3 and 5 high significantly increased travel times as expected, due to metering of the mainline downstream entrance 1. The effect is lower in scenario 3.

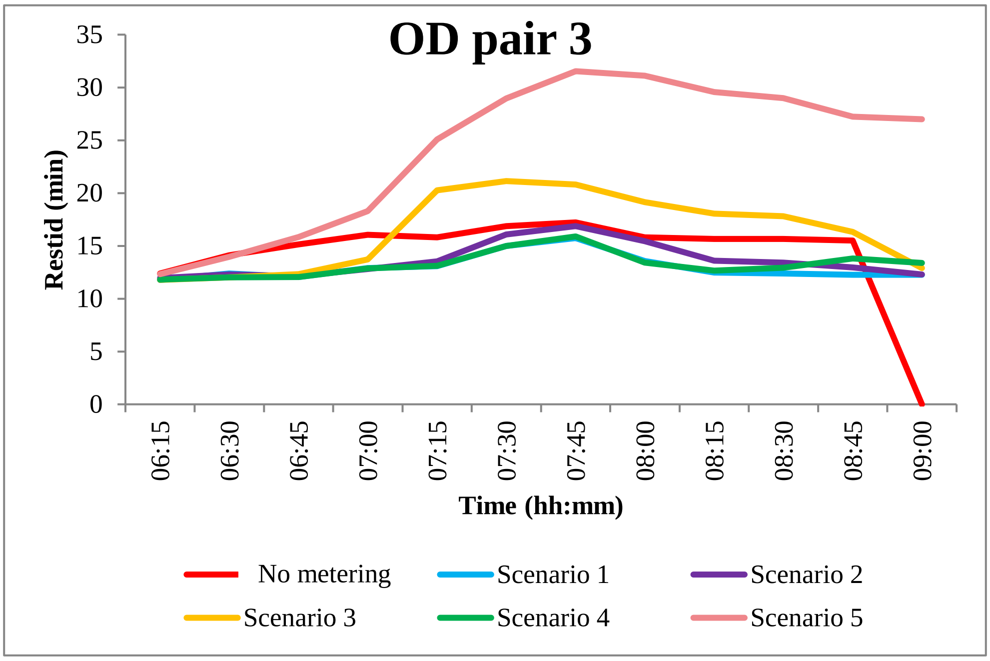


Fig. 27 Travel times.

Finally, the travel times for OD pair 4 are presented in Fig. 28 for the no metering scenario and metering scenario 5. The origin of this OD pair is at entrance 5 which is metered, therefore higher travel times are expected due to the delay at the traffic signal. The corresponding travel times for the other metering scenarios are significantly higher due to the stricter metering rate that is implemented. This indicated the need for more adequate real-time metering strategies that can control the development of queues on the metered on-ramp and minimize the delays.

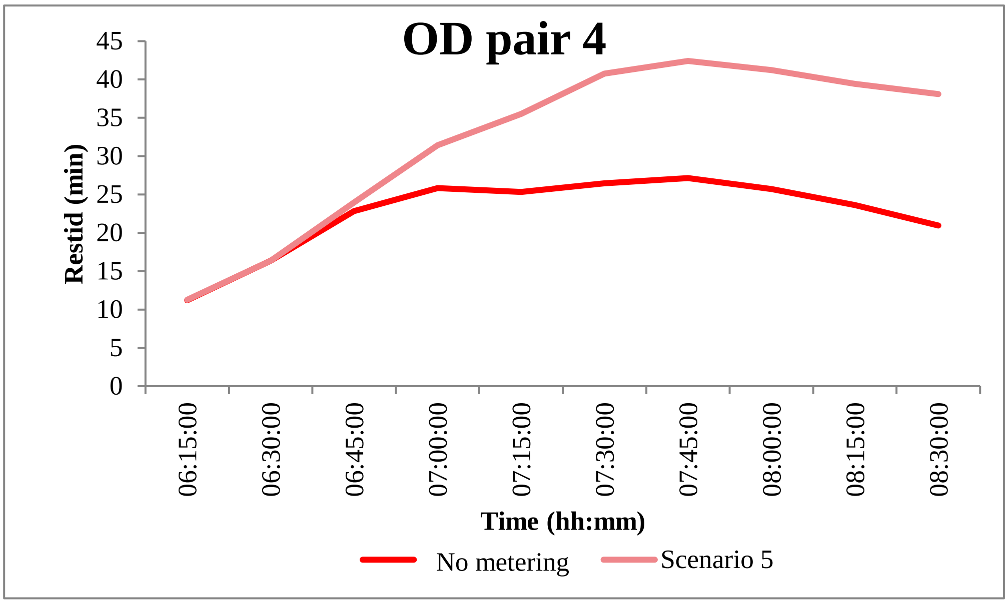


Fig. 28 Travel times.

6 Conclusions

This work investigated the implementation of ramp metering for tunnel traffic management. as Mainline metering was investigated as well for one location. The project studied the Södra Länken tunnel in Stockholm, Sweden. The methodology in order to select adequate metering strategies involved a data-driven and a simulation approach.

The proposed methodology is general and can be used with different facilities and network bottlenecks, assuming that sufficient traffic information is available. The cluster analysis revealed two congestion patterns, which differ with respect to the onset and propagation of congestion. In both cases, the congestion originates mainly inside the tunnel due to the weaving segments. On some days, congestion propagates further upstream in the tunnel. Simulation was used in order to evaluate different ramp metering strategies aiming to mitigate the congestion inside the tunnel. The selection of the strategies was based on the location of the tunnel bottlenecks, the congestion onset and the ramp characteristics. The simulation results from the tunnel traffic management analysis verify that metering is a promising strategy to mitigate congestion in tunnels. In particular, ramp metering is effective in terms of reducing the congestion and travel times inside the tunnel as well as at critical on-ramps that are very congested. Nevertheless, negative effects are observed at the metered on-ramps due to the vehicles waiting at the traffic signal. Further investigation should be performed in order to control for the on-ramp queue spillback. The need for real-time feedback control strategies is also identified in this study in order to maximize the effectiveness of the strategies and minimize the negative impacts (i.e., formed queues at the traffic signals).

7 Future directions

The results of this work point to several future research and applications. In particular, only a few metering strategies have been investigated in this work. Further strategies can be examined, such as *two-cars-per-green*. Furthermore, the proportional-integral feedback regulator (Wang and Papageorgiou, 2016) can be implemented in the simulation model in order to manage distant bottlenecks.

The application of ramp metering may lead to the formation of an on-ramp queue that may interference with the local streets. Analysing the effects of ramp metering on the surrounding network is an interesting question to be further investigated in order to evaluate the impacts of an intervention network-wide. In particular, thorough investigation of the developing queues on the metered on-ramps should be conducted so as to have more comprehensive results on the overall impacts of ramp metering in the adjustment street network. In order to decrease the on-ramp queue, ramp metering should be temporarily released if the queue length exceeds a certain threshold or apply more efficient queue-control procedures.

Local ramp metering may not be the most adequate control strategy in complex networks with multiple bottlenecks, such is the Södra Länken tunnel. Coordinated on-ramp metering can be evaluated in order to balance flows and ramp queues across the network (Faulkner et al., 2014) and enhance the network-wide performance.

A useful continuation of this work is to examine the optimal design of a comprehensive response strategy (which can be a combination of metering, closures, Variable Speed Limits, information, etc.), given the type of the emerging congestion. The optimal design includes not only the optimal metering rates and closure durations but also the location of the ramps and timing of the metering as well as the entrances to be closed. As an example, a combination of ramp metering and mainstream control methods, such as Variable Speed Limits (VSL) may be promising. The aim of VSL is to control the speed of the approaching vehicles at the tunnel bottlenecks in order to smooth out interactions between vehicles and increase capacity.

Finally, an interesting topic for future research is to analyse non-recurrent tunnel congestion, e.g. due to incidents, using the proposed framework. Data-driven analysis could be first applied to characterize non-recurrent congestion patterns and their spatiotemporal behaviour and identify different types of incidents. In relation to the tunnel management, the criteria for intervention will be more rigorous in the case of an incident. Depending on the type of incident the capacities may differ, hence, different strategies may be more beneficial in order to mitigate the non-recurrent congestion.

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9 APPENDICES

9.1 Appendix A

Ramp metering algorithms typically deliver ramp flow value $r(k)$ (in vehicles per hour) to be applied during the next period k. The next step of a ramp metering installation is the actual implementation of this value, that is, the operation of the traffic lights. There are different possible metering policies in order to translate the decision of the control strategy into specific traffic light settings. An overview of some of these policies are presented in Papageorgiou and Papamichail (2008).

Traffic lights are operated on the basis of a traffic cycle c (in seconds) consisting of the following subsequent phases:

1. Green phase $G(s)$,
2. Amber phase $A(s)$,
3. Red phase R(s), and
4. Red-amber phase $A(s)$ (this phase is applied in some countries while the switch is made from the red to the green phase) such that

$$c = G + A + R + A^{\prime} \quad (1)$$

The amber and red-amber phases A and $A^{\prime}$, respectively, have a constant duration (independent of the ramp flow value to be implemented); in some installations, one or both of these phases are not introduced (i.e., $A = 0$ or $A^{\prime} = 0$).

For given G, c, the implemented ramp flow may be estimated from

$$r = S \cdot G/c \quad (2)$$

where S (in vehicles per hour) is the ramp's saturation flow (ramp flow capacity), typically equal to $\lambda_r - 1{,}800\ veh/h$, where λ_r denotes the number of metered merging ramp lanes.

Different metering policies employ different approaches in calculating the $G(s)$, c that are necessary for the implementation of a specific flow $r(k)$ delivered by the ramp metering algorithm.

Every ramp metering installation considers a minimum admissible ramp flow value r_{min}, such that $r(k) \geq r_{min}$. If $r_{min} = 0$ are chosen, ramp closure might occur, which is usually not desired. Typical r_{min} values are 200…400 veh/h. The one-car-per-green policy is briefly described here. Detailed information for the main traffic signal operation policies are addressed at Papageorgiou and Papamichail (2008).

9.1.1 One-car-per-green

In the one-car-per-green metering policy, the green phase G is fixed, for example, to a value of $2s$, to allow exactly one car to pass at each cycle. Typically, the metering policy is announced to the drivers via a fixed sign upstream of the traffic lights, which displays the message "One car per green" or a similar message.

Under this metering policy, only the cycle c needs to be calculated, and the red phase R results directly from Equation 1. It should be noted that exactly one car is exiting each ramp lane at each cycle c. For a given r_{min} value, the maximum admissible cycle is obtained:

$$c_{max} = \frac{3{,}600 \cdot \lambda_r}{r_{min}} \quad (3)$$

which could be rounded off to obtain an integer value (in seconds) if this value is required by the employed controller device.

However, the red phase should not be less than a preselected value to avoid driver confusion. Assuming that $G + A + R + A' \geq R_{min}$ should always hold, a corresponding minimum admissible cycle is obtained from Equation 1 (with $G = 2\ s$ and $A = A' = 0$),

$$c_{min} = 2 + R_{min} \tag{4}$$

A specific ramp flow value r, delivered by a ramp metering algorithm, is translated in real time into a cycle c as follows,

$$c = \frac{3{,}600 \cdot \lambda_r}{r} \tag{5}$$

Before the final implementation, the calculated cycle c

- Could be rounded up to the next integer value (if needed), and
- Must be truncated if it exceeds the range $[c_{min}, c_{max}]$.

The main advantage of the one-car-per-green metering policy is that it releases one (or λ_r) car at a time rather than platoons of vehicles that may perturb the mainstream traffic while merging into it. The main disadvantage of the one-car-per-green metering policy is that it strongly limits the available range of ramp flows because of the R_{min} constraint. More specifically, the maximum implementable ramp flow r_{max} under this policy may be seen from Equations 4 and 5 to be

$$r_{max} = \frac{3{,}600 \cdot \lambda_r}{(2 + R_{min})} \tag{6}$$

Possible ways to partially relax this disadvantage are

- To have more than one metered ramp lane, in which case λ_r and subsequently r_{max} have accordingly higher values, and
- To skip all non-green phases whenever the ordered ramp flow $r(k)$ exceeds a prespecified threshold.

9.1.2 The ALINEA strategy

ALINEA is an integral feedback regulator (Papageorgiou et al. 1991) given by the equation

$$q(k) = q(k-1) + K_R[\hat{o} - o_{out}(k-1)] \tag{7}$$

where $k = 1,2, \ldots$ is the discrete time index, $q(k)$ denotes the control entering flow to be implemented during the new period k, K_R is a regulator parameter and $\hat{o}$ is a set (desired) value for the occupancy. Typically, may be set $\hat{o} = o_{cr}$ and in this case the motorway exit flow becomes close to q_{cap} (see Fig. 1). The same equation can be used if instead of the occupancy percentage, the number of vehicles N is measured.

ALINEA strategy is an integral (I-type) regulator, hence, at a stationary state when the inflow q_{in} remains constant, $\hat{o} = o_{out}(k-1)$ which results from Equation 3.14, independently of q_{in} value that is not used in the strategy.

The flow value $q(k)$ resulting from Equation 7 is constrained within a range $[q_{min}, q_{max}]$ and is truncated if it exceeds this range. In the next time step the truncated value is used as $q(k-1)$ in Equation 7 in order to avoid the wind-up effect in the I-regulator. ALINEA reacts smoothly even to slight differences $\hat{o} - o_{out}(k-1)$, thus stabilizing the traffic flow close to the set value (Papageorgiou et al. 1991) .

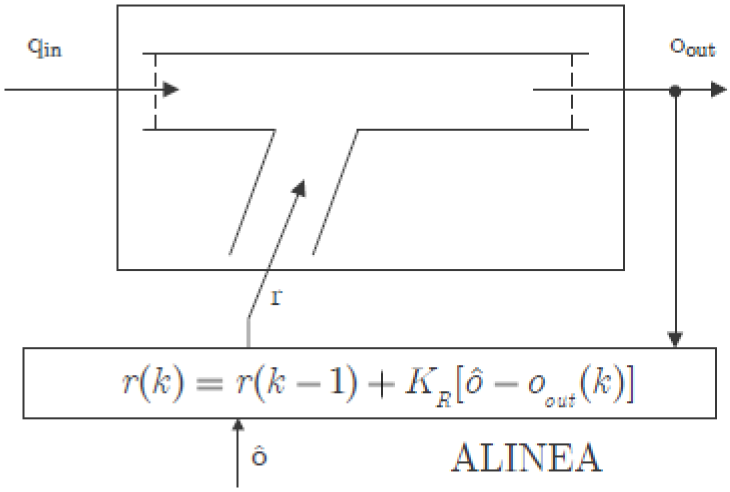


Fig. 1 The ALINEA local ramp metering strategy.

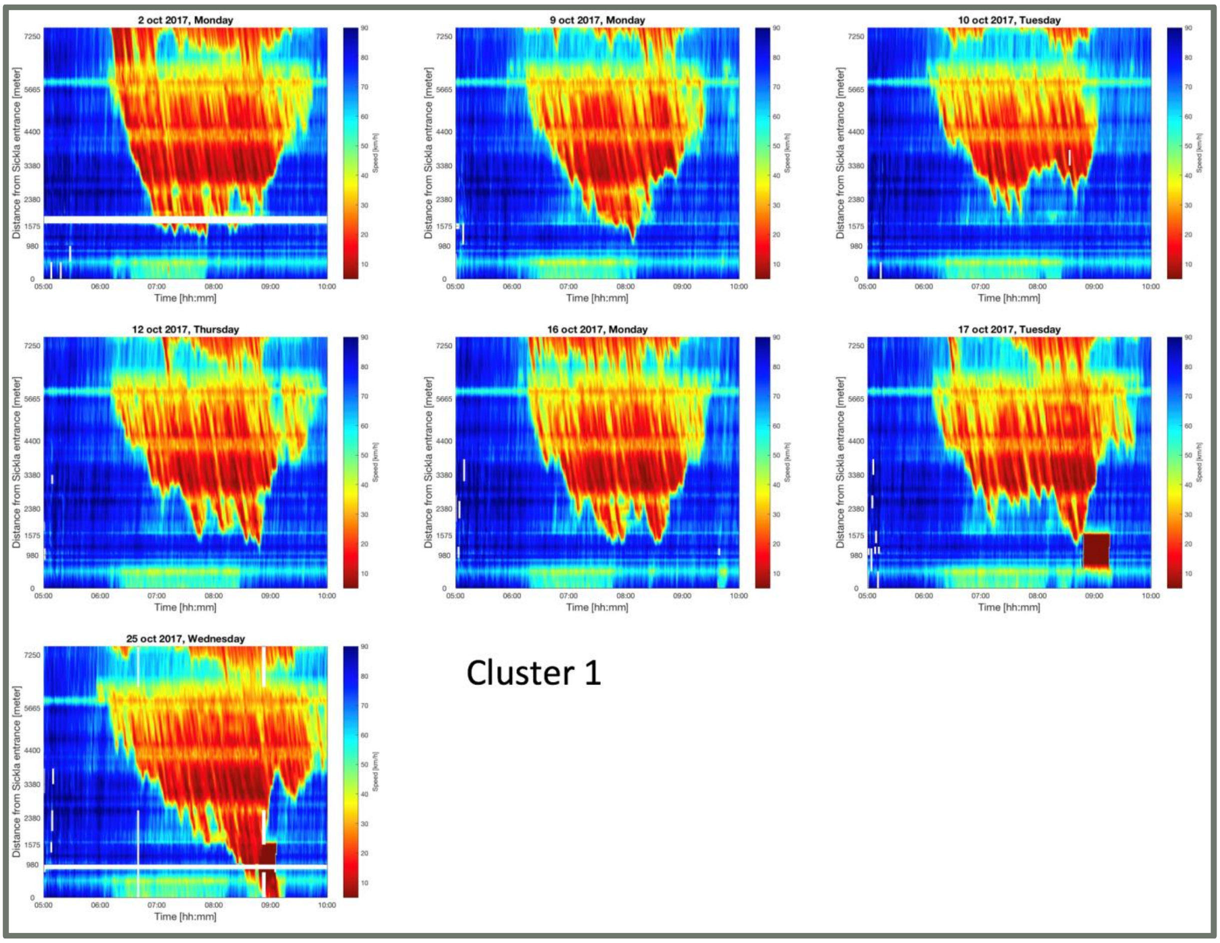
In future research, an extension of the ALINEA I-type regulator can be used. Particularly, the PI-type is used which is given by the following equation

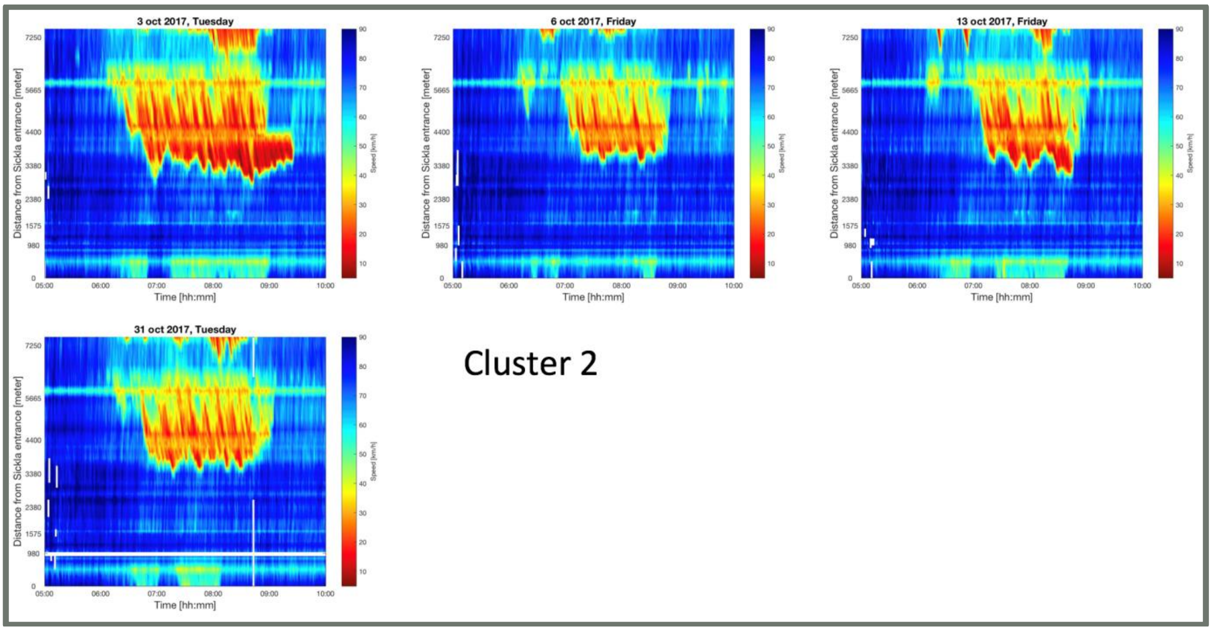
$$q(k) = q(k-1) - K_P[N(k-1) - N(k)] + K_I[\widehat{N} - N(k-1)] \quad (8)$$

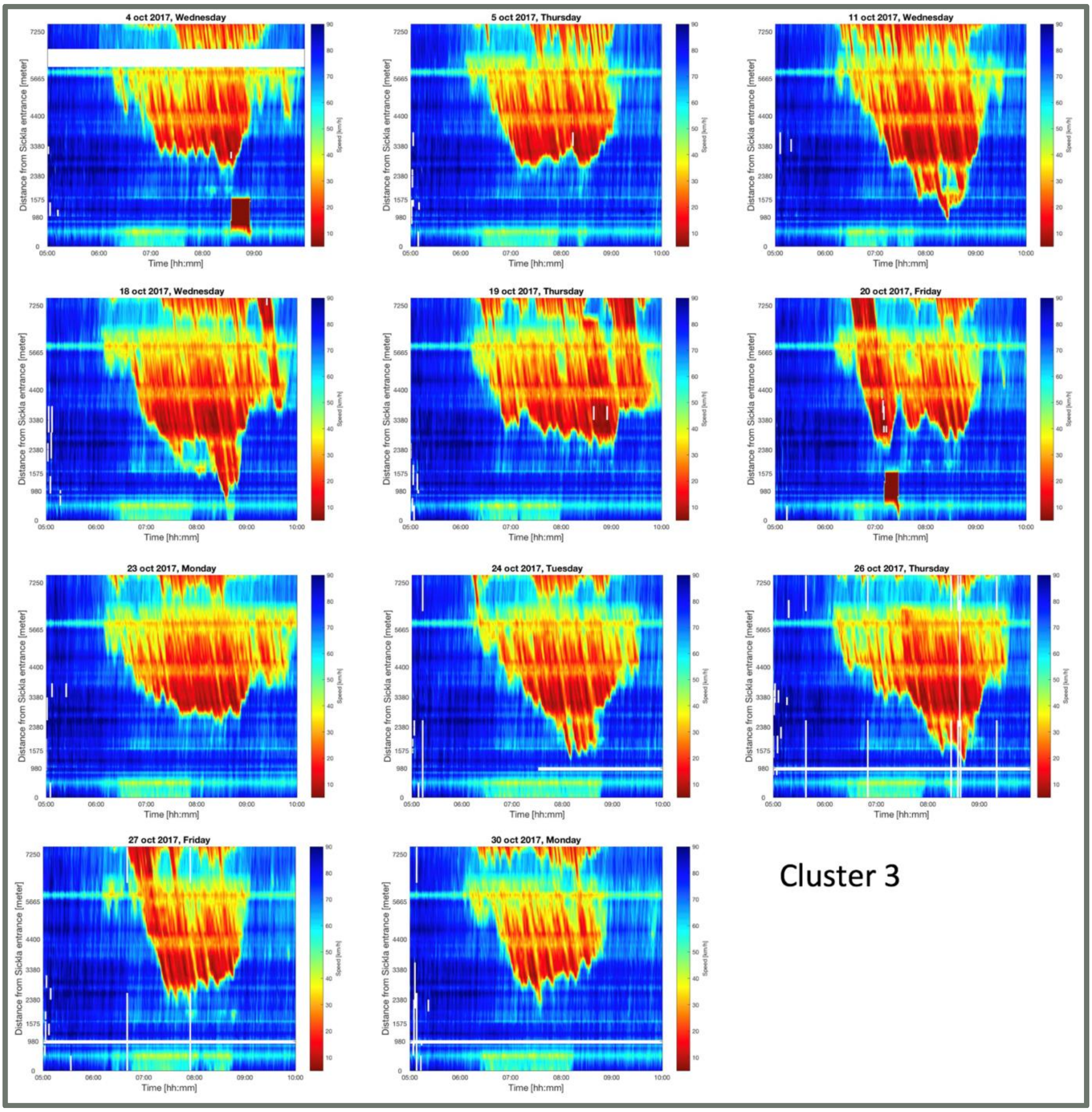
The advantage of the PI-type regulator is the better performance due to more comprehensive measurement information.

9.2 Appendix B

The speed contour plots for all days in October 2017 are presented below for each of the three identified clusters.






4 oct 2017, Wednesday
5 oct 2017, Thursday
11 oct 2017, Wednesday
18 oct 2017, Wednesday
19 oct 2017, Thursday
20 oct 2017, Friday
23 oct 2017, Monday
24 oct 2017, Tuesday
26 oct 2017, Thursday
27 oct 2017, Friday
30 oct 2017, Monday
Distance from Sickla entrance [meter]
Time [hh:mm]
Speed [km/h]
Cluster 3