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Chapter 67
Multi-lane Traffic Flow Model: Speed Versus Density Difference as Lane Change Incentive and Effect of Lateral Flow Transfer on Traffic Flow Variables

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Abstract For better and more efficient motorway traffic control strategies on a lane level, accurate modelling and prediction of traffic conditions is essential. Existing real-time traffic state estimation methods aggregate traffic across lanes. Hence, there is a need for lane-specific traffic flow models. The majority of the existing macroscopic lane-level traffic flow models use speed difference among lanes to explain lane change decisions. One of the major disadvantages of using speed difference as motivation for lane changing is the different speeds at which the lanes on a motorway operate. These models which are usually extensions of the Cell Transmission Model (CTM) also suffer in the manner in which lateral flow is transferred among cells in different lanes. In order to overcome these limitations, a model is proposed using density difference as an incentive to compute lane change rates rather than speed. A two-step transfer of lateral flow among cell segments is also considered where the lateral demand of a cell is dependent upon the receiving capacity of the adjacent and downstream cells in the target lane. The advantages of the presented approach is shown by comparing the proposed model with a conventional model. It was observed that the proposed model performed better in terms estimating densities across lanes. The proposed model is a step in the development of more accurate lane-specific traffic flow models.

67.1 Introduction

With rising congestion on motorways across the world, there is an urgent need to come up with active and efficient traffic management strategies to tackle this problem. For effective traffic management, accurate traffic flow estimation and prediction models are essential. Existing real-time estimation and prediction methods aggregate traffic across lanes without taking into account the difference among lanes. But studies [1, 2] have shown that on multi-lane motorways, lanes operate differently. Depending upon

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the conditions, proportion of flows on different lanes vary. This can lead to unbalanced lane usage. Knowledge of lane specific traffic conditions are important to achieve a more balanced distribution of traffic across the lanes and improve efficiency of motorways. Hence traffic flow models which include the dynamics of lane changing are needed for lane specific control.

The majority of the existing macroscopic lane-level traffic flow models use speed difference among lanes to explain lane change decisions. One of the major disadvantages of using speed difference as motivation for lane changing is the different speeds at which the lanes on a motorway operate. These models which are usually extensions of the Cell Transmission Model (CTM) also suffer in the manner in which lateral flow is transferred among cells in different lanes. In order to address these concerns, a model is proposed which uses density difference among lanes as an incentive to compute lane change rates rather than speed. The model also differs from existing models in the manner in which the computed lateral flows are transferred among cells. The proposed model is compared to an existing model by using real world data.

The remainder of the paper is organized as follows: Sect. 67.2 describes state-of-the-art on multilane traffic flow models. Section 67.3 describes the proposed model including the computation and transfer of lateral flows and lane change rates. In Sect. 67.4, the proposed model is tested against real world data and compared to a conventional model and finally in Sect. 67.5, we conclude the paper.

67.2 State-of-the-Art on Multilane Traffic Flow Models

Macroscopic models describe aggregate driving behavior and typically involve a relationship between the density and flow of a network. Earlier works on multi-lane macroscopic models such as [3, 4] were formulated in a continuous space-time domain. Laval and Daganzo [5] expanded on earlier works and presented a hybrid model considering the lane changers as particles with bounded acceleration rates. However, these models aggregated traffic flow variables across lanes. Further models such as [6, 7], and [8] were developed which considered individual lanes as separate entities. Most of these models (except [8]) consider speed difference lanes as an incentive to compute the percentage of flow that might change lane. But on multi-lane motorways, different lanes operate at different speeds. These models use a single fundamental diagram (FD) for the motorway.

A single FD for all lanes implies that lane changes always happen among the lanes as the speeds on lanes differ (especially in free-flow) which is not the case. Using a single FD for all the lanes might not lead to accurate results. Speeds are computed a posteriori if the flow-density relationship is used. If density-speed relationship is used, one of the disadvantages of using speed as a motivation to explain lane changing is the constant relationship between speed and density in the free-flow state (assuming a triangular FD). This implies that no lane changes take place in the free flow state which is not a realistic assumption. Considering different shapes

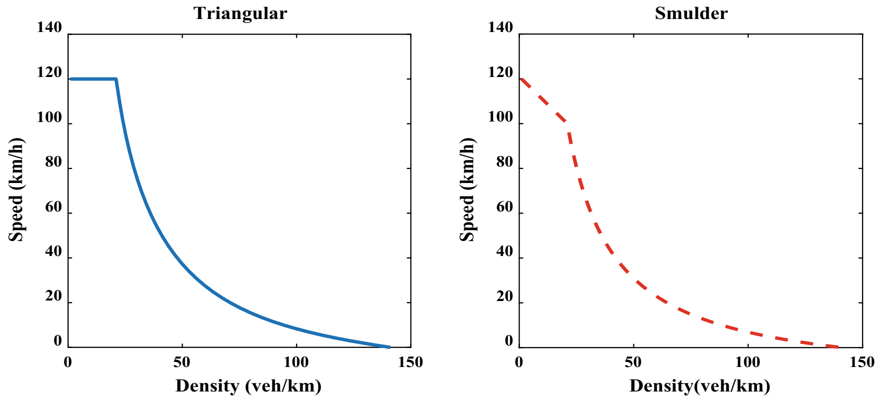

Fig. 67.1 Speed-Density relationship for different FDs

of FD to allow for lane changes in the free-flow state can increase the complexity of the model in terms of the computation of demand and supply capacities due to the introduction of nonlinear terms. As can be seen in Fig. 67.1, if a triangular FD is used, the speed does not vary in the free-flow state. This would imply that there are no lane changes. If a different shape of FD (like Smulder) is used, the number of FD parameters increases because there is a need to estimate both the free-flow and critical speed. This increases the number of parameters as well as introduces a non-linear relationship between flow and density in the free-flow state which affects the computation of demand and supply and consequently transfer of flows. Using density difference among lanes presents us with an advantage that lane changes are possible even in the free-flow state and densities are generally the state variables of traffic flow models. Although there are a number of other factors such as the current location, prevailing traffic conditions, destinations of the vehicles etc. which affect the lane changing flow, in order to keep a simple framework for lateral flows, density difference is used which can capture the basic situations.

A major element of most of the existing models is the transfer of lateral flow among cell segments in the discretization scheme. The transfer of lateral flow among cell segments in different lanes is considered to be diagonal i.e. the lateral flow from a cell depends on the supply capacity of the adjacent downstream cell. While this works in the free-flow state, it may not work in congested conditions where the lateral demand is generally dependent on the receiving capacity of both the adjacent and downstream cell in the target lane (especially when the length of the cell segments are not too long). Considering a diagonal transfer of flow among cell segments can lead to the under-estimation of the distance over which the congestion propagates as well as the erroneous estimation of the strength of congestion. In this study, the motivation behind lane changing is formulated using density as the explanatory variable. The transfer of lateral flows is also based on the assumption that the lateral demand is dependent upon the receiving capacity of the adjacent and downstream cell segments on the target lanes.

67.3 Proposed Model

As with most first order models, the starting point of the model is the well-known CTM (Cell Transmission Model) by Daganzo [9] which is extended to consider the dynamics of lane changing. A multi-lane motorway subdivided into segments, wherein each segment comprises of a number of lanes is considered. The segments are indexed i = 1,2,3….n and the lanes as l = 1,2….m. The conservation equation in discrete terms is given by Eq. (67.1) (Fig. 67.2).

$$k_{il}(t+1) = k_{il}(t) + \frac{\Delta t}{\Delta x} * [q_{i-1,l}(t) - q_{il}(t) + lq_{i,l-1\to l}(t) + lq_{i,l+1\to l}(t) - lq_{i,l\to l-1}(t) - lq_{i,l\to l+1}(t)] \quad (67.1)$$

In (67.1), k and q represent the density and flow at the boundary of the cell-segments respectively. Δt is the size of the time step and Δx is the length of the cell segment. lq denotes the lateral flow between the cell segments. t denotes the simulation horizon where t = 1,2,3…..,T and the total simulation time is given as $t_{\text{sim}} = \text{T}^* \ \Delta t$. The terms $lq_{i,l-1\to l}$ & $lq_{i,l+1\to l}(t)$ represent the lateral flow entering cell-segment i from the adjacent lanes $l-1$ and $l+1$ respectively and the terms $lq_{i,l\to l-1}$ & $lq_{i,l\to l+1}(t)$ represent the lateral flow exiting cell-segment i to the adjacent lanes $l-1$ and $l+1$ respectively. The lateral flow in (67.1) is considered to be a function of the density difference (directly proportional) rather than the speed difference and is given by Eq. (67.2) for the proposed model.

$$lq_{i,l'\to l} \propto (k_{il'} - k_{il}) \quad (67.2)$$

where, l' and l represent the original and target lane respectively. The longitudinal flows are computed as the minimum of the sending and receiving capacities of the cell. The transfer of lateral flows is considered as a 2-step process and is shown in Fig. 67.3. The figure on the left shows the conventional transfer while the figure on the right is the proposed transfer method. The proposed method is implemented in the model by modifying the sending and receiving functions of the cell to include the effect of lateral flow and instead utilize effective sending and receiving capacities to compute longitudinal flow among the cell-segments. In the 2-step transfer, the lateral

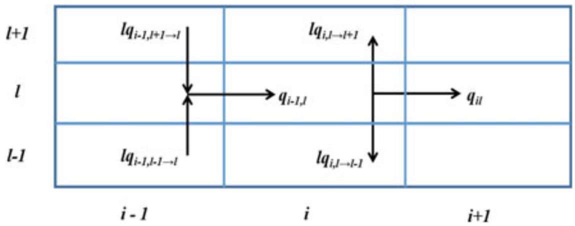

Fig. 67.2 Representation of the discretized motorway

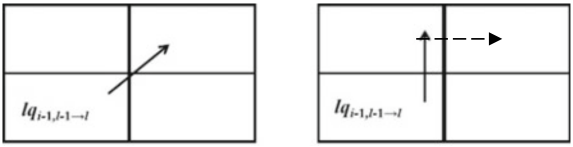

Fig. 67.3 Transfer of lateral flow among cells

demand of a cell is dependent on the receiving capacity of the adjacent as well the downstream cell of the target lane.

67.4 Results

The proposed model is tested against real world data and compared to a conventional model which uses a diagonal transfer of lateral flow. As the speeds at which the lanes are operating are different, speed difference has not been used in the conventional model as this would be lead to obvious errors. Thus only the method of lateral flow transfer is varied between the two models. Data from a lane drop bottleneck on the A12 motorway in Netherlands is selected for this purpose. 1-minute aggregated speed and flow information for the month of May, 2008 from stationary lane based detectors were used to compute densities. The chosen section is a 4-3 lane drop shown in Fig. 67.4.

The performance indicator used to compare the models is the RMSE of lane densities and is given by Eq. (67.3).

$$\text{RMSE} = \left(\sqrt{\sum_{i}^{n} \sum_{j}^{L} \left(k^{i}_{est,l} - k^{i}_{obs,l}\right)^{2}} \right) \quad (67.3)$$

The results for a particular day is shown in Fig. 67.5. The results are shown for detectors upstream of the lane drop.

It can be observed that the 2-step process leads to lower error values on lanes 1 and 2 as compared to a diagonal transfer of flow. There is not much difference on lanes 3 and 4. This can be attributed to the low lane changing activity on these lanes

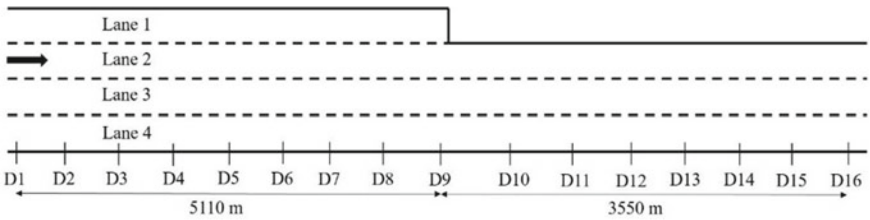

Fig. 67.4 A12 lane drop section

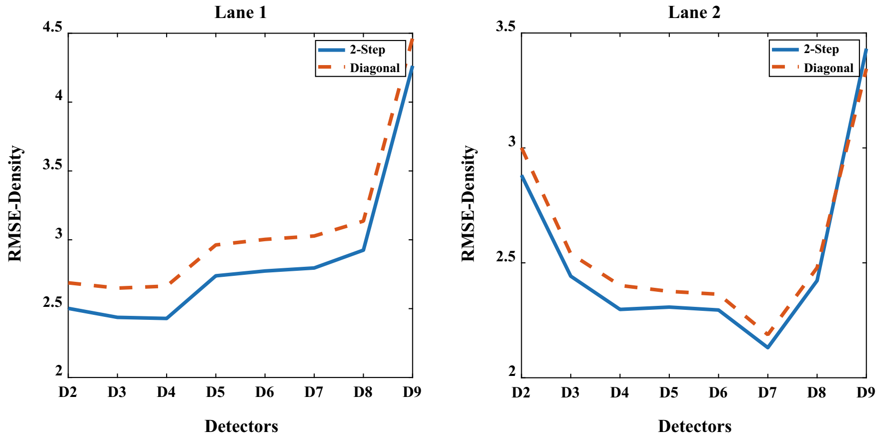

Fig. 67.5 Comparison of the proposed model with conventional model

as compared to lanes 1 and 2 where the lane changing activity is high due to the merging of vehicles. Hence it can inferred that a 2-step lateral flow transfer among cells leads to better lane-level estimations of traffic flow variables when compared a diagonal transfer of flow.

67.5 Conclusions

A multi-lane traffic flow model is proposed where the incentive to change lanes is expressed as a function of the density difference between lanes and it is argued why this suits better than using a speed difference among lanes. A 2-step process of lateral flow transfer is proposed where the lateral flows are dependent upon the receiving capacity of not only the downstream cell of the target lane but also on the adjacent cell of the target lane. The proposed model is then compared to a conventional model using real world data from a lane drop bottleneck. It was observed that the proposed changes lead to better estimation of lane densities as compared to the conventional model. Future works include further testing against real-world/synthetic data for more robust comparison as well as more robust formulation for the computation of lateral flows to include factors which can capture a variety of lane changing scenarios.

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