Ramp metering strategies: a methodology for testing the performance of microsimulation models

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Abstract

During recent decades, traffic demand has overtaken the overall capacity of existing highway and freeway networks, causing traffic delays and negative environmental impacts. Consequently, innovative traffic control strategies have been developed to improve network performance and they have proved to be effective in delaying or preventing congestion. Dynamic microsimulation models are natural contenders for reproducing the impact of traffic control measures on driver behavior and assessing their effect on traffic flows. These models aim to reproduce the flow on an entire network, by modeling individual driver behavior. Many studies have focused on the validation of microscopic models under standard (not controlled) situations. However, empirical evidence shows that traffic control strategies act on standard driver behavior and consequently, the ability of these models to reproduce traffic features under traffic control strategies can be questioned.

This paper proposes a comprehensive methodology for measuring the impact of ramp-metering strategies on microscopic simulation results. This methodology relies on traffic flow theory fundamentals and detailed basic traffic scenarios to precisely measure the capacity of metered and unmetered merges. This methodology is easy to implement and can be applied to any microsimulation simulation software. It has been applied to two commercial microsimulation softwares. Surprisingly, (i) the first microsimulation software concludes that ramp-metering strategies can increase or decrease the capacity of a merge, depending on the ramp-metering strategy (one vs several cars per green light); (ii) the second simulation software concludes that ramp-metering strategies have no impact on the capacity of a merge. The results highlight the potential and the limits of microscopic traffic flow models to reproduce complex traffic features involved in traffic control strategies and pave the way for alternative tools to measure the effectiveness of traffic control strategies.

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Keywords: Traffic flow theory; driver behavior; merge; capacity drop; traffic control; ramp metering; microscopic model; microsimulation software

1. Ramp metering strategies

During recent decades, traffic demand has overtaken the overall capacity of existing highway and freeway networks, causing traffic delays and negative environmental impacts. Consequently, innovative traffic control strategies have been developed to improve network performance and they have proved to be effective in delaying or preventing congestion.
Ramp metering (RM) is a traffic control strategy that was introduced in the middle of the seventies and is now widely used throughout the world. RM aims at controlling traffic flow from an on-ramp and entering a freeway. The flow is usually controlled by a traffic light located upstream of the acceleration lane. The flow rate is determined by the ramp metering strategies. Many strategies are proposed and Papageorgiou and Kotsialos (2000) have proposed an overview. It can be summarized as following:

- **Fixed versus dynamic strategies.** Fixed strategies consider a fixed flow rate from the on-ramp, regardless of the flow on the freeway while dynamic strategies regularly update the flow rate: it can either be based on historical or real-time traffic data.
- **Local strategies versus coordinated strategies.** Local strategies are implemented at a single merge while coordinated strategies coordinate RM strategies of several on-ramps along a freeway corridor.
- **One versus several vehicles per green.**

1.1. Expected impact of RM strategies

By controlling the traffic flow coming from the on-ramp, an overall improvement of traffic conditions on the freeway section is expected (Haj-Salem and Papageorgiou (1995), Cassidy and Rudjanakanoknad (2005), Cassidy (2007)). The overall impact can be split into two effects:

- **Transfer of the delay:** RM strategies decreases the delays on the freeway and increases the delays on the on-ramp.
- **Reduction of the capacity drop at the merge:** RM increases the total capacity of the merge.

Many research efforts have focused on the performance of RM strategies based on macrosimulation tools (Smaragdis et al. (2004)), other tools or microsimulation models (Elefteriadou et al. (1995)). Dynamic microsimulation software are natural contenders for reproducing the impact of traffic controls on driver behavior and assessing their effect on traffic flows. These models aim to reproduce the flow on an entire network, by modeling individual driver behavior. Many studies have focused on the validation of microscopic models under standard (not controlled) situations. However, empirical evidence shows that traffic control strategies act on standard driver behavior and consequently, the ability of these models to reproduce traffic features under traffic control strategies can be questioned.

The first effect of RM (transfer of the delay) is “mechanically” reproduced by microsimulation softwares. However, no methodology can be found in the literature studied to test the second effect (reduction of the capacity drop) in classic microsimulation models.

The present paper proposes a comprehensive methodology for measuring the impact of ramp-metering strategies on microscopic simulation results. This methodology relies on traffic flow fundamentals and proposes basic traffic scenarios to measure accurately the capacity of metered and unmetered merges.

The paper is organised as follows.

- Section 2 presents traffic flow fundamentals around merges.
- Section 3 proposes a rigorous methodology that aims to verify that these fundamentals are correctly reproduced in microsimulation softwares.
- Section 4 presents the results obtained when the methodology is applied on two popular microsimulation softwares (Aimsun and Dynasim).
- Section 5 concludes with recommendations to properly calibrate microsimulation models. It also paves the way for alternative tools that measure the effectiveness of RM strategies.
2. Traffic flow merges: fundamentals

2.1. General description and empirical evidence

A merge represents a conflicting point on a traffic network, where two incoming (upstream) links merge into a single (downstream) link. The two incoming links include a major stream and a minor stream.

From a microscopic point of view, traffic flow dynamics at a merge are driven by the vehicles’ merging behaviors. When the traffic is free-flowing on the major stream, the way minor stream vehicles will merge depends on the surrounding available space on the major stream. This merging behavior can be modeled with gap-acceptance models. On the contrary, when the traffic is congested on the major stream, major stream vehicles and minor stream vehicles now share the available downstream capacity, respecting a fixed priority ratio.

These behaviors have been observed empirically (Cassidy and Ahn, 2005, Reina et al., 2012) and merge models have been proposed and validated (Chevallier and Leclercq, 2008).

2.2. Existence of the steady-state capacity curve

(Chevallier and Leclercq, 2009) have extensively studied the connection between the microscopic merging behavior and the resulting macroscopic flow allocation scheme at the merge, first proposed by Daganzo (1995). Theoretically, the capacity of a merge does not depend on the demands from the two upstream links. Consequently, the resulting SSCC should be a straight line, as represented in the figure 2.a. On this figure:

- \( \alpha \) represents the mean priority sharing process when both major and minor stream are congested
- \( Q_M \) represents the flow on the major stream
- \( C_M \) represents the capacity on the major stream
- \( Q_m \) represents the flow on the minor stream
- \( C_m \) represents the capacity on the minor stream

However, real on-field observations have revealed the presence of capacity drops at merges (Elefteriadou, 1995). The capacity drop is a consequence of several factors: low speeds of the inserting vehicles during the merging maneuver (Duret et al., 2010), bounded acceleration rate of inserting vehicles (Leclercq, 2007), drivers aggressivity or hesitance (Laval and Leclercq, 2010), etc. The shape of the SSCC is directly related to the amplitude of the capacity drop (Leclercq et al., 2011) and figure 2.b shows the impact of the capacity drop on the shape of the SSCC.
Many formulas can be found in the literature to describe SSCC shapes. For example, see formulas proposed in the well-known Highway Capacity Manual (HCM, 2000).

2.3. Impact of RM strategies on the SSCC

RM strategies reduce congestion by utilizing the capacity of the merge more efficiently and reducing the amplitude of the capacity drop (Cassidy and Rudjanakanoknad, 2005). Consequently, the shape of the SSCC has to be impacted by the activation of the RM strategy. Figure 3 illustrates the expected impact of the reduction of the capacity drop when a RM strategy is activated. In this figure, $Q_r$ denotes the flow rate allowed by the metering traffic light.

It is important for microscopic models to be consistent with SSCC observed out on the field, since most recurrent congestion is triggered at merges. The next section presents a comprehensive methodology for measuring SSCC in microscopic simulation models. This methodology relies on traffic flow fundamentals and
detailed basic traffic scenarios to accurately measure SSCC on unmetered and metered merges. This methodology is easy to implement and can be applied to any microsimulation simulation software.

3. Methodology for measuring the SSCC in microscopic models

If the following sections, we use the subscripts $M$ and $m$ to denote the major stream and the minor stream respectively.

3.1. Network and detectors

The network is composed of a major stream with $k_M$ lane(s) and a minor stream with $k_m$ lane(s). The length of the major and minor upstream links are 1000m and 200m respectively. The acceleration lane is 240m long (prescribed length on French networks). The free-flow speed on the major stream is 110km/h (30.5m/s) and the speed on the minor stream is 50km/h (14m/s).

Three detectors are located on the network.

- Detectors $C_{u,M}$ and $C_{u,m}$ are located at the entries of major and minor streams respectively. They collect flows ($Q_{u,M}$ and $Q_{u,m}$) and speeds ($V_{u,M}$ and $V_{u,m}$) at the entry of the major and the minor upstream links respectively.

- Detector $C_d$ is located immediately downstream from the merge: it collects flows per origin ($Q_{d,M}$ from the major stream and $Q_{d,m}$ from the minor stream) and speeds ($V_{d,M}$ from the major stream and $V_{d,m}$ from the minor stream). The following table summarizes the data collected by detectors $C_{u,M}$, $C_{u,m}$ and $C_d$.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Data collected</th>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{u,M}$</td>
<td>Flow</td>
<td>$Q_{u,M}$</td>
<td>Flows measured at the entry of the major upstream link</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>$V_{u,M}$</td>
<td>Speeds measured at the entry of the major upstream link</td>
</tr>
<tr>
<td>$C_{u,m}$</td>
<td>Flow</td>
<td>$Q_{u,m}$</td>
<td>Flows measured at the entry of the minor upstream link</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>$V_{u,m}$</td>
<td>Speeds measured at the entry of the minor upstream link</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Flow (from major upstream link)</td>
<td>$Q_{d,M}$</td>
<td>Flows measured downstream from the merge coming from the major upstream link</td>
</tr>
<tr>
<td></td>
<td>Flow (from minor upstream link)</td>
<td>$Q_{d,m}$</td>
<td>Flows measured downstream from the merge coming from the minor upstream link</td>
</tr>
<tr>
<td></td>
<td>Flow</td>
<td>$Q_d$</td>
<td>Total flow measured downstream from the merge</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>$V_d$</td>
<td>Harmonic mean speed measures downstream from the merge</td>
</tr>
</tbody>
</table>
During the simulation, the demands were defined as follows:

- The demand on the major stream was fixed at 85% of the capacity of a single lane.
- The demand on the minor stream was initially $D_m = 100 \cdot k_m$ veh/h. Then, $D_m$ increased progressively with a rate of 50 veh/h/min. Finally, the simulation ended when the merge was fully congested, i.e., vehicle respected a fixed priority ratio at the merge.

3.2. Analysis of the results

The same scenario was replicated many times (ten to thirty times). Flows $Q_{d,M}$ and $Q_{d,m}$ were then averaged to represent the SSCC. One can then analyze the shape of the SSCC, the amplitude of the capacity drop and the fixed priority ratio when the merge is congested.

4. Application on two microsimulation softwares

This methodology was applied to two commercial microsimulation softwares: Aimsun (6.1) and Dynasim (3.0.3). The scenario was implemented for $K_M = 1$ and $K_m = 1$. The demand was composed of cars only. The following paragraphs present the results obtained with unmetered merges.

4.1. Unmetered merge

![Fig.5. (a) Aimsun – SSCC with default parameters   (b)   Aimsun – SSCC with calibrated parameters](image)

Figure 5.a shows the SSCC of Aimsun with its default parameters. When the minor stream demand is low, the total capacity of the merge approaches 2500 veh/h. Then, the capacity of the merge decreases as the minor stream demand increases. When the minor stream demand exceeds 700 veh/h, the capacity drop is maximum (~ 15%) and the total capacity of the merge equals 2100 veh/h. With default parameters, one can observe a fixed priority ratio that is very favorable to major stream vehicles (1400/700). However, empirical observations show that the priority ratio has the same level of order as the lane ratio (1/1), as confirmed by Bar-Gera and Ahn (2010). Consequently, parameters have to be calibrated to come to a priority ratio close to 1.

The distribution of the headway time distribution was calibrated and the final set of parameters were: mean =...
1.5s; standard deviation = 0.3s; minimum = 1s; maximum = 2 s. The SSCC obtained with the calibrated set of parameters is presented in figure 5.b. One can observe that the maximum capacity of the merge decreased (~2000 veh/h) as well as the amplitude of the maximum capacity drop (~10%). The fixed priority ratio (1000/950) now has the same level of order as the lane ratio.

The same work was performed with the simulation software Dynasim and the results are presented in figures 6.a and 6.b.

Figure 6.a shows that with default parameters, the maximum capacity of the merge is 2250 veh/h. Then, the capacity of the merge decreases as the demand on the minor stream increases: the amplitude of the capacity drop reaches 20% (2250 veh/h → 1800veh/h). When the merge is fully congested, the fixed priority ratio is 700/1200. That is lower than the expected fixed priority ratio. Consequently, default parameters were calibrated in order to increase the fixed priority ratio.

The calibration modified two car-following parameters: “AccelerationPlus” (default value = 0.6; calibrated value = 0.9) and “Beta0” (old value = 0.3; calibrated value = 0). The calibration process also modified a lane-changing parameter “lead” (default value = 1.541; calibrated value = -100). Figure 6.b represents the SSCC obtained with the calibrated set of parameters. The fixed priority ratio (1200/1200) is now consistent with the lane ratio (1/1). The total capacity of the merge is around 2400 veh/h and the shape of the SSCC does not reveal any capacity drop.

Here, the calibration of the capacity drop is not proposed. Although efforts have been made in that direction, unfortunately the results of both models revealed that the simultaneous calibration of the capacity drop and the fixed priority ratio is a tough task since:

- both depend of the same set of parameters
- the accurate calibration of the fixed priority ratio impairs the amplitude of the capacity drop, and reciprocally, the accurate calibration of the the capacity drop impairs the fixed priority ratio.

The onset of ramp metering strategy increases the total capacity of the merge and modifies the shape of the SSCC (see figure 3). To test this hypothesis, the SSCC of Aimsun and Dynasim was estimated for different RM strategies.

4.2. Metered merge
The methodology was adjusted to estimate the SSCC when a RM strategy is activated.

Two RM strategies were tested. The first strategy allows one vehicle per green light. The duration of the green phase was calibrated to ensure that only one vehicle can pass during the green phase. The duration of the red phase was adjusted to fit the expected metered flow rate.

The second strategy allows several vehicles per green light.

Figures 7.a and 7.b present the SSCC obtained for Aimsun (i) for an unmetered merge (ii) for a metered merge with one vehicle per green light and (iii) for a metered merge with several vehicles per green light.

Figure 7.a presents the SSCC obtained by the microsimulation software for an unmetered merge (solid black line), a metered merge with strategy 1 (dashed blue line) and a metered merge with strategy 2 (dashed red line). Note that the results are averaged over 30 replications and the results are significant with a level of confidence interval of 95%. The results show that:

- when the metering rate is low (< 500 veh/h), strategy 1 slightly increases the capacity on the merge (~ +2 %) and strategy 2 slightly decreases the capacity of the merge (~ -2 %).
- when the flow rate from the on-ramp is moderate (between 550 veh/h and 650 veh/h), strategies 1 and 2 do not provide any benefit compared to the unmetered situation (unsignificant difference with a level of confidence of 95%).
- when the metering rate is higher (between 700 veh/h and 900 veh/h), strategy 2 leads to an increase of the total capacity of the merge (~ +4 %).

Figures 8.a and 8.b present the results obtained with Dynasim.
Figure 8. a shows that the activation of a RM strategy does not impact the shape of the SSCC of a merge. The results are surprising since empirical evidence clearly shows that the activation of a RM strategy has an impact on the total capacity of a merge (Cassidy and Rudjanakanoknad, 2005). Figure 8.b confirms the analysis: there are no significant differences between the three lines (with a 95% level of confidence).

5. Conclusion

This paper proposes a comprehensive methodology for measuring the impact of ramp-metering strategies on microscopic simulation results. This methodology relies on traffic flow fundamentals and detailed basic traffic scenarios to precisely measure the capacity of metered and unmetered merges.

With an unmetered merge, the results obtained by microsimulation models with default parameters are poor: the SSCC obtained by microsimulation models are not consistent with empirical expectations. To improve the performance of the models, they were properly calibrated regarding:

- the fixed priority ratio when the merge is congested
- the total capacity of the merge

A calibration procedure was performed. A new set of parameters was proposed for each model to accurately reproduce the fixed priority ratio and the capacity with the same set of parameters.

The methodology was adapted to estimate SSCC when the merge is metered. Surprisingly, with a metered merge, the two microsimulation softwares tested in this paper do not provide the same conclusion.

The first microsimulation software (Aimsun) concludes that ramp-metering strategies can increase or decrease the capacity of a merge, depending on the ramp-metering strategy (one vs several cars per green light) and flow rate from the on-ramp. On the contrary, the second simulation software (Dynasim) concludes that ramp-metering strategies have no impact on the shape of the SSCC. In other words, it does not reproduce the reduction of the capacity drop when the merge is metered.

A rigorous method has to be implemented to properly calibrate the SSCC of microsimulation models. The calibration procedure can be time-consuming and does not guarantee that the microsimulation models accurately
reproduce the SSCC pattern observed out on the field. The results also highlight the limits of microscopic traffic flow models for reproducing complex traffic features involved in merging behaviors and RM strategies.

The conclusions can argue in favor of the validation of microscopic merging behavior models based on simplified scenarios, as proposed in the paper. This approach is the only guarantee that microscopic models accurately reproduce well-know macroscopic patterns of traffic flows at merges. More research is needed to validate microscopic merging models on the basis of empirical data. In parallel, a similar methodology has been proposed by the author to test the ability of microscopic lane-changing models to reproduce lane-flow distribution patterns observed on multilane freeways (Duret et al., 2012).

These results also pave the way for alternative tools that measure the effectiveness of traffic control strategies. These models would be simple, with few parameters, based on a demand/supply rule, and would allow for a simplified calibration process. The CETE is currently carrying out research in this direction.

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