A hybrid traffic flow model for large-scale federated networks

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1 INTRODUCTION

Traffic flow models are categorized as microscopic and macroscopic. Microscopic models focus on individual vehicle behavior, while macroscopic models consider aggregated behavior (Imai et al., 2024). These models are coupled forming a hybrid modeling approach to study various traffic dynamics (Leclercq, 2007) (Storani et al., 2022). However, the present hybrid approaches pose computational challenges, particularly in federated network level modeling.

Typically, urban traffic networks are segmented into zones, each exhibiting distinct traffic characteristics, modeled using zonal Macroscopic Fundamental Diagram (MFD) models (Kouvelas et al., 2017). Motorways, characterized by complex traffic dynamics such as shockwaves, are often modeled using macroscopic models (Imran et al., 2024).

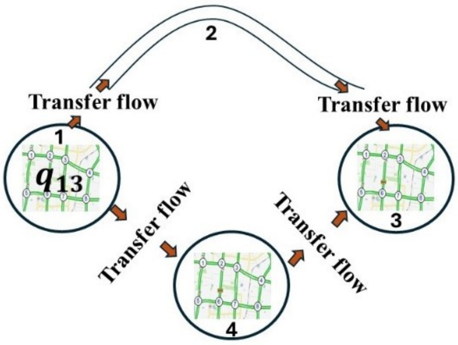

Figure 1 – *Schematization of the proposed hybrid approach*

This paper proposes a hybrid approach, integrating zonal MFD-based and a macroscopic model to simultaneously capture traffic dynamics across both urban zones and motorways (see Figure 1). This integration aims to provide a comprehensive understanding of traffic dynamics and facilitate improved traffic management strategies. Furthermore, the proposed approach is computationally efficient with a few modeling complexities, and it can be efficiently applied in traffic control applications.

2 METHODOLOGY

In the zonal MFD model, the total accumulation of zone i is computed as

$$n_i(k) = \sum_{j \in \mathcal{N}} n_{ij}(k), \tag{1}$$

where

$$n_{ii}(k+1) = n_{ii}(k) + T_p\left(q_{ii}(k) - M_{ii}(k) - \sum_{h \in \mathcal{N}_i} M_{ii}^h(k) + \sum_{h \in \mathcal{N}_i} M_{hi}^i(k) \right), \tag{2}$$

$$n_{ij}(k+1) = n_{ij}(k) + T_p\left(q_{ij}(k) - \sum_{h \in \mathcal{N}_i} M_{ij}^h(k) + \sum_{h \in \mathcal{N}_i} M_{hj}^i(k) \right). \tag{3}$$

$\mathcal{N} = 1, 2, .., N$ are the urban zones, $\mathcal{N}_i$ represents zones adjacent to i, $n_{ij}(k)$ is the number of vehicles in i destined for j, T_p is the time step. $q_{ij}(k)$ represents the demand from i to reach destination j. $M_{ii}(k)$ is the internal trip completion rate of i, while $M_{ij}^h(k)$ is the flow of vehicles from i to adjacent zone h, en-route to destination j (transfer flows).

The transfer flows M_{ij}^h is the minimum between the receiving capacity $C_{ih}(n_h(k))$ of the zone h and the sending flow from i to h, calculated as

$$M_{ij}^h(k) = \min\left(C_{ih}(n_h(k)), \theta_{ij}^h(k) \frac{n_{ij}(k)}{n_i(k)} \frac{P_i(n_i(k))}{L_i} \right), \tag{4}$$

and $M_{ii}(k)$ is computed as

$$M_{ii}(k) = \theta_{ii}(k) \frac{n_{ii}(k)}{n_i(k)} \frac{P_i(n_i(k))}{L_i}, \tag{5}$$

where, $\theta_{ij}^h(k)$ and $\theta_{ii}(k) \in [0, 1]$ are the route choices. Travel production, $P_i(n_i(k))$ is calculated using MFD function, and L_i is the zonal trip length. The motorway dynamics are computed employing the continuum model. The density dynamics are computed as

$$\rho_i^{n+1} = \rho_i^n + \frac{\Delta t}{\Delta x}\left(\rho_i^n(v_i^n - v_{i+1}^n)\right) + \frac{\Delta t}{\Delta x}\left(v_i^n(\rho_{i-1}^n - \rho_i^n)\right), \tag{6}$$

while the speed dynamics are

$if \ v_i^n \leq A$

$$v_i^{n+1} = v_i^n + \frac{\Delta t}{\Delta x}(A - v_i^n)(v_{i+1}^n - v_i^n) + \frac{\Delta t}{T}(V(\rho_i^n) - v_i^n), \tag{7}$$

else

$$v_i^{n+1} = v_i^n + \frac{\Delta t}{\Delta x}(A - v_i^n)(v_i^n - v_{i-1}^n) + \frac{\Delta t}{T}(V(\rho_i^n) - v_i^n), \tag{8}$$

where ρ and v is the density and speed, Δt and Δx are the time and road steps. i and n are the space and time indices, respectively. $V(\rho)$, the speed and density relation given by

$$V(\rho) = v_m . exp[-\frac{1}{c}(\frac{\rho_i^n}{\rho_{cr}})^c], \tag{9}$$

where v_m and ρ_{cr} represent the maximum speed and critical density, c is the shape factor, T is the relaxation time. "A" is the backward propagation speed of perturbation, which is

$$A = (L + \frac{v^2}{2dm} + v.\tau)/\tau, \tag{10}$$

where L, dm and τ are the average length of a vehicle, deceleration rate the transition time, respectively.

The proposed model's challenge lies in accurately modeling transfer flow between urban zones and the motorway. This approach addresses the heterogeneous nature of traffic characteristics and variables. Zone 1 transfer flow initiates the motorway's model, focusing on density and speed, while the zonal model emphasizes traffic accumulation. The urban zone capacity can exceed motorway's on-ramp capacity, necessitating careful transfer flow modeling. Specifically, transfer flow $M_{ij}^h(k)$ denotes the motorway influx, converted into the motorway's ingress density ($\rho_{\mathrm{on-ramp}}$) for establishing secondly initial conditions as

$$\rho_{on-ramp}(k) = M_{ij}^{h}(k)/v_{on-ramp}(k), \tag{11}$$

where $v_{onramp}(k)$ represents the speed of the on-ramp of the motorway, computed through (9).

3 NUMERICAL APPLICATIONS

3.1 Case study

The urban network is illustrated in Figure 1. It comprises four distinct traffic zones with unique traffic dynamics. Zones 1, 3, and 4 are urban zones, sharing identical topological characteristics, while the motorway, namely 2, is considered as extra-urban zone within the proposed hybrid approach. This network, although simplified, serves as a robust testbed for evaluating the efficacy of the proposed hybrid model in describing traffic dynamics across diverse traffic contexts. It is presumed that on average, vehicles traverse each urban zone over 3 km. Conversely, the motorway is a single-lane, and spanning over a length of 10 km. Traffic flow is generated in zone 1 with destination to 3 via motorway or 4. The simulation parameters are given in Table 1.

Table 1 - *Simulation parameters*

Parameter	Value
T_p	300 $[s]$
L_i	3000 $[m]$
Δt	1 $[s]$
Δx	100 $[m]$
v_m	36 $[\frac{m}{s}]$
ρ_{cr}	0.021 $[\frac{veh}{m}]$
c	2.3
T	15 $[s]$
L	4 $[m]$
dm	3.5 $[\frac{m}{s^2}]$
τ	1.5 $[s]$

3.2 Results

To validate the efficacy of the proposed model, simulations are performed. In scenario S_1, a triangular demand was simulated, thereby enabling observation of traffic flow propagation throughout the network as shown in Figure 2(a). Subsequently, in S_2, S_3, and S_4, capacity drops (CDs) were induced to assess the model's capacity to accurately replicate dynamics resulting from CDs, employing a constant demand profile.

In S_2, the CD was positioned at the on-ramp of the motorway, thereby impeding the flow between zone 1 and motorway. From Figure 2(b), when CD occurs, the overall accumulation decreases in the motorway. Consequently, the accumulation increases in zone 1 and 4, while it decreases in 3. In S_3, the CD was positioned at 9 km into the motorway. In Fig. 2(c), when CD occurs, the motorway accumulation increases, however, this impact is only limited to the motorway, after the CD, accumulation elevates in zone 3. In S_4, the CD was positioned on the link connecting the motorway and zone 3, affecting their interactions. In Fig. 2(d), when the CD occurs, accumulation in the motorway increases, while a decrease in zone 3.

The results demonstrate that the proposed model is able to simulate almost all kinds of traffic conditions and reproduce various traffic phenomena. Indeed, it can be used to design control strategies considering the dynamics of traffic flow in the federated networks and not only focusing on zone or only the motorway.

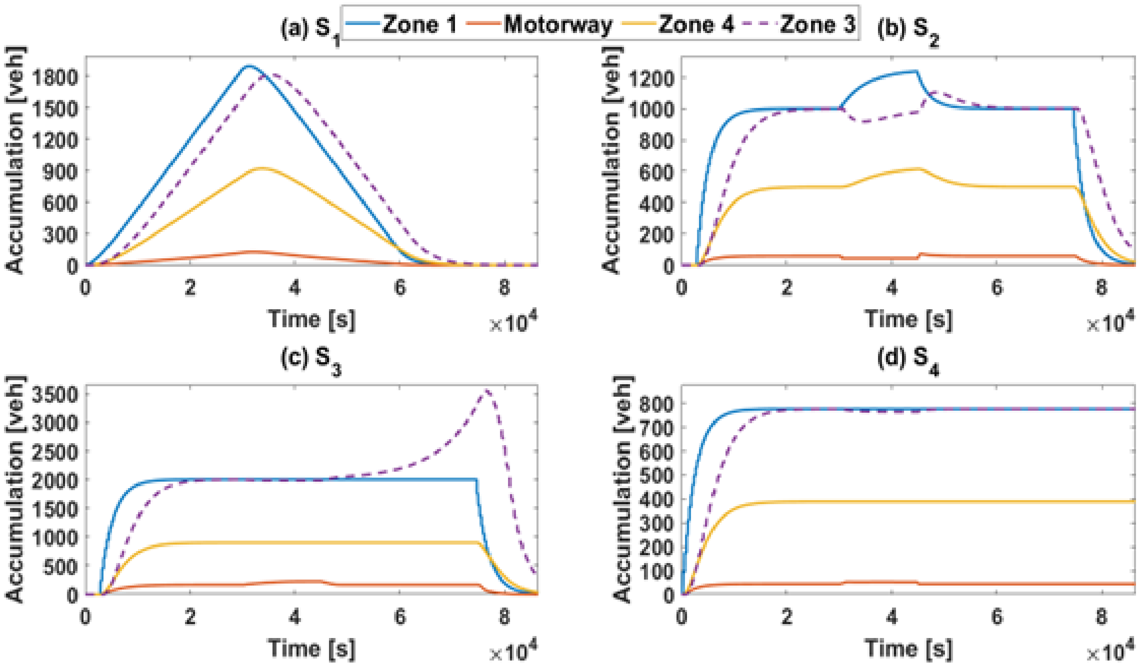

Figure 2 – *Zonal traffic accumulation with various demand patterns and settings.*

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