A Data-based Ex-ante Assessment Method for Ramp Metering

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by

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1. Introduction

With the rapid increase of vehicle ownership, the present traffic facilities are gradually unable to meet the existing traffic demand, especially during peak hours in cities. Due to the explosive growth of vehicles, the narrowing roads or accidents would turn into serious traffic congestion. The traffic congestion would not only bring plenty of time loss but also generates exhaust gasses and noise, harming the environment.

Apart from constructing new facilities to increase the road capacity, traffic management is a more economical and achievable solution to reduce congestion. By conducting more rational and accurate management of the traffic flow, the traffic flow can be reasonably controlled, and the efficiency of the network can be improved. For different location and traffic flow features, there are different traffic management methods. For instance: intersection signal control, variable speed limit, ramp metering, routing guidance, etc. To decrease vehicle congestion that occurs at ramp merging sections on highways, this research is focusing on the ramp metering approach. Ramp metering controls the merging flow at on-ramps to orderly merge into the mainstream. This reduces the impact of merging vehicles and increases traffic efficiency.

The existing research on ramp metering control has produced impressive outcomes with various algorithms. However, there is a research gap in a concise, fast and reliable method of assessing the feasibility and efficiency of a ramp metering controller before applying it in practice. The typical scenario simulation used in the theoretical validity test is usually not sufficient for a real ramp metering implementation. In practice, conditions are more complex and different than the limited typical scenarios, a more generic and universal approach is needed to assess the effectiveness of a ramp metering controller. In comparison with typical scenarios, real empirical data is more representative of actual traffic conditions. The objective of the ex-ante test model in this research is to offer a credible ramp metering efficiency prediction, by applying empirical data and specifications of the target area. The ramp metering algorithm used in this research is based on the classic demand-capacity algorithm. With the help of the assessment approach, the ramp metering controller can be set up more precisely to increase efficiency. Due to a limited condition of time and data source, the model effects could not be tested with empirical data. The validity estimation is now carried out with different demand pattern settings and METANET model results, regarded as the alternative to the empirical data.

In the following paragraphs, the literature review is introduced in Section 2. Section 3 is about the methodology of the ex-ante ramp metering assessment model in detail. In Section 4, the data-driven validity test and result analysis are elaborated on. Conclusion and future research outlooks are discussed in Section 5.

2. Literature Review

Ramp metering is a classic traffic management measure, and it is proven that it has positive impacts on traffic operations in the Netherlands (Middelham & Taale, 2006). The effectivity of ramp metering is not only in improving the traffic efficiency, but ramp metering also has significant effects on traffic safety and the environment (Lee et al., 2006; Mizuta, 2014). Due to the space restriction of the queue on the ramp, the congestion solvability of ramp metering could be limited (Hegyi et al., 2005; Papageorgiou & Kotsialos, 2002). The main objective of ramp metering is to improve traffic flow on the main road by regulating the inflow of traffic and in this way to postpone the 10% to 20% capacity drop caused by congestion (Srivastava & Geroliminis, 2013).

Ex-ante assessment is an important method to predict the impact of ramp metering. Some ex-ante methods will be discussed in the following lines.

An ex-ante ramp metering assessment research was done by Grošanić, which simplified the evaluation process to a queue theory model. (Grošanić et al., 2010). She applied the classic M/M/1 queuing theory to ramp metering. It regarded the inflow and outflow of the merging section as the coming and leaving customs, the bottleneck as the only server in the queuing theory. It assumed that the arriving and leaving time of traffic flow is a Markov chain. Then the ramp metering process can be abstracted as an M/M/1 queueing theory problem. The effectivity of the management was regarded as the probability that the ramp metering is on.

Hegyi's SPECIALIST control algorithm (Hegyi et al., 2014) and Van de Weg's variable speed limit control (van de Weg et al., 2014) ex-ante analyses were done based on the fundamental diagram of freeway traffic flow characteristics. Different from the queueing theory model, these two studies were focused on the "solvability" of congestion. These two traffic management methods have an explicit criterion of whether they are effective, i.e. whether the congestion can be unblocked by applying the management within a certain spatial or temporal limit. By analysing traffic flow in different stages with the spatial-temporal diagram after applying the management, the "solvability" limits could be modelled. Same as this research, the studies applied empirical data to the "solvability" model for ex-ante assessment. The input of the model is the raw traffic flow data without control. Through the management model, analysing the status changes of traffic flow in different periods, the output metric shows whether and how the congestion can be solved and improved. With collation and analysis of results, the effectiveness of the traffic management method could be concluded.

The two ex-ante assessment types are informative, but both differ from this study. The first method abstracted the bottleneck problem to a queuing theory problem, which cleverly uses the independent and random arrival of traffic flows. The queue length restriction on the ramp also inspired this research to set it as an objective. However, the method ignored the capacity drop process and the interactions between vehicles during queueing, which is too simple for an engineering referable evaluation. The second method made sufficient consideration of traffic flow variables changes after the traffic management application and the data evaluation of different traffic flow stages is valuable for this research, but there is still something different. The ramp metering in this research is isolated and classified as local traffic management, while both SPECIALIST and variable speed limit control are coordinated traffic management measures between multiple road sections. Additionally, the ramp metering cannot be evaluated with the criterion "solvability", because it usually cannot completely solve congestion due to multiple restrictions but prevents breakdowns, so a qualitative conclusion cannot reflect the effects of ramp metering. A quantitative metric is necessary for this evaluation model to represent the improvement in traffic efficiency.

3. Methodology

In this chapter, the mechanism of the ramp metering control is introduced. Initially, the criteria of ex-ante assessment will be clarified in Section 3.1. Different from the qualitative ex-ante assessment methods, the ramp metering should have a metric to conduct quantitative analysis. The metric used in this research is the TTS (Total Time Spent), describing the summation of time spent on all the vehicles passing through the research area. In Section 3.2, the typical research area layout and detector settlement are introduced. As for the control details, in Section 3.3, the activation and deactivation conditions are described based on the magnitude of predicting traffic flow. Section 3.4 pays attention to the important phenomenon of "capacity drop", the change of capacity at the bottleneck should be well described in the model to maximize the throughput. Section 3.5 is about the ramp metering rate determination, the classic demand-capacity model will be used. Besides that, it defines the method of controlling the queue length on the ramp. Finally, in Section 3.6, the control structure is summarised with a flow chart.

Additional control measures for ramp rate by detecting the length of motor vehicle queues on the ramp were also proposed in this topic, but ultimately not adopted due to unsatisfactory results. Considering that this part is part of the model building process, it will be presented in the Appendix.

3.1. Evaluation criteria

The evaluation criteria of ramp metering effectivity are based on total time spent (TTS) as the indicator. The total time spent is the total time that all the vehicles spent in the system, which reflects the efficiency of the infrastructure. By comparing the TTS value of the research area before and after the ramp metering was implemented, the improvement of TTS could be regarded as the effectivity of the control method.

The calculation of TTS is based on the cost function, shown in Equation 1. In the equation, T is the size of one timestep (unit: second), decided by the data collection frequency; k represents the timestep, the range of k is from 1 to K; $N(k)$ is the number of vehicles in the system at timestep k. The variables T, K and $N(0)$ are constant when the data collection method and research time span are determined. The following $q^{d}(k)$ and $q^{out}(k)$ (unit: vehicle per hour) are the demand and the outflow of the whole system at timestep k.

$$J^{TTS} = T \cdot K \cdot N(0) + T^2 \sum_{k=1}^{K} (K-k)(q^d(k) - q^{out}(k)) \quad \text{Eq. 1}$$

ΔJ^{TTS} presents the relative improvement on total time spent factor brought by the ramp metering control, which is regarded as the metric for the control effectivity. ΔJ^{TTS} equals to TTS uncontrolled scenario minus the TTS of controlled scenario, divide by TTS uncontrolled. Since in this research, the road is empty at the first timestep, i.e. $N(0) = 0$, thus the constants are eliminated. The objective of ramp metering control is to minimise the TTS, in other words, maximising the outflow of the bottleneck (Equation 2). ΔJ^{TTS} indicates the improvement on total time spent with the implementation of the ramp metering controller.

$$\max \left(\sum_{1}^{K} (K-k)\, q_{ctr}^{out}(k)\right) \quad \text{Eq. 2}$$

$$\Delta J^{TTS} = \frac{(J^{TTS})^{unctr} - (J^{TTS})^{ctr}}{(J^{TTS})^{unctr}} \quad \text{Eq. 3}$$

3.2. Layout & detectors

The layout of the research area is shown in Figure 2, which consist of a two-lane main road with a single-lane on-ramp merging section. The main road length in the target area is L_m, and the onramp length is L_r. Ramp acceleration lane merges into the rightmost lane of the main road, the length of the acceleration lane in the Netherlands is usually 300 to 500 metres (Calvert & Snelder, 2013). Where the acceleration lane ends, the number of main road lanes turns back to 2, forming a "bottleneck".

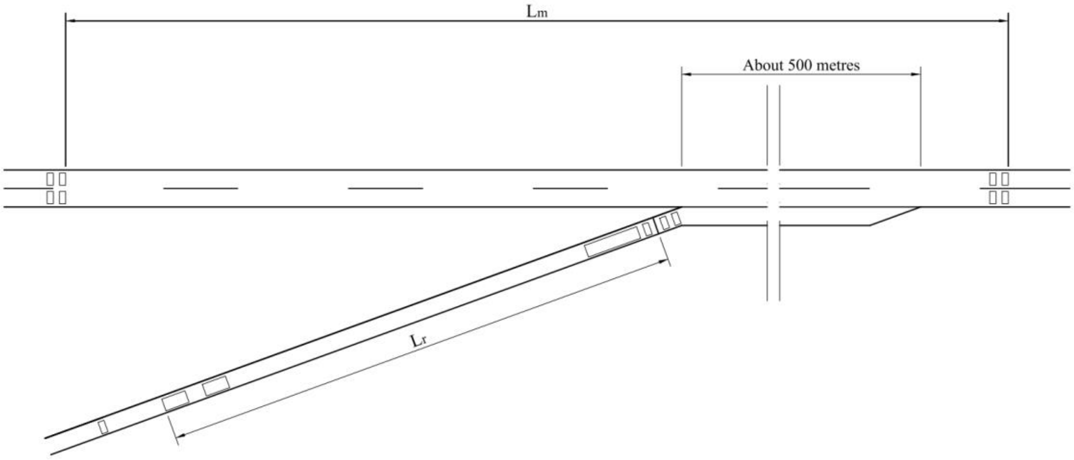


Figure 1, the layout of research site

In the research area, there are loop detectors installed on the main road and the onramp. On the upstream side of the ramp, the detectors are installed for detecting the queue length on the ramp, adjusting the ramp metering rate and minimising the impacts to adjacent road.

3.3. Activation and deactivation

The objective of ramp metering is to avoid or postpone the congestion forming in a bottleneck, which makes the on-ramp flow controlled. The timing of activation and deactivation has great influence on the effectivity of ramp metering. When activating the ramp metering too late, the flow in the bottleneck would have formed into congestion and the effects of ramp metering are limited. On the other hand, an early activation or late deactivation would block the flow and cause unnecessary delays. In this chapter, the method of activation and deactivation will be discussed.

The methods of activation and deactivation are similar, the main idea is using single exponential smoothing to follow the trend of traffic flow data, which is a practical method used on the Dutch freeway network (Taale, 2019). By predicting traffic flow of next timestep, making the ramp metering response to the future traffic state in advance. The activation condition is that the predicting traffic flow is higher than the pre-set threshold. Similarly, when the predicting traffic flow is lower than the threshold, the ramp metering would be deactivated.

The traffic flow data used in activation and deactivation determination is the upstream mainstream flow q_{mink} at timestep k of the bottleneck. Traffic flow prediction is based on the single exponential smoothing, proportionally weighting the real data and the predicted data of last timestep, the equation is shown as Equation 4. The smoothed value $\bar{q}_{mink}$ is regard as the predicting value of q_{mink+1}, i.e. the mainstream flow of the next timestep. The values of smoothing parameters α is setting different when the q_{mink} is higher or lower than its predicting value. Normally, the α_{dec} and α_{inc} are set to 0.15 and 0.25 (Taale, 2019). By setting different value of α, the prediction is more sensitive when the traffic flow is increasing, in order to make a quick response to traffic flow surge.

$$\bar{q}_{mink} = \alpha q_{mink} + (1-\alpha)\bar{q}_{mink-1} \ where\ \bar{q}_{min1} = q_{min1} \qquad \text{Eq. 4}$$

$$\alpha = \begin{cases} \alpha_{dec}, & q_{mink} < \bar{q}_{mink} \\ \alpha_{inc}, & q_{mink} \geq \bar{q}_{mink} \end{cases} \qquad \text{Eq. 5}$$

With the smoothing traffic flow calculated, the activation and deactivation are depending on the comparison between the pre-set thresholds and the predicting traffic flow. The threshold calculation equations and determination equations are shown below. Q_0 represents the free flow capacity of the bottleneck.

$$Q_{on} = Q_0 * 80\% \quad \text{Eq. 6}$$

$$Q_{off} = Q_0 * 60\% \quad \text{Eq. 7}$$

$$S_k = \begin{cases} 0, & when \begin{cases} S_{k-1} = 0, & \bar{q}_{mink} \leq Q_{on} \\ S_{k-1} = 1, & \bar{q}_{mink} \leq Q_{off} \end{cases} \\ 1, & when \begin{cases} S_{k-1} = 0, & \bar{q}_{mink} > Q_{on} \\ S_{k-1} = 1, & \bar{q}_{mink} > Q_{off} \end{cases} \end{cases} \quad \text{Eq. 8}$$

The variable S_k is for describing the status of the ramp metering controller. When $S_k = 0$, means the controller is off. On the contrary, when $S_k = 1$, the ramp metering controller is activated. The status of the present timestep depends on the previous status S_{k-1} and the current demand q_{ink}. The threshold of the activation is set to Q_{on}, which is 80% value of the theoretical free flow capacity. When the smoothed mainstream inflow is higher than this value, the ramp metering would start working. The deactivation would occur when the smoothed mainstream flow is lower than the deactivation threshold Q_{off}, which is 60% value of the theoretical capacity. Lower setting of deactivation than activation threshold is for minimising the impact from traffic flow fluctuation.

3.4. Ramp metering rate

In this chapter, the determination of the ramp metering rate will be discussed. The ramp metering method used in this model is the demand-capacity model. For minimising the impacts brought by the control lag, the smoothed mainstream traffic flow used in the model, which was introduced in Chapter 3.3.

$$r_k = min[max(0, Q_2 - q_{mink}), q_{rink}]$$
$$where\ r_k \in [r_{low}, r_{up}] \quad \text{Eq. 9}$$

The Q_2 is the typical value used in ramp rate determination, which should be an interval value between the free flow capacity Q_0 and the queue discharge rate Q_1. In practice, the value of Q_2 usually equals to 90% of Q_0. As it shown in Equation 9, maximum achievable ramp rate r_k is the difference between Q_2 and the mainstream flow q_{mink}. Meanwhile, the ramp rate should be controlled within a value range, ensuring the minimum rate and limiting the maximum rate. Typical values of r_{low} and r_{up} are 200 and 900 vehicle per hour. When the predicting mainstream inflow is higher than typical value Q_2, the ramp rate should be set to the lower bound value r_{low}, rather than calculate a negative rate.

3.5. Capacity drop

The ability of ramp metering to solve congestion is limited, sometimes the congestion at bottleneck is inevitable. When the flow exceeds the capacity of the bottleneck, congestion and capacity drop occurs. With capacity drop, the throughput of the bottleneck will witness a sharp decrease, turning into queue discharging rate. In this part, the changing of bottleneck capacity is modelled. Besides, in the Appendix.1, there is an on-ramp queue length control method being proposed, which is not applied to this topic, but can be used for future research of a more comprehensive ramp metering evaluation.

In the capacity drop model, there are several variables regarded constant and can be derived by the empirical data of the research area. The variables are the free flow capacity Q_0 and the queue discharging rate Q_1.

The binary variable y_k representing the status of the traffic flow at the bottleneck. When $y_k = 0$, the traffic flow is at free flow condition, the bottleneck capacity is Q_0. However when $y_k = 1$, there is congestion at the bottleneck, the capacity at bottleneck falls to Q_1.

C_k stands for the capacity of the bottleneck at timestep k. The value of the binary variable y_k is determined by whether the bottleneck is congested, and the criteria is whether the total inflow at timestep k to the bottleneck exceeds the current bottleneck capacity C_k. This congestion status is subjected to the inflow to the bottleneck q_{ink} (equals to the summation of mainstream inflow q_{mink} plus the ramp inflow r_k), current capacity C_k and accumulating queuing flow at the bottleneck. The queue flow $vehque_k$ on the bottleneck is accumulated from timestep 1 to k-1. The capacity C_k and total inflow q_{ink} can calculate the queuing flow $vehque_{k+1}$ for timestep k+1. The value of $vehque_{k+1}$ is the total bottleneck inflow q_{ink} plus accumulated queue flow from the previous timestep $vehque_k$ minus the bottleneck capacity C_k, the minimum queue flow is 0. In Equation 13, the determination of y_k is elaborated, which is based on the comparison of y_k and the previous value y_{k-1}. After determining y_k by Equation 13, substituting y_k to Equation 10 to calculate the ramp metering rate.

$$C_k = Q_0 - y_k(Q_0 - Q_1) \quad \text{Eq. 10}$$

$$q_{ink} = q_{mink} + r_k \quad \text{when } \mathrm{k} = 1, \mathrm{r}_1 = q_{rin1} \quad \text{Eq. 11}$$

$$vehque_{k+1} = \max(0, vehque_k + q_{ink} - C_k) \quad \text{Eq. 12}$$

$$y_k = \begin{cases} 0, when \begin{cases} y_{k-1} = 0, q_{ink} + vehque_k \leq Q_0 \\ y_{k-1} = 1, q_{ink} + vehque_k \leq Q_1 \end{cases} \\ 1, when \begin{cases} y_{k-1} = 0, q_{ink} + vehque_k > Q_0 \\ y_{k-1} = 1, q_{ink} + vehque_k > Q_1 \end{cases} \end{cases} \quad \text{Eq. 13}$$

3.6. Outflow determination

After the ramp rate r_k and capacity of the bottleneck have been determined, the outflow of bottleneck of timestep k can be determined.

$$O_k = \min(C_k, vehque_k + q_{ink})$$

The outflow of bottleneck is the lower value of the capacity C_k and the summation of total bottleneck inflow q_{ink} and the cumulative mainstream queue $vehque_k$ at timestep k. The maximum value of outflow O_k is the capacity C_k. If the total bottleneck inflow plus accumulated queue flow is not higher than capacity, the outflow O_k equals to $vehque_k + q_{ink}$.

3.7. Control structure

To sum up, the ramp metering mechanism in this research consists of predicting traffic flow calculation, activate or deactivate determination, bottleneck capacity determination and ramp rate calculation. The four main modules and key equations are printed in the following flow chart, the Figure 2. The loop ends based on the timestep k, from $k = 1$, pulsing 1 after each loop. When $k = K$, the loop ends, then the total time spent of all vehicles will be calculated. Based on Equation 3, the ΔJ^{TTS} will be calculated for evaluating the ramp metering effectivity.

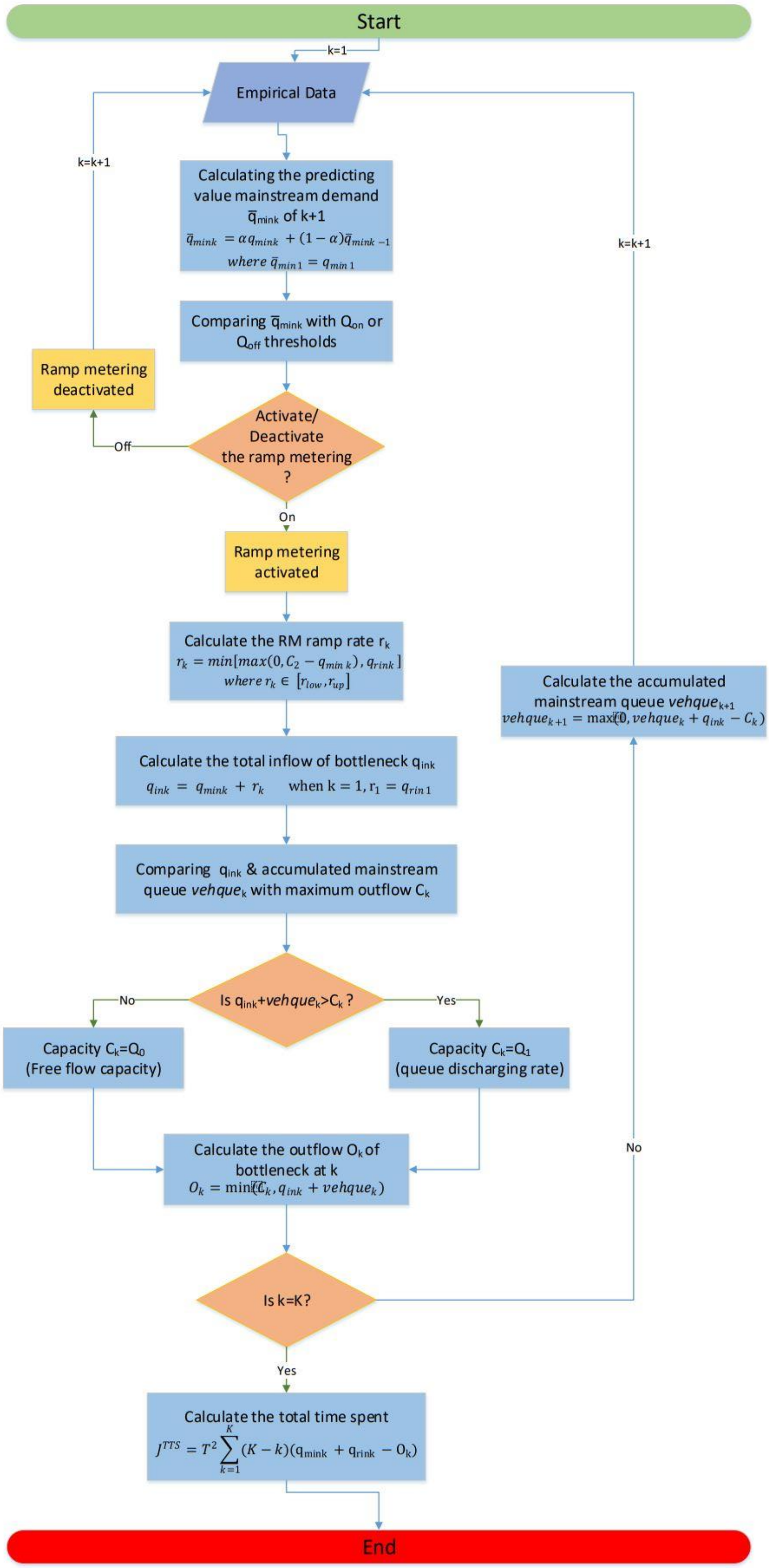


Figure 2, flow chart of methodology

4. Validity test

In this chapter, the validity test of the ramp metering data evaluation model and the test results are elaborated on. The effectivity of the data evaluation method is discussed.

Due to time limits and the constraints of data availability, the substitution of empirical data are the pre-set traffic demand data of traffic scenarios and METANET simulation results. The pre-set traffic demand patterns are regarded as the upstream inflow data collected by loop detectors. While the METANET model simulates the interactions between vehicles in the reality, whose results with or without ramp metering applied are regarded as the alternative of vehicles dynamics in the reality. The determination of free flow capacity and queue discharge rate will be based on METANET model simulation results, using empirical data method.

The main objective of the test is to prove the model proposed in this research is capable and credible for an ex-ante assessment of the ramp metering controller. The effectivity of the data evaluation method will be assessed on the effects of ramp metering controller, and the closeness between the data evaluation model results and the "real" METANET simulation model results.

This chapter consists of three sections. Section 4.1 introduces the basic information and parameter setting about the test scenarios. Section 4.2 shows the results from both data evaluation model and METANET model and make comparison. Discussion of the results is conducted in Section 4.3.

4.1. Test environment

The test environment is a typical two-lane main road link, with a one-lane on ramp. The main road has 20 segments, the length of each segment is 300m. The on-ramp is connected to the segment 12 of the main road. There is a ramp metering controller with signal controllers set at the downstream of the ramp, before the starting of the rightmost acceleration lane. The settings of road layout are essential for the reference METANET simulation model (Messmer & Papageorgiou, 1990).

The default demand pattern (scenario 1) setting is designed to simulate the scenarios of peaking hours, the timespan of the experiment is 70 minutes. The mainstream demand is fluctuating between 3300 to 4200 vehicle per hour. For ramp demand, the value linearly increases from 200 to 900 vehicle per hour in the first 15 minutes, then the demand is kept on 900 vehicle per hour till the end of the experiment.

In reality, both mainstream and ramp flow are not always linear increasing or decreasing. In order to test the robustness of the evaluation model under fluctuating demand patterns, other demand pattern settings are tested around the fluctuation in data. In scenario 2, the merging demand on ramp is fluctuating from 164 to 1108 vehicle per hour, adding fluctuation to the origin linear increasing ramp demand. While the mainstream demand is constant at the average value of scenario 1, 3871 vehicle per hour. Both mainstream and ramp demands are set to be fluctuating in scenario 3, the mainstream flow fluctuates from 3300 to 4200 vehicle per hour. To add fluctuation to the ramp demand, the original ramp demand times a cosine function with an amplitude of 180, the ramp demand fluctuates from 164 to 1108 vehicle per hour. The scenario 4 is quite opposite, either mainstream or ramp flow is linear, the mainstream is constant at average flow 3871 vehicle per hour, whereas the ramp demand is same as the scenario 1, linear increasing from 200 to 900 vehicle per hour. The table and plots for demand setting are shown in Table 1 and Figure 3.

Table 1, demand settings of test scenarios

Scenario	**1**	**2**	**3**	**4**
Mainstream	Fluctuating (3300 t/m 4200 vph)	Linear (3871 vph)	Fluctuating (3300 t/m 4200 vph)	Linear (3871 vph)
Ramp	Linear (200 t/m 900 vph)	Fluctuating (164 t/m 1108 vph)	Fluctuating (164 t/m 1108 vph)	Linear (200 t/m 900 vph)

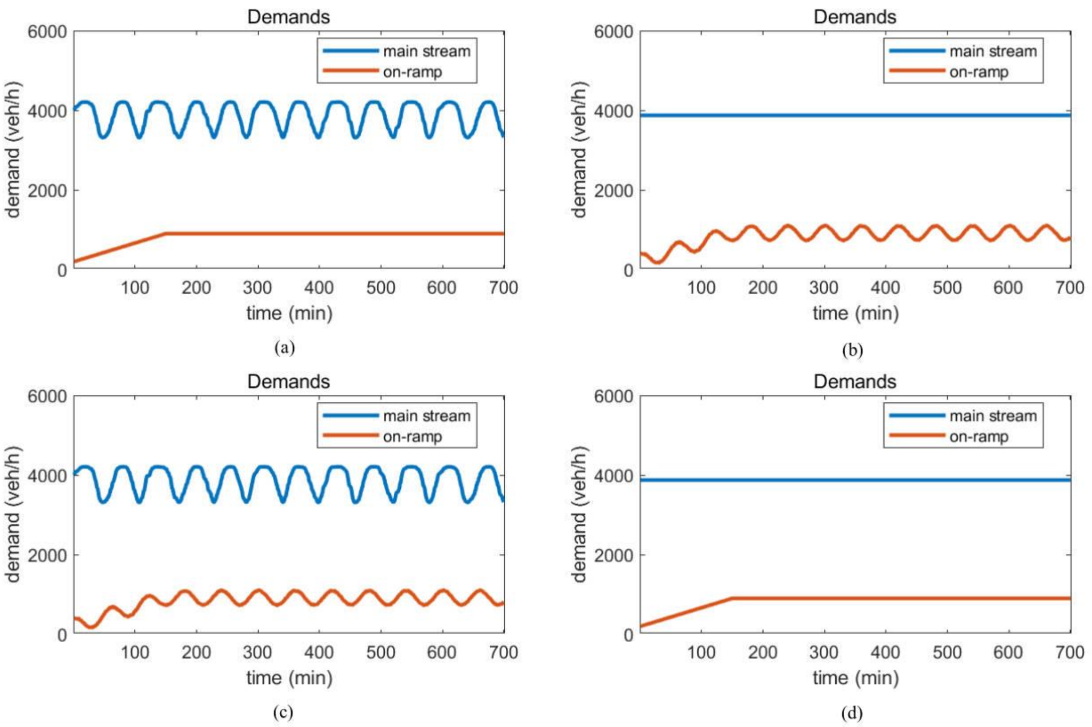


Figure 3, demand setting plots of test scenarios. (Plot (a) to (d): Scenario 1 to Scenario 4)

The empirical free flow capacity and queue discharge rate is derived from the downstream cumulative curve of the bottleneck. Without the implementation of ramp metering, the METANET model generates counterplots and outflow graphs describing the congested traffic flow, shown in Figure 4. The average slopes of cumulative curve of segment 12, i.e. the first segment from the bottleneck, can reflect the free flow capacity and queue discharging rate. As it is shown in Figure 5, the average slope of the ascending curve from 0 to 18 minutes, representing the free flow Q_0 before the congestion, the value is 4453.42 vehicle per hour. Besides, the average slope of the descending curve in Figure 5 from 18 to 69 minutes is 3555.03 vehicle per hour, regarding as the queue discharging rate Q_1 after the congestion and shockwaves occur.

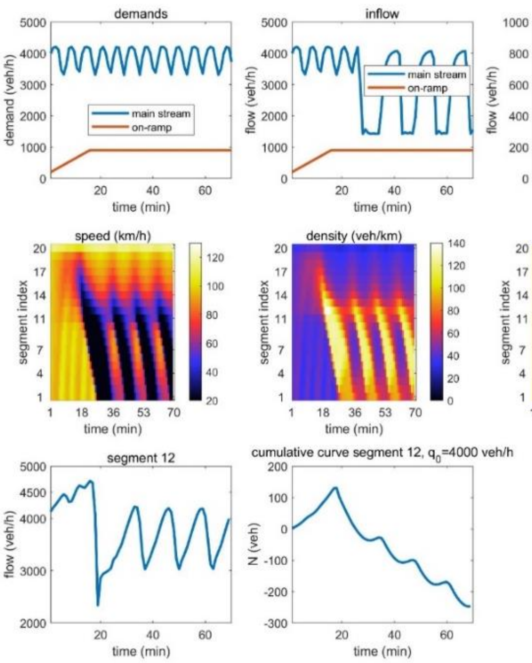


Figure 4, METANET simulation results without ramp metering (scenario 1)

The constant value settings follow the typical value mentioned in Chapter 3. The values of smoothing constants α_{dec} and α_{inc} are set to 0.15 and 0.25 (Taale, 2019). The value range of ramp rate r_{low} and r_{up} are 200 and 900 vehicle per hour.

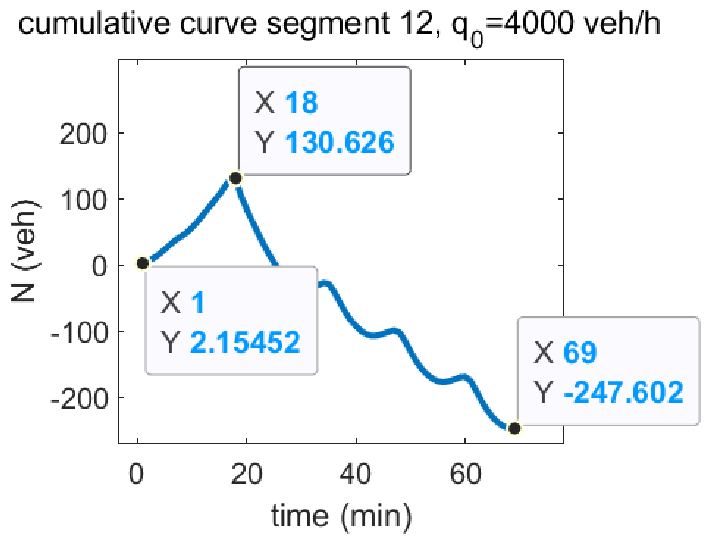
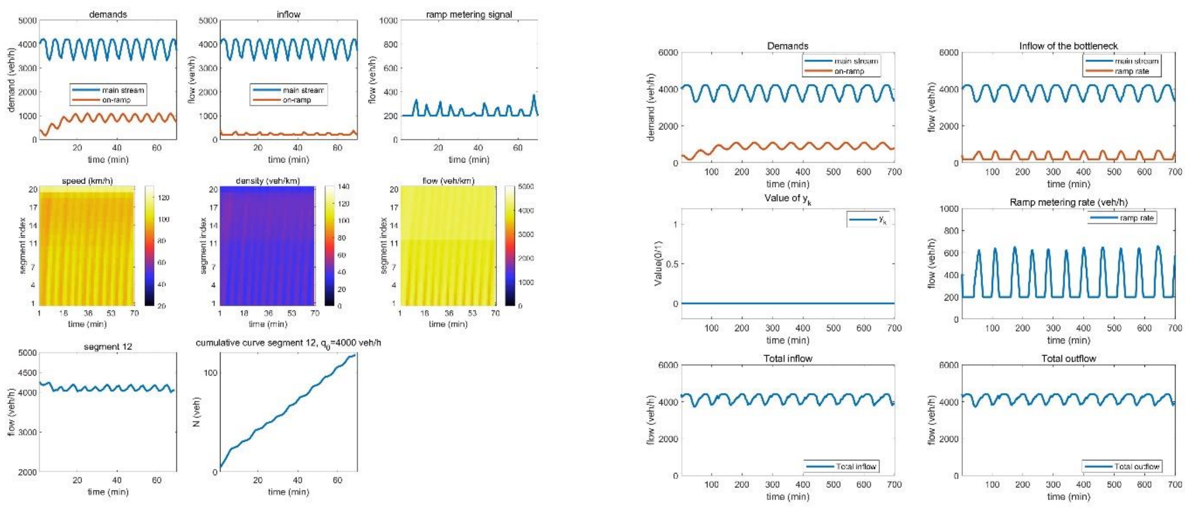


Figure 5, cumulative curve of downstream bottleneck (METANET, no ramp metering, scenario 1)

4.2. Test results

The four scenarios are tested with both the data evaluation model and the reference METANET model. Each scenario is tested 3 times, no ramp metering (METANET model), with ramp metering (METANET model) and with ramp metering (data evaluation model). The METANET model without ramp metering applied is regarded as the uncontrolled scenario of the demand pattern.

The examples of the METANET model with ramp metering and data evaluation plot results are shown in Figure 6 (taking scenario 3 as the example).



(a) (b)

Figure 6, the example plots results of (a)METANET model and (b) data evaluation model (scenario 3)

ΔJ^{TTS} of the two types of models are calculated respectively based on the total time spent (TTS) value generated from the tests. The variance rate is the difference between the results of controlled METANET model and data evaluated model, for examining the credibility of the data evaluation model. The test results of the four scenarios are listed in Table 2.

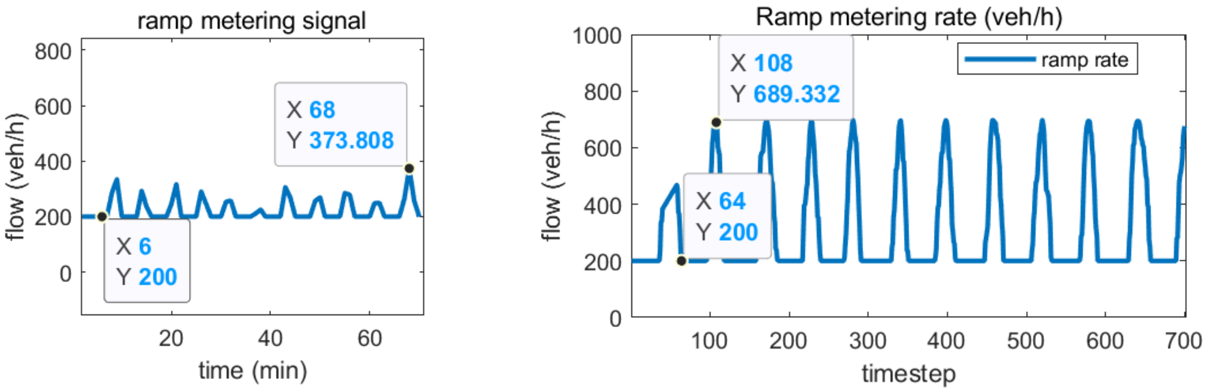
Table 2, TTS test results of 4 demand scenarios

Scenario	Origin (h)	METANET (h)	ΔJ_{TTS} (%)	Data Evaluation (h)	ΔJ_{TTS} (%)	Difference (%)
1	523.8824	366.1018	-30.12%	309.9917	-40.83%	-10.71%
2	540.5358	384.0056	-28.96%	391.8609	-27.51%	1.45%
3	545.6379	373.1002	-31.62%	318.567	-41.62%	-9.99%
4	523.4964	377.0124	-27.98%	382.1806	-26.99%	0.99%
Average	533.3881	375.055	-29.67%	350.65005	-34.24%	-4.57%

4.3. Result discussion

By analysing the results in Table 2, it shows that both METANET model and data evaluation model show that the ramp metering is an efficient method to prevent and reduce delay. In METANET model results, the average value of ΔJ^{TTS} is -29.67%, the improvement in total time spent is significant. On the other hand, the average ΔJ^{TTS} with data evaluation model is -34.24%, slightly higher than the METANET model, the average difference of the improvement on TTS is -4.57%. It suggests that the data evaluation model proposed in this article can reflect most of the "realistic" situations calculated by the METANET model.

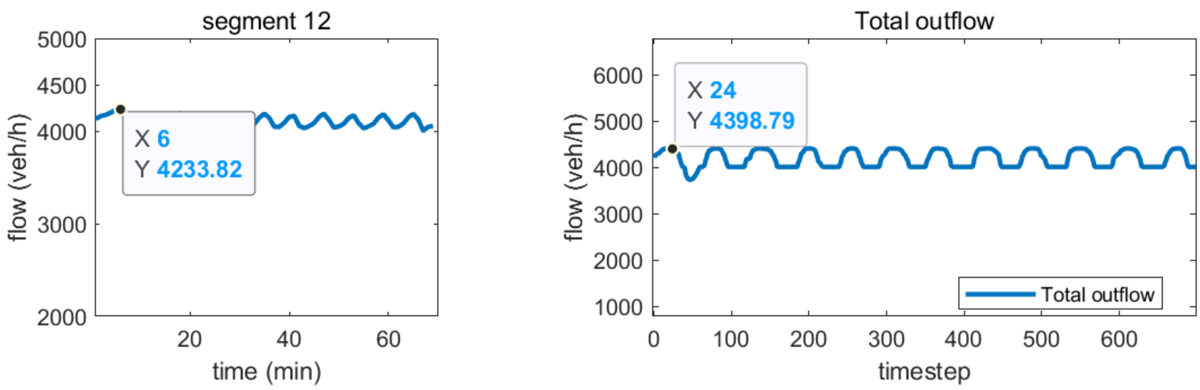
Comparing the results of the same demand scenario with different models, it can be easily found that in for scenario 1 and 3, the data evaluation model even has lower TTS results than the METANET model. Through comparison between the plots of ramp rate and outflow of the two scenarios, the reasons why there is relatively large gaps are similar. Taking scenario 1 as an example (Figure 7), from the plots of ramp metering rate it can be found that the peak value of ramp rate for data evaluation model (689.33 veh/h) is higher than the METANET model (373.81 veh/h). The possible reason is that the time gap between simulations of the two model is different, the METANET model aggregates 10 timesteps as one simulation gap, while the data evaluation model simulates every timestep, which means the fluctuation of demand has been narrowed by the aggregated timesteps, the difference between the peak and trough value of the mainstream demand is narrowed. And in demand-capacity method, ramp rate is calculated by the typical value Q_2 minus the mainstream demand value, the narrowed fluctuating demand makes the ramp metering value and bottleneck downstream outflow of METANET model are lower than the values of the data evaluation model (Figure 8).



(a) (b)

Figure 7, the ramp metering rate of (a)METANET model and (b)data evaluation model of scenario 1

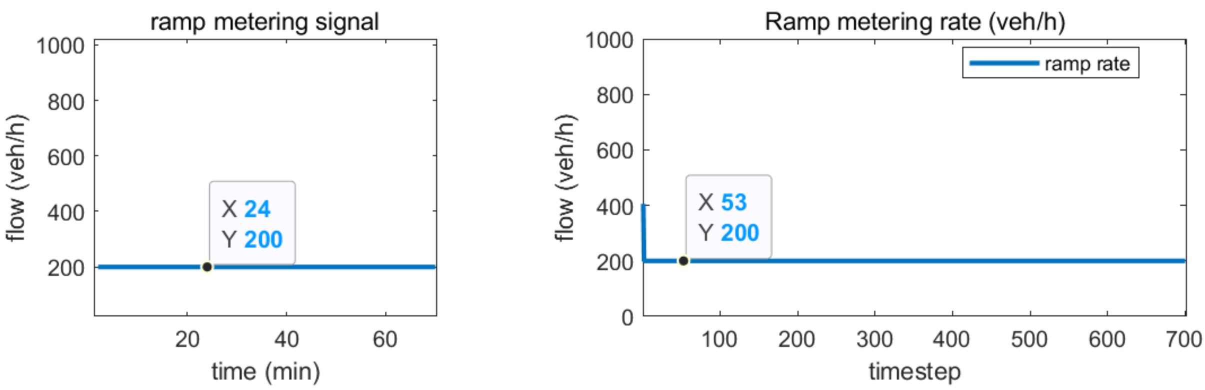
As for the reason why the difference between the two models in scenario 2 and scenario 4 is slight,



(a) (b)

Figure 8, the bottleneck downstream outflow of (a)METANET model and (b)data evaluation model of scenario 1

it is because of the stability of the mainstream demand, the ramp metering rates of the two models are limited to a same constant value, which is not influenced by the difference of the length of simulation time gap. The figures below are the ramp rate and outflow plot of the METANET model and the data evaluation model from scenario 2 as the example.



(a) (b)

Figure 9, the ramp metering rate of (a)METANET model and (b)data evaluation model of scenario 2

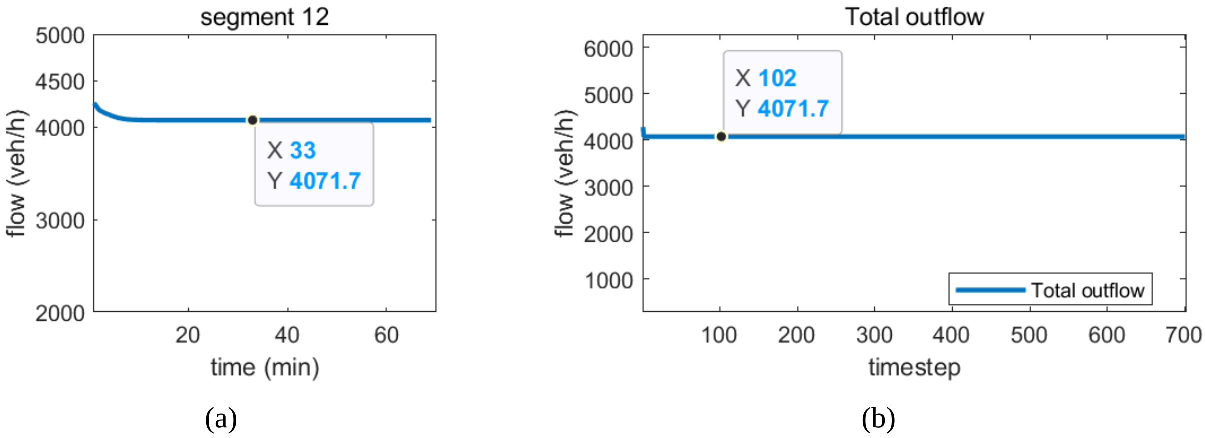


Figure 10, the bottleneck downstream outflow of (a)METANET model and (b)data evaluation model of scenario 2

Overall, the ramp metering controller in data evaluation model shows a close resemblance to the METANET model. The data evaluation model results show the ramp metering controller has a good effectivity in the test, the average improvement in total time spent is 34.24%. The difference from the METANET model is 4.57%, which shows that the data evaluation model is feasible for ex-ante assessment. The fluctuation of ramp flow demand has slight influence on the difference between the two models, having little impact on results and can be improved by using empirical data.

5. Conclusion and outlook

A data evaluation model for ex-ante ramp metering effectivity assessment is presented, which is proved to successfully demonstrate the expected effects of the traffic management measure ramp metering. The data evaluation method shows that the improvement of the total time spent (TTS) at highway bottlenecks is on average 28.48% in a typical on-ramp situation. The objective of the research was to propose an ex-ante assessment method for un-applied traffic management and therefore the credibility of the evaluation results is also an indicator. In this study, due to the time and data constraints, the simulation results of METANET model with and without ramp metering are regarded as the "real" scenarios of controlled and uncontrolled highway on-ramp bottlenecks. Marking METANET as the reference, the proposed data evaluation model has very close resemblance with the results of METANET. The average difference of the improvement percentage of indicator ΔJ^{TTS} is only 1.30%. With this similarity it can be concluded that the data evaluation is feasible for the ex-ante assessment of ramp metering, it can show the benefits of ramp metering control to a large extent. But only in comparison with a METANET simulation.

Future research can be conducted focusing on the use of real empirical data, increasing the accuracy of the ex-ante assessment. With empirical traffic flow data collected in highways, the calculation of the free flow capacity, queue discharging rate and other specification of the road can be more accurate. With long-period empirical data testing, the calibration of parameters in the model, for instance the activation and deactivation threshold indexes, can be processed in various real demand dynamics. In this study, the model robustness of data fluctuation has been tested. In the future, the research can test the robustness and sensitivity of other aspects of the model, for example the magnitude of data, the collecting frequency of data, or the irregular fluctuation of traffic demand.

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Appendix

1. Queue spillback length and response strategy

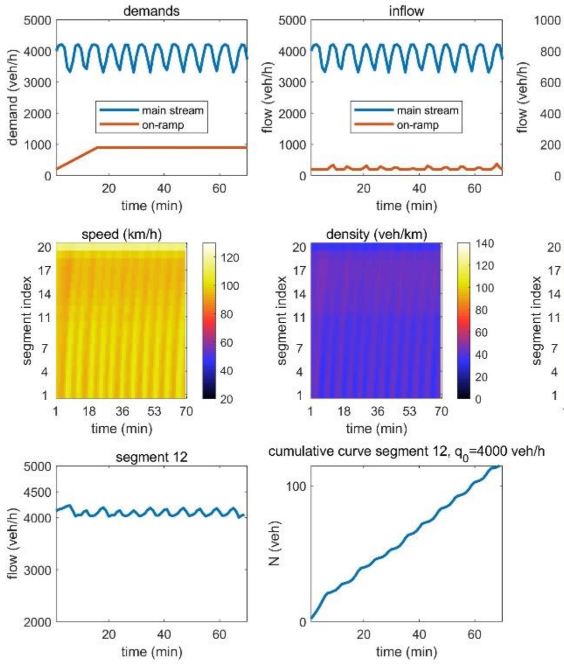
The onramp queue would accumulate when the merging demand is higher than the ramp rate. When there is queue spillback detected by the queue detectors on the rare side of the ramp, the alleviating spillback mechanism should work.

The queue forming on ramp could be considered as a cumulative process. The merging vehicles flow into the ramp at timestep t is q_{rint} vehicle per hour, the value could be directly collected by the rare-side detectors on ramp. The outflow rate of the ramp is controlled by the ramp metering mechanism, thus the outflow rate at t is r_t. With the queue length on the previous timestep, the length of one timestep T and the average length of vehicles with a headway distance l_i, the ramp queue length at timestep t could be calculated. The typical value of l_i is 7.6 m (25 ft) (Long, 2002).When the L_{rqt} has reached the ramp length L_r, the ramp queue spillback response strategy works.

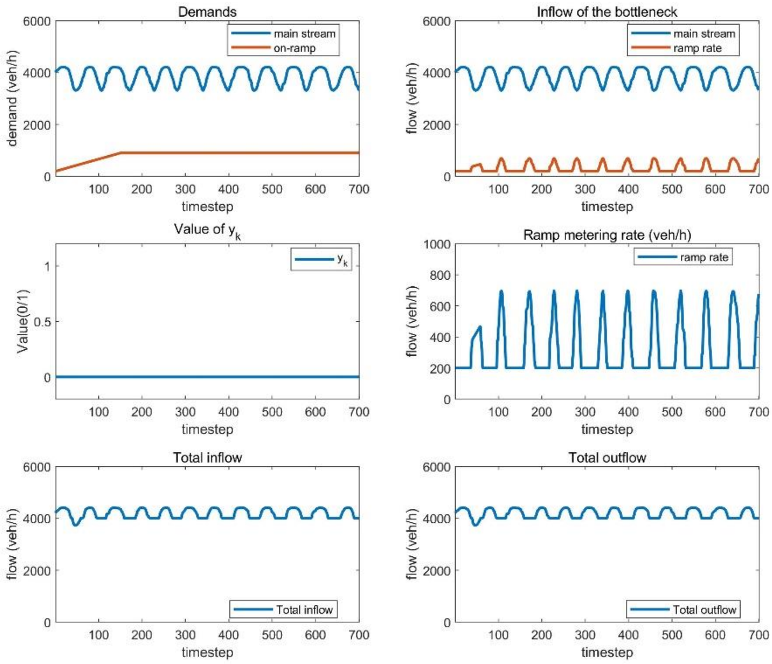
$$L_{rqt} = L_{rqt-1} + T(q_{rt} - r_t) * l_i \qquad \text{Eq. 14}$$

Inferring from the queue controlling rules in use in California, the US, the method to solve the queue override in this model is gradually increasing the ramp rate when detecting the queue spillback, until it reaches the preconfigured maximum rate. (D. Kan et al., 2017) For instance, the ramp rate calculated by demand-capacity model at time k is 400 vehicle per hour. While at the same timestep, the queue detectors recognise the queue spillback. Then in the next timestep, the onramp rate would get Δr vehicle per hour adding rate on top of the calculating rate by the model, the typical value is 100 veh/h. If the queue spillback could still be detected in the following time steps, the ramp rate would keep increasing Δr vehicle per hour in every time step, until the rate reaches r_{max} vehicle per hour, for example, 900 vehicle per hour.

2. Plots result of METANET model and data evaluation model

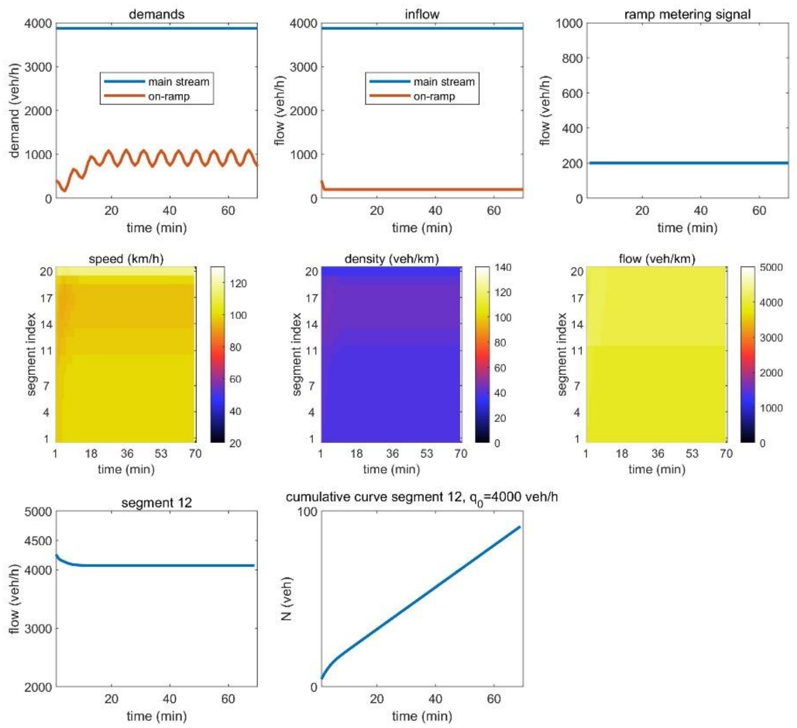


(a)

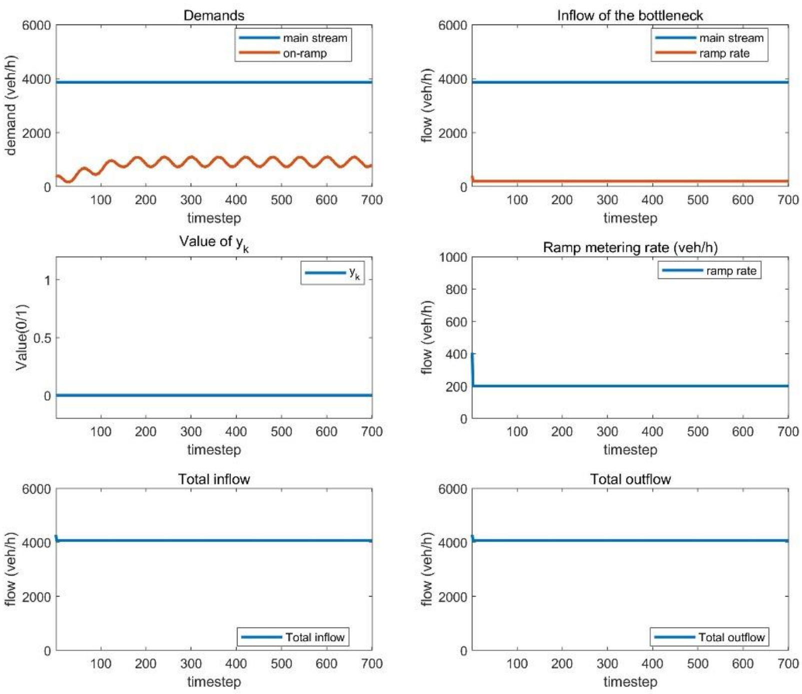


(b)

Figure 11, the plot results of (a)METANET model and (b) data evaluation model (scenario 1)

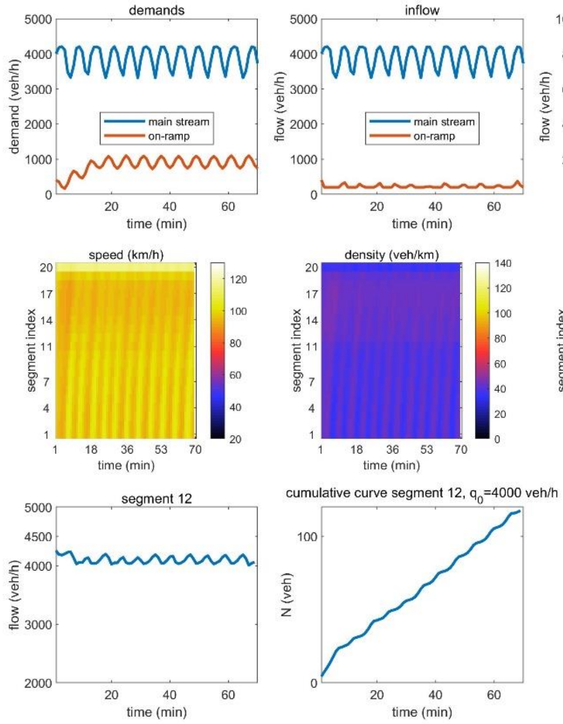


(a)

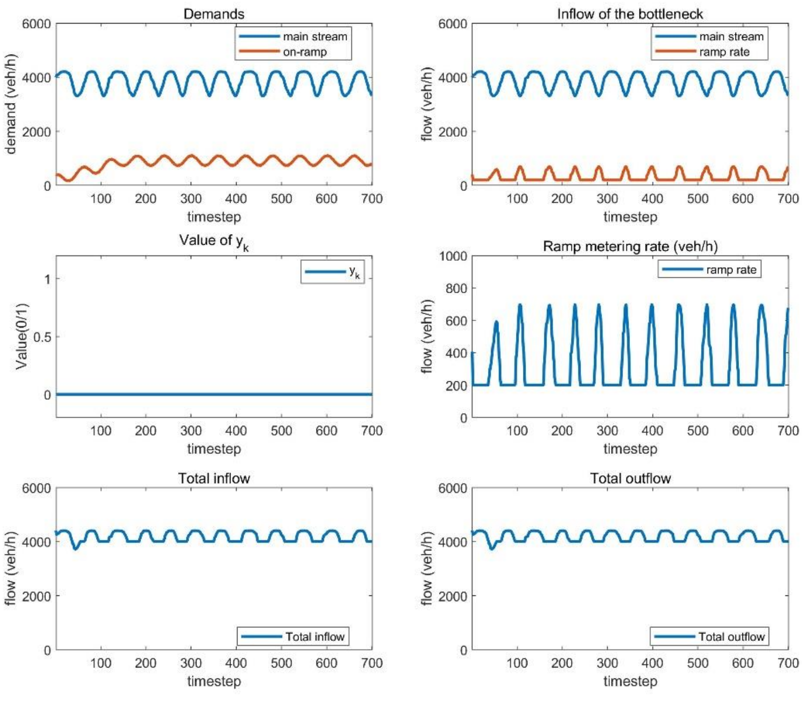


(b)

Figure 12, the plot results of (a)METANET model and (b) data evaluation model (scenario 2)

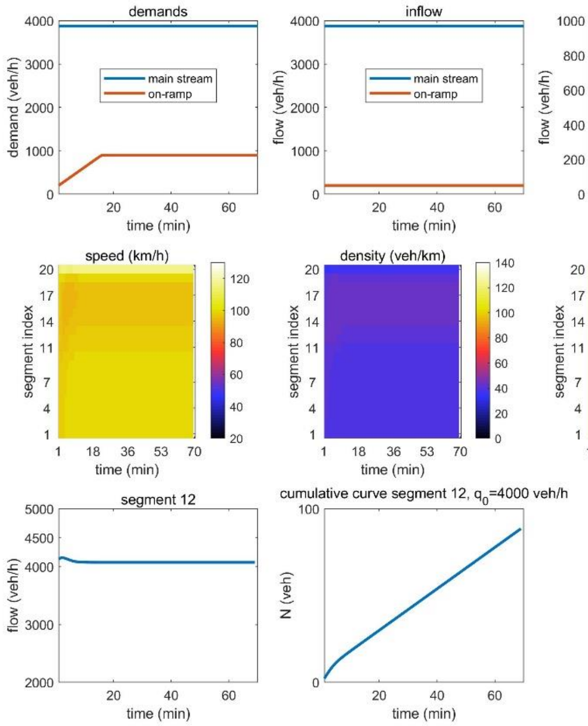


(a)

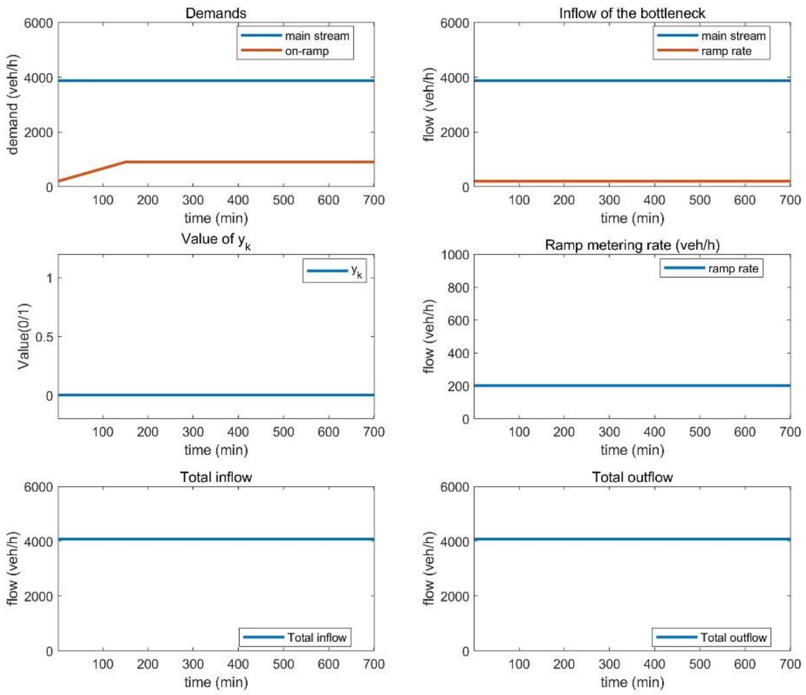


(b)

Figure 13, the plot results of (a)METANET model and (b) data evaluation model (scenario 3)



(a)



(b)

Figure 14, the plot results of (a)METANET model and (b) data evaluation model (scenario 4)