Modifications of asymmetric cell transmission model for modeling variable speed limit strategies

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1 Motivation

Most of freeway traffic models dealing with variable speed limits (VSL) rely on second order models [1-3]. In general, these models consist of two equations: the first expresses the vehicles conservation law, whereas the second features the drivers' delayed reaction and anticipation (i.e. the hysteresis phenomenon). However, most of them are not sufficiently based on real traffic flow behavior and may lead to nonphysical effects. Until now, first order models has not been used due to its hypothetical inability to reproduce capacity drop phenomenon which is crucial for reproducing congested periods in bottleneck sections. The paper tries to fill this gap by presenting some extensions of the asymmetric cell transmission model (ACTM) [4] and incorporating the ability to model VSL strategies.

2 ACTM extensions

In the vicinity of an area with mandatory lane changes (e.g. due to an on-ramp or a lane drop) two different mechanisms may trigger an additional restriction of the mainline capacity (i.e. capacity drop): instabilities inside a queue (type 1) and the merging itself (type 2) (Figure 1). The first can arise along the length of the queue and the second in the merging area. These capacity restrictions will not always become active and can fluctuate according to three different scenarios:

(i) traffic flows through the bottleneck at freeway capacity and without capacity drop (i.e. free-flow capacity, “C-free flow”);

(ii) queue is an active restriction limiting capacity to the queue discharge rate (“C-queue”) due to frequent lane changes, (de)accelerations or drivers’ distractions;

(iii) the merging is an active restriction limiting the capacity to “C-merge” value.

It should be noted that “C-merge” capacity will only occur in areas with mandatory smooth merges under free-flow conditions. If demand increases and queues are created, the available freeway capacity will drop to “C-queue”. Consequently, it is considered that when the bottleneck is performing at queue discharge rate both mechanisms are active.

For the construction of the macroscopic model, it’s essential to capture both capacity drop phenomena in the fundamental diagram calibration procedure. In fact, a recent study has partially succeeded in this issue, proposing useful fundamental diagram calibration methodologies for both triangular and inverse lambda shapes [5].

Even so, currently available ACTM implementations can’t exploit these features of the fundamental diagrams. For this reason, the main ACTM extension presented here is the ability to reproduce capacity drop. This phenomenon is attempted to be reproduced thanks to the inverse-lambda shaped fundamental diagram incorporated in the model. The fundamental diagram is defined as a two subdomains piecewise linear function which contains a jump discontinuity at critical density value (Figure 1).

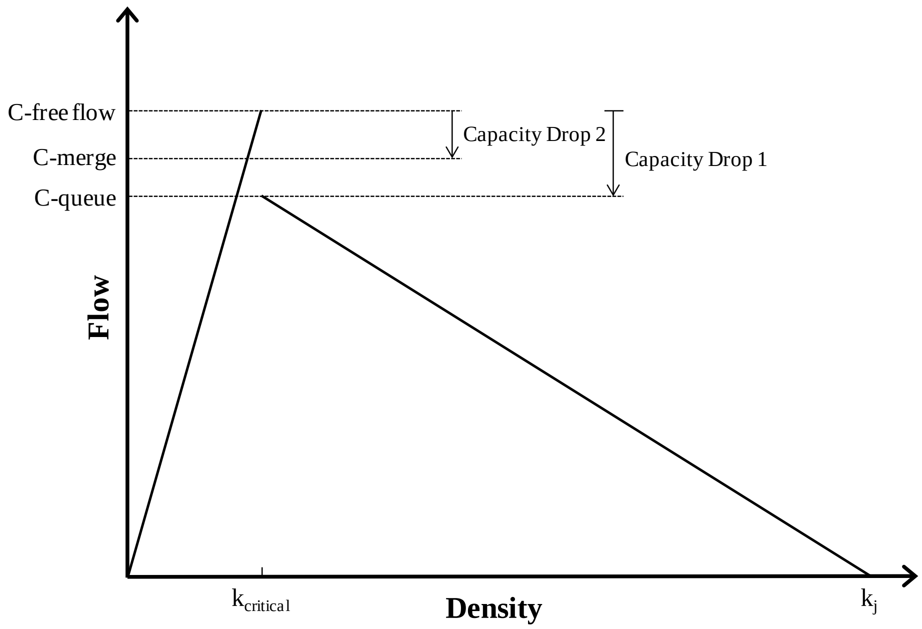

Figure 1 Inverse-lambda shaped fundamental diagram

This model extension is introduced in the simulation process through the cell-capacity modification. Two simple rules were defined for this purpose, depending on the cell configuration (i.e. with/without merges):

(i) Merging cells: for density values lower than critical ones, cell-capacity drops to "C-merge". Otherwise, cell-capacity corresponds to "C-queue".

(ii) Non-merging cells: for density values lower than critical ones, cell-capacity corresponds to "C-free flow". Otherwise, cell-capacity corresponds to "C-queue".

Special attention should be given to the cell "j" located immediately downstream of the bottleneck caused by a merge. Assume there is only one active bottleneck in the network limiting the cell-capacity (Figure 2a). Cell density will drop from congested (in the bottleneck-cell) to uncongested values (downstream of the bottleneck-cell) (Figure 2b and 2c). Cell "j" will perform with "f_j = C-free flow" by default, i.e. without capacity drop, which is not realistic (Figure 2b). To solve it, it may be assumed that under active bottleneck conditions the capacity of the cell "j" is equally reduced than its precedent (Figure 2c). Otherwise, capacity drop phenomenon wouldn't be reproduced.

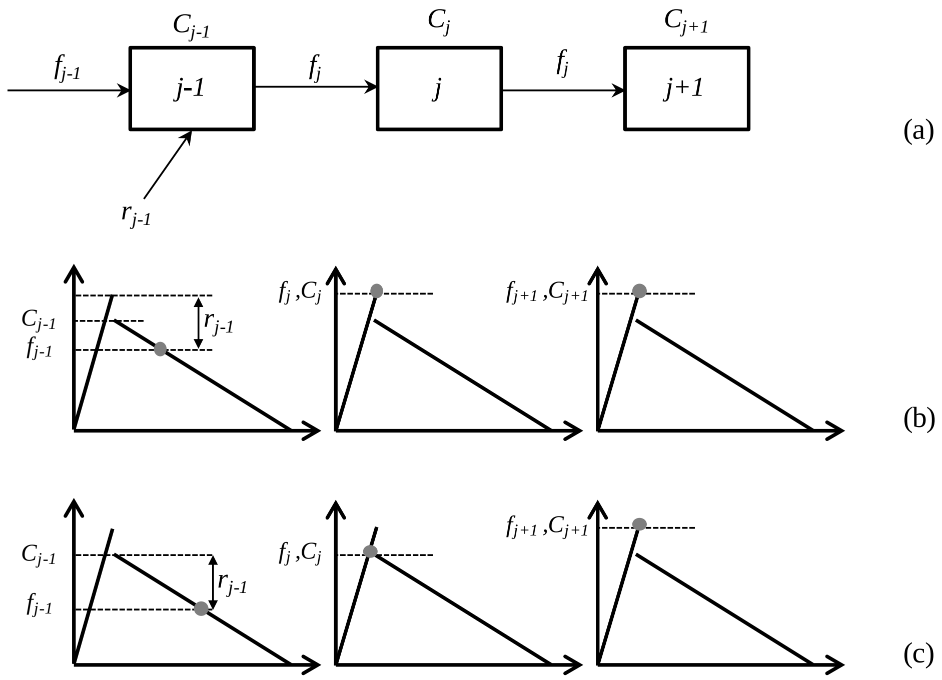

Figure 2 (a) Cells configuration indicating its capacity (“C”), entering flow (“*f* ”) and on-ramp rate (“r”), if exists. Current flow and available capacity of each cell (c) considering and (b) without considering capacity drop in cell “j”.

The study also focuses on merging behavior of ACTM. Assuming that two-parameter ACTM merging dynamics should be consistent with one-parameter CTM approach, a new equation relating both ACTM’s parameters was defined. It’s remarkable to say that with common calibration of ACTM in practical applications merging behavior becomes unrealistic. E.g. a case where both mainline and on-ramp are highly demanded but no queues are created in the onramp because all vehicles are allowed to enter in the congested trunk.

VSL strategies can be introduced in ACTM as well. Speed limits have been modeled varying the free-flow speed branch of the fundamental diagram: the lower the speed, the gentler the slope. It’s known that the activation of speed limits below critical speed (upstream of a mainstream bottleneck in under critical but high demanded conditions) will increase travel time and hence produce an active restriction to flow [1, 3, 6]. In that case, this effect may be similar to a mainstream ramp metering. At the same time, the decrease of the mainstream flow arriving to the bottleneck section may avoid capacity drop to be triggered. Then the final bottleneck outflow is maximized, leading to a corresponding decrease of the total time spent in the system. It should be noted that this is the main VSL impact that will be exploited. Preliminary results of a simplistic motorway stretch with a unique on-ramp show savings in the total time spent in the network of the same order than the capacity drop modeled. These results are consistent with the general fact that the higher the bottleneck outflow the less time vehicles will spend in the network.

3 Conclusions

Capacity drop phenomenon is well reproduced thanks to the inverse-lambda shaped fundamental diagram and extensions both introduced in ACTM. The new model calibration equation helps merging dynamics to become more realistic. It has been demonstrated that in on-ramps producing mainline congestion, VSL strategies can effectively reduce the total time spent by vehicles in the network.

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