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ADDRESSING FIDELITY BETWEEN MESO- AND MICRO-SIMULATIONS TO EVALUATE TRAFFIC FLOWS IN MULTI-RESOLUTION MODELING (TASKF)

SOLARIS Consortium, Tier 1 University Transportation Center
Center for Advanced Transportation Education and Research
Department of Civil and Environmental Engineering
University of Nevada, Reno, NV 89557

Kerem Demirtas, PhD student
Pitu Mirchandani (PI), Sc.D.
School of Computing, Informatics, and Decision Systems Engineering
Arizona State University
Tempe, AZ 85287
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EXECUTIVE SUMMARY

Currently, traffic management strategies such as adaptive control and ramp metering systems go through the following steps: (i) conceptualization of strategies, (ii) development of logic and software algorithms, (iii) simulation-based testing of the strategies, (iv) hardware implementation, (v) field testing of hardware/software systems, (vi) operational testing of the proposed systems, (vii) implementation and evaluation of the system. The simulation testing done in step (iii), when performed, is conducted using models based in one of the several off-the-shelf-simulation packages. Such models and simulation testing have been quite successful for isolated intersections and single intersections, and small networks with 1-3 intersections – where the effect of re-routing due to incidents, major events that result in changes in traffic patterns, have none or only minor impacts on the simulations.

Mesoscopic simulation models that simulate large networks, on the other hand, are used mostly at a planning level to evaluate long-term impacts of network-wide transportation decisions and management strategies such as network changes (e.g. adding a lane), congestion pricing, dynamic messages, etc. Simulation based “Dynamic Traffic Assignment” (DTA) are typical of such models – where planners input traffic demand in terms of time-dependent Origin-Destination travel demands, and the models outputs traffic conditions, usually at the time resolution of 5-15 minutes, or hourly, each day of the week. Such DTA mesoscopic simulation traffic models are really a spatial-temporal approximations of traffic loading on a network where only time-dependent travel times on links are considered in the underlying route-choice model and not the actual flow dynamics on the links. Even more of a concern is that neither traffic signals are modeled with fidelity nor lanes are considered in the model (only link level representation is used).
Furthermore, such models are usually calibrated by statistically fitting travel times and traffic flows for a small subset of the network links, where the fitting a shallow convex objective results in a large number of possible fits.

Part of the lack of fidelity among the meso- and micro-models is due to scope; DTA-type models usually approximate links and path loads for planning purposes while scope of micro-simulation models is on traffic management through small networks. What this project attempted to do was to develop a mesoscopic model that approximates the spatial-temporal traffic patterns of a VISSIM model. In other words, instead of fitting a large DTA model based on fitting flows on a few measured links, this project developed a new model that approximates all the flows of a VISSIM model albeit faster than VISSIM. To make it computationally manageable, the scope of this new model currently considers only a single two-lane link, with merges and diverges.

**Keywords:** Microscopic simulation Modeling, VISSIM, Mesoscopic-simulation, Dynamic Traffic Assignment, Multi-resolution Simulation, Simulation Fidelity
1. INTRODUCTION AND BACKGROUND

Microscopic traffic simulation models consider the interactions of individual vehicles with nearby vehicles, as well as the transportation infrastructure, in a very detailed resolution to calculate the next position of the vehicles for a short-term horizon (typically around 0.1 to 1 second) that gets updated as the simulation runs. Car-following (CF) models, which describe the longitudinal motion of a vehicle under the physical laws of motions along with a car following behavioral aspect, and lane changing (LC) models which probabilistically define the lateral movements of a vehicle as instantaneous decisions, are the two types of models applied in microscopic traffic simulation. On the other hand, in mesoscopic models, traffic dynamics of a network are modeled in a level that sits between microscopic and macroscopic model resolutions. In mesoscopic models, vehicles are considered either individually or in platoons, and how they move through the links of the network are governed by macroscopic traffic conditions rather than each vehicle having the freedom of making their own decisions based on microscopic conditions. In this study, we have considered a commercial microscopic traffic simulation software, namely VISSIM as our ground truth generator, and, we developed a mesoscopic traffic simulation model that can also account for individual lanes of a link in order to approximate the travel times and densities generated by VISSIM.

There is a vast amount of literature on link-based traffic simulation models. However, the number of studies that consider individual lanes of a link is limited. Zheng (1) gives a summary of recent work done and points out the needs about modeling lane changes. Jin (2) extends the kinematic wave model by introducing a lane changing intensity variable and argues that a lane changing maneuver disrupts the flow on both the original
and the target lane. Jin (3) studies the weaving and non-weaving vehicles as two different commodities and use the kinematic wave model to come up with a fundamental diagram whose parameters are driven by lane changing and car following characteristics. Laval and Leclercq (4) include macroscopic lane changing theory within microscopic models with a single additional parameter and simplify the lane changing process compared to the original microscopic models. Laval and Daganzo (5) extend the original LWR model to incorporate traffic streams in a continuous domain.

There are two types of lane changing maneuvers in traffic flow, namely, mandatory and discretionary. Mandatory lane changes are due to the necessity of following a certain path in order to reach the final destination. Taking an off-ramp on a freeway, making a left turn at an intersection are two common examples of situations that trigger such mandatory lane changing maneuvers. On the other hand, in discretionary lane changing; the drivers, without the necessity of lane changing, make their own decisions of lane changing, mostly in order to travel on a faster lane than the lane they are traveling on. Sketches in Figure 1 illustrate discretionary and mandatory lane changing. In VISSIM, both mandatory and discretionary lane changing are integrated in the microscopic traffic flow model that is used to mimic the behavioral dynamics of individual vehicles.
Figure 1. Sketch illustrating mandatory and discretionary lane changing
2. NETWORK REPRESENTATION

VISSIM’s network structure consists of links and connectors. For the mesoscopic model, we developed a lower level lane-based representation of the physical network of VISSIM, which allows studying different properties under specific user-defined scenarios in a flexible manner that can incorporate multiple layers of fidelity between the microscopic and mesoscopic levels of resolution. The network abstraction from the physical network to the lower level network is illustrated in Figure 2.

**Figure 2. Abstraction of the physical network from VISSIM for the mesoscopic model**

In Figure 2, there is a single link with two lanes at the top. The bottom part is the corresponding lower level network that includes forward (yellow) segments and diagonal (red) lane changing segments. It is also possible to increase the resolution of this representation by introducing intermediate checkpoints.
3. SPECIFICATIONS OF THE MESOSCOPIC SIMULATION MODEL

For the mesoscopic simulation model, we considered two options, namely Discrete-Event Simulation (DES) and Time-Based Simulation (TBS). Both methods have their own advantages and disadvantages in terms of computational efficiency, and the level of detail that can be captured by the method. In any case, the vehicles are modeled as individual agents, interacting with other agents as well as the supply infrastructure of the physical network. However, in mesoscopic models vehicle movements are not modeled in detail as it would occur in a microscopic simulation environment like VISSIM. In DES, the jump of simulation clock is from an event to the next event stored in an event list, and therefore, the intervals between two consecutive computation epochs need not be the same. In TBS, a computation takes place every $\Delta t$ time units, which is a parameter of the simulation, often referred to as the simulation interval. As can be expected, there might be several unnecessary computations in the TBS simulation models, especially when the system state does not change significantly, as $\Delta t$ gets smaller. Hence, the research team’s attempt in building the mesoscopic simulation model is based on DES to favor computational efficiency.

Due to its efficiency of runtime interaction with VISSIM, and the rich open source libraries available for a vast spectrum of tasks, Python is chosen as the programming language that mesoscopic simulation model is built upon. Main libraries to be used in the mesoscopic model consist of but are not limited to:

  Discrete event simulation library for Python that can also handle time-based simulation.

* **pandas** (http://pandas.pydata.org/pandas-docs/stable/)
  Data management and analysis library for Python that will be used for input and output analysis as well as data storage and manipulation.
Three major events are defined for the lane-based mesoscopic discrete event simulation framework. These events represent the moments when the system states change, or when they become subject to a possible change soon. Here, we provide the events with their descriptions and their detailed explanations.

**segment_departure**: The event when a vehicle exits a segment. It triggers a shockwave (if any, calculated from the downstream link) that will propagate upstream, which will be used in the travel time calculation/re-calculation of the vehicles that enter the segment, or are already in the segment.

**segment_arrival**: The event when a vehicle enters a segment. It can either be due to the origin-destination demand pattern arrival, or the end of traversing a segment and joining the next segment on the path of the vehicle.

**procedure_move**: The event when a vehicle starts to traverse a segment, either by going through or by lane changing to follow its path towards the destination. Before a vehicle starts traversing a segment, it first assesses the necessity of making a mandatory lane change. If a lane change is required, then the travel time for the diagonal (red) segment is calculated for that vehicle and its tentative arrival at the next node is scheduled. Otherwise, by comparing the speed of the current lane $v_c$ and the speed of the target lane $v_t$, probability of a possible lane change is calculated. This probability increases with the speed difference between the two lanes assuming that the target lane is faster and is determined by $p = \frac{v_t - v_c}{v_t}$. Finally, if the calculated probability exceeds a certain threshold value $p > p_0$, the vehicle starts traversing a diagonal segment as well. If no lane change is required or desired at all, the travel time of a through traversal is calculated and the vehicle
is scheduled to arrive its next node on its path. The flowchart of the movement procedure is given in Figure 3.

![Flowchart of procedure_move](image)

**Figure 3. Flowchart of procedure_move**

When a vehicle makes a lane changing move, it has to traverse some portions of each lane before reaching the destination node. Therefore, the travel time for a lane changing segment is calculated as the convex combination of travel times on each lane. Suppose that the travel time of a through movement is $t_1$, whereas the travel time on the other lane is $t_2$ as illustrated in Figure 4. Then, the travel time of the lane changing segment is calculated as $\alpha t_1 + (1 - \alpha)t_2$, where the parameter $\alpha$ determines how far the vehicle will travel on its current lane before actually executing the lane changing move. Note that $0 < \alpha < 1$. 
Figure 4. Travel time for a lane changing segment

Calculation of the travel time for a through movement requires a fundamental relationship between density and speed, given by $V(k) = v_f \left(1 - \frac{k}{k_{jam}}\right)$, where $v_f$ and $k_{jam}$ represent the free-flow speed and jam density, respectively. At any time in the simulation, the density $k$ is known, so, it is straightforward to calculate the speed using $V(k)$. Once the speed is calculated, the travel time is computed by dividing the length of the segment by the speed.
4. TEST SCENARIO, GROUND TRUTH GENERATION AND COMPARISON

After several initial runs to understand and grasp the lane changing behavior of VISSIM, a test scenario with a 1 km single link with two lanes is developed. As stated before, there are two types of lane changing occasions, namely mandatory and discretionary. In the test scenario we have developed, discretionary lane changing is less likely to be observed since the vehicle input composition consists of similar vehicle types. Without any modifications on the test case, having a single link only allows a single route that goes from the beginning to the end of the link, which prevents us from observing mandatory lane changes. Therefore, we have extended the end of the link with two dummy additional links that behave like diverging points at the end of the link allowing us to define two different routes. A sketch of the test scenario is given in Figure 5 below.

*Figure 5. Single Link Test Scenario with Two Routes*

In VISSIM, for a defined route, there are three important decision points. The first one is the decision point that assigns a static route to a vehicle as it passes that point. The second decision point triggers a lane changing pulse for a vehicle that passes it if the vehicle has to change lanes in order to reach its destination according to its assigned route. The final point acts like an emergency stop right before (10-20 m) the diverge point, forcing
the vehicles to change lanes that did not make a mandatory lane change after passing the second decision point. In the test scenario, the first decision point is located immediately after the start of the link where the vehicles are created. At this point, the vehicles are assigned a final destination, which is connected through the connectors between the links that constitute the route. Then, before reaching the second decision point, which is located halfway between the start and end points of the original link, the vehicles can make discretionary lane changes. However, after reaching the second decision point, the vehicles are forced to make lane changes according to their routes with a higher probability than they would under discretionary lane changing circumstances. At the last decision point, which can also be referred to as the emergency stop point following the terminology of VISSIM, the vehicles that are not on the appropriate lane according to their routes are strictly forced to slow down and make the necessary lane changing maneuver to stay on their routes. Our observations indicate that mandatory lane changing occurs mostly when the vehicles get close to their destinations on their routes (at emergency stops or close to emergency stops), even though there is free-flow conditions and favorable opportunities on the way, after a routing decision is made at the upstream end of the link. In other words, the vehicles tend to change lanes when they get close to their destinations which cause unrealistic stop and go waves at the downstream end of the link which may not suit a realistic real-life scenario.

In Figure 6 below, the mesoscopic network representation of the above microscopic scenario is provided. The intermediate nodes (1, 1, 1) and (1, 2, 1) correspond to the second decision points of the microscopic VISSIM simulation scenario for lanes 1 and 2,
respectively. The yellow segments indicate a through traversal, whereas the red segments represent a traversal that includes a lane changing maneuver.

**Figure 6. Mesoscopic Network Representation of the Single Link Test Scenario**

A mesoscopic simulation model is developed for the test scenario described in this section. The results of the mesoscopic model are compared with the results of the VISSIM output, which is considered as the ground truth. Speed contour plots provided in Figure 5 show the stop and go waves generated by VISSIM simulation. For both lanes, the first backward moving shockwave can be seen around 150 seconds, emanating from the emergency point and reaching the upstream end of the link by time 300. After the congestion is dissipated, there is a weaker second shockwave from the emergency point which can only travel 100 meters upstream. However, at the same time, again for both links, there is a backward moving shockwave, emanating from 700 meters and around 400 seconds, traveling all the way to the downstream end of the link. There are three more such waves until the end of the simulation (900 seconds), which can be visualized by the plots given in Figure 7. Similar stop and go waves can be observed for the density and can be visualized by the plots in Figure 8.
Our mesoscopic simulation model also keeps track of the density throughout the simulation by the cumulative counts at the nodes for comparison with VISSIM. For our simple model with two segments, the density contours given in Figure 9 roughly match the density contours provided by VISSIM. The first shockwave around time 150 seems to be caught by the mesoscopic model. However, for the rest of the shockwaves, the upstream segment of the mesoscopic model cannot recover from congestion. Moreover, the mesoscopic model reports lower density values when compared to the VISSIM output. This is an expected outcome, since the aggregation of VISSIM values are for every 100 meters, whereas the mesoscopic model aggregates the values for 500 meters. In addition to
that, due to the nature of the simulation, further aggregation is made while the mesoscopic simulation runs since we do not keep track of the vehicles every second.

**Figure 9** Density contour plots from mesoscopic model

As a next step, we have included multiple intermediate points in our mesoscopic simulation network in order to assess the fidelity of our mesoscopic model. Having multiple intermediate points on the link allows the mesoscopic simulation model to approximate the behavior of the microscopic simulation model from VISSIM with higher fidelity. Figure 8 gives the network schematic of a single link with two lanes having 5 intermediate points labeled from 0 to 4. The triplet (i, j, k) on a node represents the link number, lane number and intermediate point, respectively.

In Figure 10, the two middle lane changing decision points of VISSIM are (1,1,2), (1,2,2) for lanes 1 and 2, respectively. Similarly, (1,1,4), and (1,2,4) represent the emergency stop points for lanes 1 and 2.
For this slightly more complicated network, the density estimates can be visualized in the density contour plots provided in Figure 11.

It is obvious that introducing more intermediate points pulls the density estimates given by the mesoscopic model closer to the VISSIM output. However, the density values are still lower than the ones provided by VISSIM.

As another measure of consistency, travel times before and after the second decision point are compared in order to observe how the stop and go waves affect the travel times in the first 500 meters and the second 500 meters. Figure 12 shows the travel time patterns for both halves of the link provided by VISSIM.
From Figure 1, we can easily observe that the travel time for the second half of the link is less than the travel time on the first half, which is due to the congestion spillback resulting from lane changing after the decision point which is located at the middle of the link. We have also compared the travel times provided by the mesoscopic model with the travel times from VISSIM (see Figure 13). Results indicate that both models give similar travel time results on average for both halves of the link. Microscopic results show significantly more fluctuation than those provided by the mesoscopic model, which is once again due to the aggregation process. Both models use an aggregation interval of 30 seconds. However, in VISSIM travel time information is available at every second, whereas travel time updates in the mesoscopic model are available in discrete points in time which are then further aggregated in 30 second intervals. In addition, as expected, the travel time in the first 500 meters is higher than the travel time for the next 500 meters for both models since the congestion spills back after the second decision point due to several
lane changing maneuvers. Another observation is that, mesoscopic travel time averages are less than microscopic travel time averages for each segment, which is consistent with the density comparison given before, where the density estimates of the mesoscopic model were lower than the VISSIM values resulting in higher speeds, hence shorter travel times. A possible reason for this is poor calibration of mesoscopic model parameters, which can be overcome by specific methods designed just for calibration purposes.

**Figure 13.** Travel time comparison VISSIM vs mesoscopic model

<table>
<thead>
<tr>
<th>VISSIM Average: 50.44 seconds</th>
<th>MESO Average: 45.32 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISSIM Average: 30.09 seconds</td>
<td>MESO Average: 25.87 seconds</td>
</tr>
</tbody>
</table>
5. CONCLUDING REMARKS

In this research we developed a lane-based discrete event mesoscopic traffic simulation model that can approximate the ground truth output provided by the microscopic traffic simulation software VISSIM. We came up with a network structure for the mesoscopic model, which is suitable for different resolutions depending on the needs of the end user to address multiple levels of fidelity between two models. We have tested our mesoscopic model and compared its results with VISSIM on a single link two lane scenario. Here we state our observations, findings, challenges and possible future research directions.

- First, in order to approximate the output of VISSIM by a mesoscopic model on a lane level, it is essential to fully understand the dynamics of the underlying traffic model used by VISSIM, especially in terms of lane changing behavior.
- Abstraction of the physical network in VISSIM for the mesoscopic model should be completely compatible in terms of lane changing decisions regarding where it is more likely to take place; since, on a single link with two lanes and homogeneous vehicle composition, the only trigger for a shockwave to arise becomes a lane changing maneuver.
- For homogeneous vehicle composition, discretionary lane change has minimal effect as it is unlikely to be observed. Mandatory lane change is the dominant factor behind shockwaves and congestion formation.
- Lane changing affects and disrupts the flow behavior on both lanes. In other words, whenever a lane change occurs, separate shockwaves arise on each lane and congestion spills back for the whole link.
• With proper network construction for the mesoscopic model, we were able to capture important phenomena such as shockwave detection and congestion formation. Density and travel time estimates of the mesoscopic model were comparable with VISSIM output even though they were consistently lower in both high and low resolution runs of the mesoscopic model. Most likely reason behind that is poor calibration of the mesoscopic model parameters such as jam density, free-flow speed, and backward wave speed. This issue requires additional effort in designing models just for calibration purposes.

• Increasing the resolution of the mesoscopic network leads to better approximation of VISSIM in terms of congestion dissipation without sacrificing too much computation time. Computation time required for the mesoscopic model was roughly one tenth of the time spent by VISSIM for the higher fidelity mesoscopic model.

• For slightly larger networks, it becomes cumbersome to keep track of the decision points located on the links of VISSIM per route. However, it is crucial so that a consistent abstraction of the mesoscopic network can be constructed. Otherwise, VISSIM and mesoscopic model outputs are highly likely to be off.

• Shockwave theory can further be exploited to have more accurate tentative travel times, since every vehicle exiting a segment will be an indicator of the trajectories of the following vehicles according to the car following models.
REFERENCES


