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STOPPED FRACTION AND CLOSURE FAILURE IN CONGESTED MACROSCOPIC FUNDAMENTAL DIAGRAMS: A SUMO-BASED SIMULATION STUDY

Tomoo Noguchi*

Waseda University, School of Social Sciences, Tokyo, Japan

*E-mail of the corresponding author: tomo@waseda.jp

Tomoo Noguchi 0009-0008-2222-7165

Resume

Congested macroscopic fundamental diagrams (MFDs) often display scatter since accumulation alone does not fully describe immobilization within stored traffic. In this paper, the stopped fraction, defined as the share of vehicles that are stopped or nearly stopped, is examined as a complementary macroscopic state variable. A compact analytical framework shows why accumulation-only closure can fail when stopped fraction varies at fixed accumulation. The mechanism is tested using the Simulation of Urban MObility (SUMO) platform on a stylized signalized grid. Adding stopped fraction reduces the root mean squared error (RMSE) from 41.32 to 18.79 overall, and from 55.84 to 23.40 in the congested regime, where R^2 rises from 0.8777 to 0.9785. Stopped fraction therefore provides a practical diagnostic for congestion states omitted from accumulation-only MFD representations.

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1 Introduction

Macroscopic fundamental diagrams (MFDs) provide a compact representation of urban network performance by relating aggregate variables, such as accumulation, flow and production [1-4]. Their practical appeal is that a complex urban traffic network can, under suitable conditions, be represented by a low-dimensional relation. If a network production can be written as a closed function of accumulation, then the network state can be summarized by the number of vehicles stored in the network.

This closure requirement is demanding. In congested regimes, scatter, hysteresis and instability are frequently observed in accumulation-production relations [5-9]. Such phenomena are often treated as empirical irregularities or measurement noise. In this paper, they are instead interpreted as symptoms of an incomplete macroscopic state description. Accumulation measures how much traffic is stored in the network, but it does not directly measure how much of that stored traffic is effectively immobilized by stopping, blocking or spillback.

The focus is placed on stopped fraction as a complementary state variable. The stopped fraction is the proportion of vehicles in the network whose speeds are below a small threshold. The central hypothesis is simple: two traffic states may have similar accumulation but different stopped fractions, and these differences can generate different production levels. In that case, an accumulation-only MFD may remain a useful first-order representation, but it is not fully closed in the congested regime.

The novelty of this paper lies in reframing congested MFD scatter as a closure problem caused by omitted immobilization information, and in positioning stopped fraction as a simple macroscopic state variable that exposes this missing dimension. Existing extensions of the MFD have emphasized spatial heterogeneity, multimodal interactions, delay relationships and richer network descriptions. Instead, emphasis is placed on stopped fraction, a directly interpretable indicator of the share of stored vehicles that is not effectively contributing to movement. This makes stopped fraction operationally attractive: it can be computed directly from microscopic simulation or full trajectory data, and

can be approximated from connected-vehicle trajectories or speed-based sensing data when sampling coverage is sufficient, without requiring full reconstruction of the spatial density field.

This framing yields three specific contributions to congested MFD analysis. First, a compact analytical representation that separates traffic storage from traffic immobilization in congested MFDs is provided. Second, a controlled microscopic simulation with SUMO is used to show that stopped fraction explains systematic residual variation left by an accumulation-only production model [10]. Third, it is demonstrated that the improvement is strongest in congested regimes and robust to alternative accumulation thresholds, establishing stopped fraction as a useful diagnostic state variable rather than merely an additional fitting variable.

The remainder of the paper is organized as follows. The relevant MFD literature is reviewed in Section 2, and stopped fraction is positioned within existing research. The analytical representation, SUMO simulation design and empirical model comparison are presented in Section 3. The simulation results and robustness checks are reported in Section 4. The interpretation, operational implications and limitations of the findings are discussed in Section 5. The main conclusions are summarized in Section 6.

2 Literature review

The MFD concept was developed to describe urban network performance at an aggregate scale [1-3]. Subsequent reviews have emphasized that MFD-based modelling has become a central framework for network-wide traffic state estimation, control and performance evaluation [4]. A well-defined MFD provides a basis for network-level monitoring and control, including perimeter control and gating strategies [11]. Analytical approximation methods have also been developed to derive MFDs from network structure and traffic-flow assumptions, and their performance has been evaluated using microscopic simulation and arterial-network settings [12]. The stopped fraction concept is also related to the classical two-fluid view of urban traffic, which distinguishes moving and stopped vehicles at the aggregate level [13]. The distinctive contribution here is not the use of stopped vehicles per se, but the use of stopped fraction as a macroscopic diagnostic variable for testing whether accumulation-only MFD closure omits immobilization information in congested states.

At the same time, empirical and simulation studies have shown that urban MFDs may exhibit scatter and hysteresis, especially when congestion becomes spatially uneven [5-9, 14]. A major explanation for MFD scatter is heterogeneity. Spatial variability in density can reduce effective network capacity and weaken the uniqueness of the accumulation-production relation [5, 7]. Other studies have examined the dynamics of heterogeneity,

hierarchical control and network partitioning [9, 15]. In signalized urban networks, local intersection dynamics and turning movements may also affect aggregate performance, which further motivates attention to microscopic mechanisms behind macroscopic scatter [16-17].

Extensions of the MFD have considered three-dimensional, multimodal and physically interpretable formulations [18-22]. More recent work has moved towards richer state descriptions and richer data sources. For example, MFD formulations with volume-delay relationships connect accumulation to network delay, while reviews of multimodal network macroscopic fundamental diagrams (NMFDs) emphasize observability, stability and data-fusion challenges in empirical calibration [23-24]. Data-rich studies based on drone trajectories, mobile observations and multi-source sensing further illustrate the value of measuring more than a single aggregate storage variable [25-26]. The MFD concept has also been extended beyond traffic production to network-level environmental performance, including emission-MFD relationships [27].

Microscopic simulation provides a controlled way to examine such mechanisms. SUMO is widely used as an open-source microscopic traffic simulator [10], and a comparison of open-source and commercial microsimulation platforms, including SUMO, was recently presented in this journal for traffic simulation case studies [28].

Taken together, the state of the art shows that MFD research has progressively enriched the description of network traffic through heterogeneity measures, multimodal formulations and increasingly detailed data sources. However, the specific role of stopped fraction as a compact diagnostic of accumulation-only closure failure remains underexplored. This gap is addressed by using stopped fraction as a diagnostic state variable to test whether accumulation-only closure suppresses relevant immobilization information in congested states.

3 Methodology

The analytical representation of the closure problem is introduced in this section, followed by a description of the SUMO simulation design and presentation of the empirical model comparison used to evaluate the diagnostic role of stopped fraction.

3.1 Analytical representation

Let $n \geq 0$ denote the network accumulation in vehicles, let $s \in [0,1]$ denote stopped fraction, and let P denote network production measured as total distance travelled per unit time over a given aggregation interval. Accumulation represents traffic storage. Stopped fraction represents the share of vehicles that

are stopped or nearly stopped. The moving component of accumulation is therefore

$$n^m = (1 - s)n. \quad (1)$$

If $v(n, s)$ denotes the effective per-vehicle productivity of the moving component, with units of distance travelled per vehicle per unit time, network production can be represented as

$$P = (1 - s)nv(n, s). \quad (2)$$

This representation separates two mechanisms. A higher stopped fraction directly reduces the number of effectively moving vehicles through $(1 - s)$, and it may also reduce the productivity of the moving component through $v(n, s)$.

An accumulation-only MFD assumes

$$P = f(n), \quad (3)$$

whereas the augmented representation considered here is

$$P = g(n, s). \quad (4)$$

The closure issue is whether the production is uniquely determined by accumulation. If two states have

the same n but different s , and if P varies with s as in Equation (2), then Equation (3) suppresses relevant state information. Stopped fraction is therefore interpreted as a complementary macroscopic state variable rather than a purely statistical regressor.

3.2 SUMO simulation design

A controlled microscopic simulation was conducted using Simulation of Urban MObility (SUMO). The use of an open-source microsimulation platform is consistent with recent transport-simulation applications that compare SUMO with commercial microsimulators and with urban-intersection studies that use microscopic traffic-flow parameters to examine delay at signalized intersections [17, 28]. The network was a synthetic 10×10 signalized grid with one lane per direction, 200 m link length and a speed limit of 13.9 m/s (Figure 1). The simulation horizon was 7200 s with a 1 s simulation step. Traffic demand followed three phases: a loading phase from 0 to 2400 s, a high-demand congested phase from 2400 to 4800 s, and a recovery phase from 4800 to 7200 s. Vehicles were generated by a Poisson process with time-varying demand and assigned to boundary-to-boundary trips across the grid. These choices define a stylized mechanism test rather than a fully specified benchmark instance: the network size, link length, speed limit,

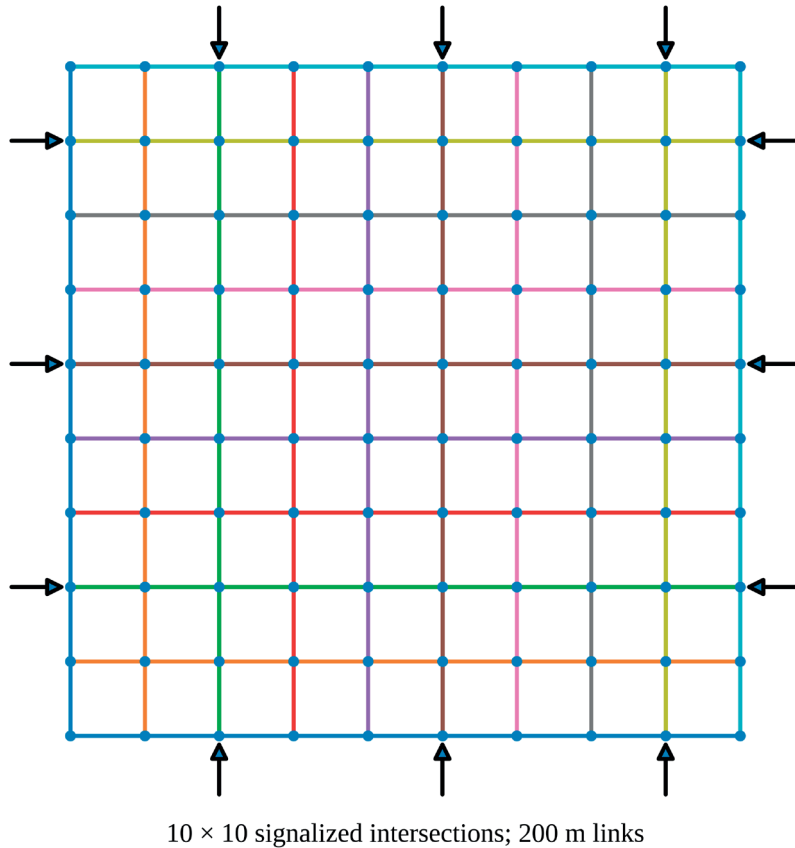


Figure 1 Schematic representation of the synthetic signalized grid implemented in SUMO, boundary arrows indicate the boundary-to-boundary demand structure; each link is 200 m long and has one lane per direction

simulation horizon, aggregation interval and demand phases are reported in the article, but reproducibility of the numerical trajectory from the manuscript alone is not claimed without the corresponding demand, route and signal input files.

The traffic states were aggregated every $\Delta t = 60$ s. Let T_t denote the set of 1 s simulation samples in aggregation interval t , with $|T_t| = 60$, and let V_τ denote the vehicles present in the network at sample τ , so that $N_\tau = |V_\tau|$. For each aggregation interval, accumulation was measured as the sample average number of vehicles in the network:

$$n_t = \frac{1}{|T_t|} \sum_{\tau \in T_t} N_\tau. \quad (5)$$

For samples with $N_\tau > 0$, the instantaneous stopped share was computed from the vehicles in V_τ ; when $N_\tau = 0$, this instantaneous share is defined as zero. Stopped fraction was then defined as

$$s_t = \frac{1}{|T_t|} \sum_{\tau \in T_t} \sigma_\tau, \quad (6)$$

$$\sigma_\tau = \begin{cases} \frac{|\{i \in V_\tau : v_{i,\tau} \leq 0.1m/s\}|}{N_\tau}, & N_\tau > 0, \\ 0 & N_\tau = 0, \end{cases}$$

where $v_{i,\tau}$ is the speed of vehicle i at simulation step τ . Let $V_t = \bigcup_{\tau \in T_t} V_\tau$ denote the set of vehicles present at least once during interval t . Network production was measured as a distance travelled per unit time:

$$P_t = \frac{1}{\Delta t} \sum_{i \in V_t} \Delta d_{i,t}, \quad (7)$$

where $\Delta d_{i,t}$ is the distance travelled by vehicle i inside the network during interval t . The unit of P_t is therefore distance per unit time. The resulting dataset contained 120 aggregated observations.

3.3 Model comparison

Two empirical specifications were compared. The accumulation-only model used a cubic polynomial in n :

$$f(n_t) = \beta_0 + \beta_1 n_t + \beta_2 n_t^2 + \beta_3 n_t^3. \quad (8)$$

The augmented model used the complete total-degree-three polynomial basis in n and s :

$$g(n_t, s_t) = \alpha_0 + \alpha_1 n_t + \alpha_2 s_t + \alpha_3 n_t^2 + \alpha_4 n_t s_t + \alpha_5 s_t^2 + \alpha_6 n_t^3 + \alpha_7 n_t^2 s_t + \alpha_8 n_t s_t^2 + \alpha_9 s_t^3. \quad (9)$$

The fitted relationships are $P_t = f(n_t) + \varepsilon_t$ and $P_t = g(n_t, s_t) + u_t$. The comparison is not intended as a structural calibration of Equation (2). Instead, it tests whether the stopped fraction contains systematic information about production that remains after conditioning on accumulation. Model performance was evaluated using in-sample R^2 and in-sample root mean

squared error (RMSE), so the reported values should be interpreted as diagnostic fit measures rather than out-of-sample prediction accuracy. Congested regimes were defined by upper-quantile subsets of accumulation.

4 Results

The simulation evidence is reported in this section, beginning with the baseline accumulation-production relation and followed by the model comparison, robustness to the congestion threshold, and the loading-recovery trajectory.

4.1 Accumulation-only scatter and stopped fraction

The production-against-accumulation plot for the 120 aggregation intervals obtained from the SUMO experiment is shown in Figure 2. The diagram exhibits the expected unimodal structure: production first increases with accumulation, reaches a maximum at an intermediate level, and then declines as the network becomes congested. This pattern confirms that the simulation generates a conventional MFD-like relation and provides a suitable basis for examining whether accumulation alone is sufficient to describe congested states.

Figure 2 also clarifies why a simple goodness-of-fit statistic can be misleading when the purpose is to evaluate closure. A smooth accumulation-production relation can be visually apparent even when observations with similar accumulation differ in their internal mobility conditions. The accumulation-only plane contains no information about whether the stored vehicles are moving continuously, repeatedly interrupted by signals, or immobilized by local queues. Therefore, the apparent compactness of the relation should be interpreted as a baseline representation rather than as evidence that no omitted state dimension remains.

The same observations are re-plotted in Figure 3, with each point colored by stopped fraction. This figure is central to the interpretation of the simulation results. If stopped fraction were only random noise with respect to production, no systematic organization of colors would be expected in the accumulation-production plane. Instead, the colored plot shows that stopped fraction varies across the simulated trajectory and that observations with higher stopped fraction tend to be located toward the lower side of otherwise comparable accumulation levels. The color pattern therefore reveals information that is hidden in Figure 2: part of the vertical dispersion in the MFD plane is associated with the extent to which the stored traffic is immobilized.

The visual comparison between Figures 2 and 3 is consistent with the analytical representation in Equation (2). At a given accumulation, a larger stopped

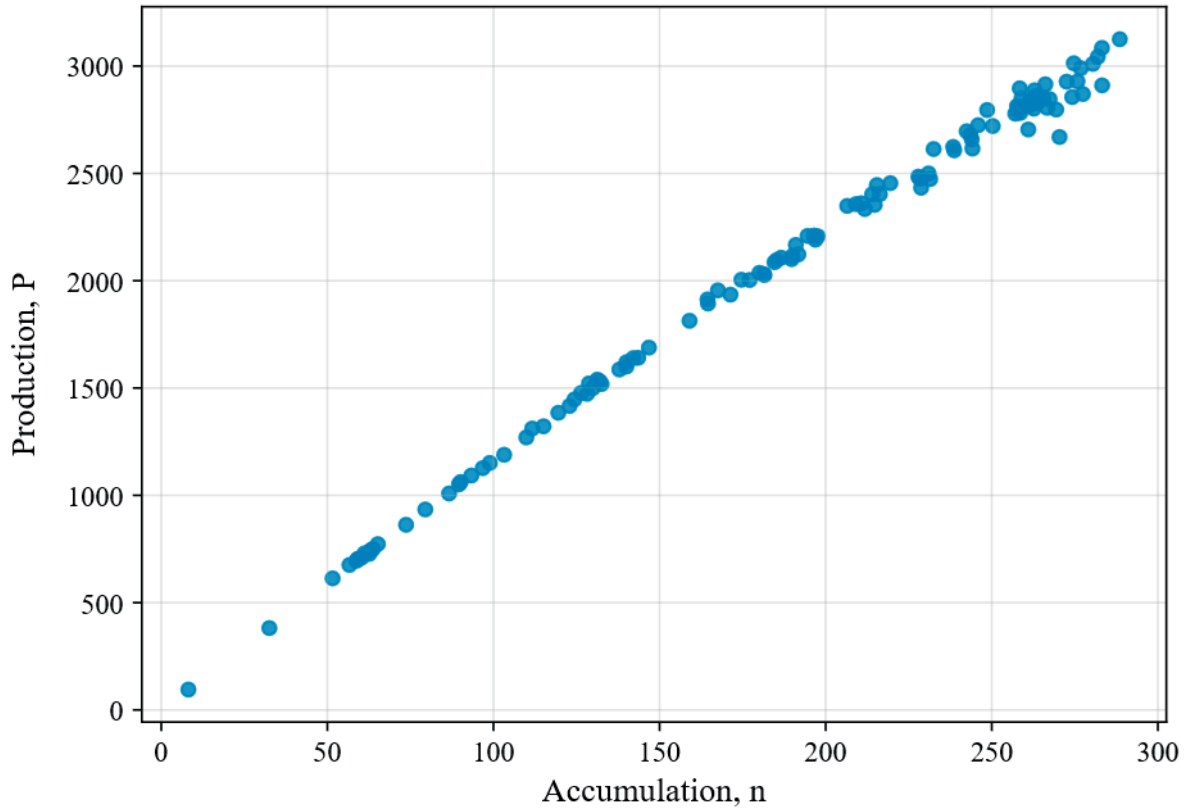


Figure 2 Accumulation-production diagram from the SUMO grid simulation, the figure provides the baseline accumulation-only MFD representation. It confirms that accumulation is a strong first-order descriptor, but it does not reveal differences in stopping conditions between the states with comparable accumulation

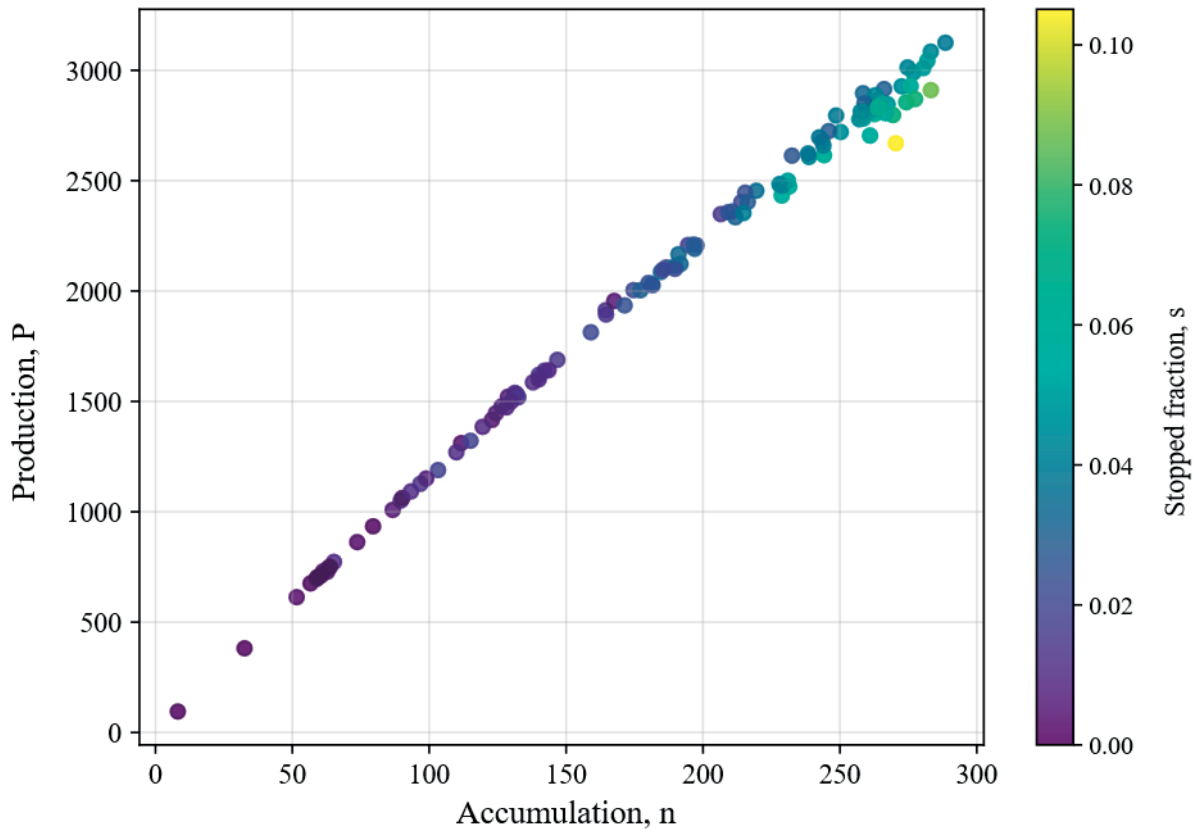


Figure 3 Accumulation-production diagram colored by stopped fraction, the color scale reveals a systematic immobilization dimension that is suppressed in the accumulation-only representation, higher stopped fractions tend to correspond to lower production between observations with comparable accumulation

fraction reduces the moving component of accumulation and may also reduce the effective productivity of the vehicles that remain mobile. The colored diagram does not by itself prove causality, but it provides a useful diagnostic indication that stopped fraction is not merely an auxiliary label attached after the fact. Rather, it appears to organize a residual dimension of the simulated MFD. This motivates the formal model comparison reported in the following subsection.

4.2 All observations and congested regime

A comparison of the accumulation-only specification $P = f(n)$ with the augmented specification $P = g(n, s)$ is provided in Table 1. The comparison should be read as a diagnostic test rather than a structural calibration exercise. Both models use flexible cubic polynomial terms, so the purpose is not to identify a unique behavioral law. The purpose is to ask whether stopped fraction contains systematic information about

production after accumulation has already been taken into account.

For all observations, the accumulation-only model achieves a very high explanatory power, with $R^2 = 0.9971$. This result is expected in a controlled grid simulation and confirms that accumulation remains the dominant aggregate descriptor of production. However, adding stopped fraction reduces in-sample RMSE from 41.32 to 18.79, corresponding to a 54.5% reduction. The improvement is therefore substantial even when the baseline model already fits the overall relation well. This is an important point for interpretation: the contribution of stopped fraction is not primarily to create an MFD where none exists, but to explain the part of production variation that remains unresolved after conditioning on accumulation.

The effect is more informative in the congested regime, defined here as observations above the 60th percentile of accumulation. In this subset, the accumulation-only model becomes much less adequate: its R^2 falls to 0.8777 and its RMSE increases to 55.84.

Table 1 Model comparison for all observations and the congested regime

Sample	Model	R^2	RMSE	Reduction
All observations	$P = f(n)$	0.9971	41.32	-
All observations	$P = g(n, s)$	0.9994	18.79	54.5%
Congested regime	$P = f(n)$	0.8777	55.84	-
Congested regime	$P = g(n, s)$	0.9785	23.40	58.1%

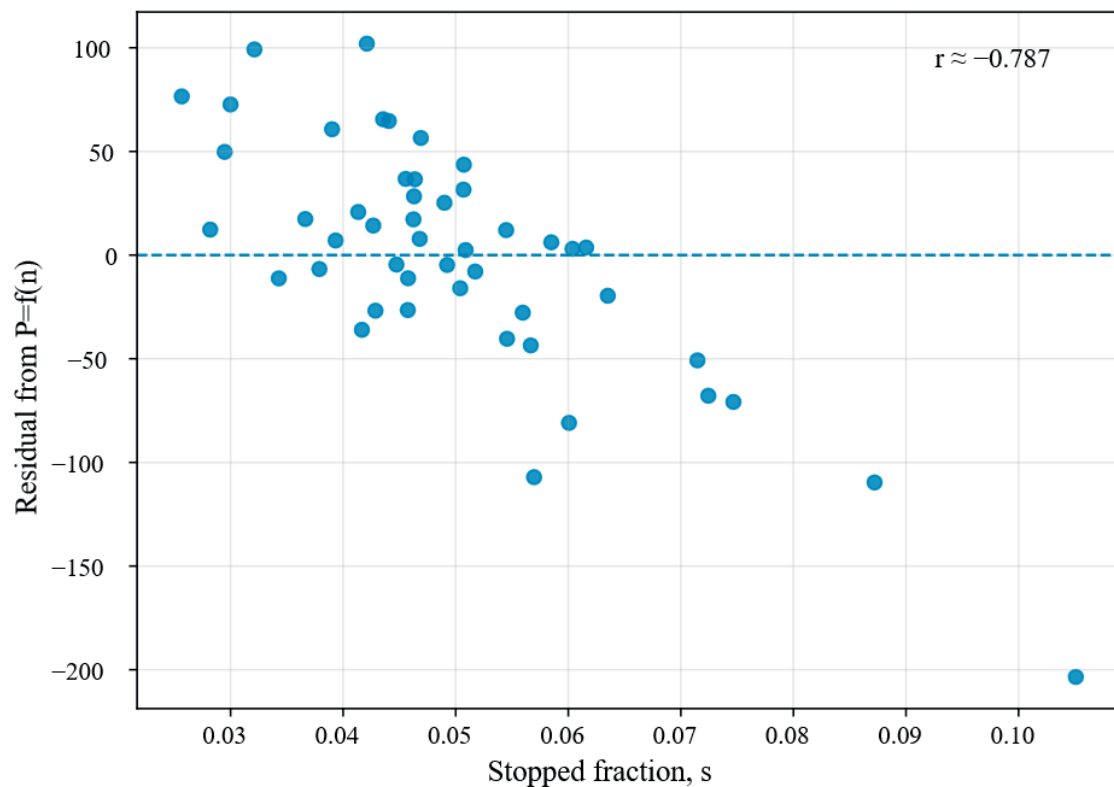


Figure 4 Residual diagnostics for the accumulation-only model in the congested regime, residuals are plotted against stopped fraction. The negative association indicates systematic overprediction for states with high stopped fraction

Table 2 Robustness to congestion threshold

Sample	R^2 f(n)	R^2 g(n,s)	RMSE f(n)	RMSE g(n,s)	Reduction
$n \geq Q_{50}$	0.9377	0.9902	56.35	22.31	60.4%
$n \geq Q_{60}$	0.8777	0.9785	55.84	23.40	58.1%
$n \geq Q_{70}$	0.6607	0.9381	59.58	25.45	57.3%

After the stopped fraction is added, R^2 rises to 0.9785 and in-sample RMSE falls to 23.40, corresponding to a 58.1% reduction. The contrast between the full sample and the congested regime is theoretically meaningful. It indicates that the limitation of accumulation-only closure is not uniform over all traffic states, but becomes more visible when the network is heavily loaded and stopping conditions become more variable.

The residual analysis provides a more direct diagnostic of the same mechanism. The residuals of the accumulation-only model are plotted against stopped fraction for the congested regime in Figure 4. A positive residual means that the accumulation-only model underpredicts production, whereas a negative residual means that it overpredicts production. The downward pattern therefore has a clear traffic interpretation: observations with higher stopped fraction tend to generate less production than would be expected from accumulation alone. In other words, accumulation-only modelling treats those states as comparable to other states with similar storage levels, but their greater immobilization makes them less productive.

The corresponding correlation is $r = -0.787$, indicating a strong negative association between stopped fraction and the residual component of production in the congested regime. This result is stronger than a simple improvement in fit because it identifies the direction of the omitted information. The high stopped fraction does not merely add arbitrary explanatory power; it is associated with lower-than-predicted production at a given accumulation, which is precisely the sign implied by Equation (2). The residual plot therefore shows that a meaningful part of accumulation-only scatter is not random noise but a systematic signature of omitted immobilization information.

4.3 Robustness to the definition of congestion

Since congestion is not a sharply defined state in aggregate data, the results should not depend on a single threshold. A robustness check in which the congested regime is defined by alternative upper-quantile subsets of accumulation is therefore reported in Table 2. The pattern is stable across all three definitions. When congestion is defined as observations above the 50th, 60th and 70th percentiles of accumulation, adding stopped fraction reduces RMSE by 60.4%, 58.1% and 57.3%, respectively.

The threshold comparison also reveals a second pattern. As the definition of congestion becomes more

restrictive, the explanatory power of the accumulation-only model deteriorates: R^2 falls from 0.9377 for $n \geq Q_{50}$ to 0.6607 for $n \geq Q_{70}$. This decline is consistent with the idea that accumulation becomes less sufficient as the analysis focuses on heavily congested states, where the same amount of stored traffic can correspond to different degrees of immobilization. By contrast, the augmented model remains substantially more accurate across all thresholds, with R^2 above 0.93 even in the highest accumulation subset. The robustness check therefore strengthens the main conclusion: stopped fraction is the most useful precisely in the regime where accumulation-only closure is most vulnerable.

4.4 Loading-recovery trajectory

Finally, the simulated loading-recovery trajectory provides a qualitative view of how the same mechanism can appear dynamically. The sequence of 60 s aggregation intervals is plotted in the accumulation-production plane in Figure 5, with the loading, congested and recovery phases distinguished. This figure is not intended as a formal test of hysteresis, since the experiment was designed primarily to diagnose the contribution of stopped fraction. Nevertheless, it is useful for interpreting why path dependence matters in congested MFDs.

During the loading phase, accumulation increases as demand rises. During the recovery phase, demand is reduced, but the network does not necessarily return immediately to the same internal state that characterized the corresponding loading accumulation. Queues, blocked movements and stopped vehicles may persist after total accumulation has begun to decline. Therefore, observations with comparable accumulation can occur in different phases of the experiment and can be associated with different production levels. This dynamic pattern is consistent with the broader interpretation of stopped fraction as an omitted state dimension: the accumulation coordinate alone records how many vehicles are present, but not how mobile those vehicles are at that point in the traffic history.

5 Discussion

The results should not be read as evidence that accumulation is unimportant. On the contrary, the accumulation-only model explains much of the overall variation in production. This is consistent with the

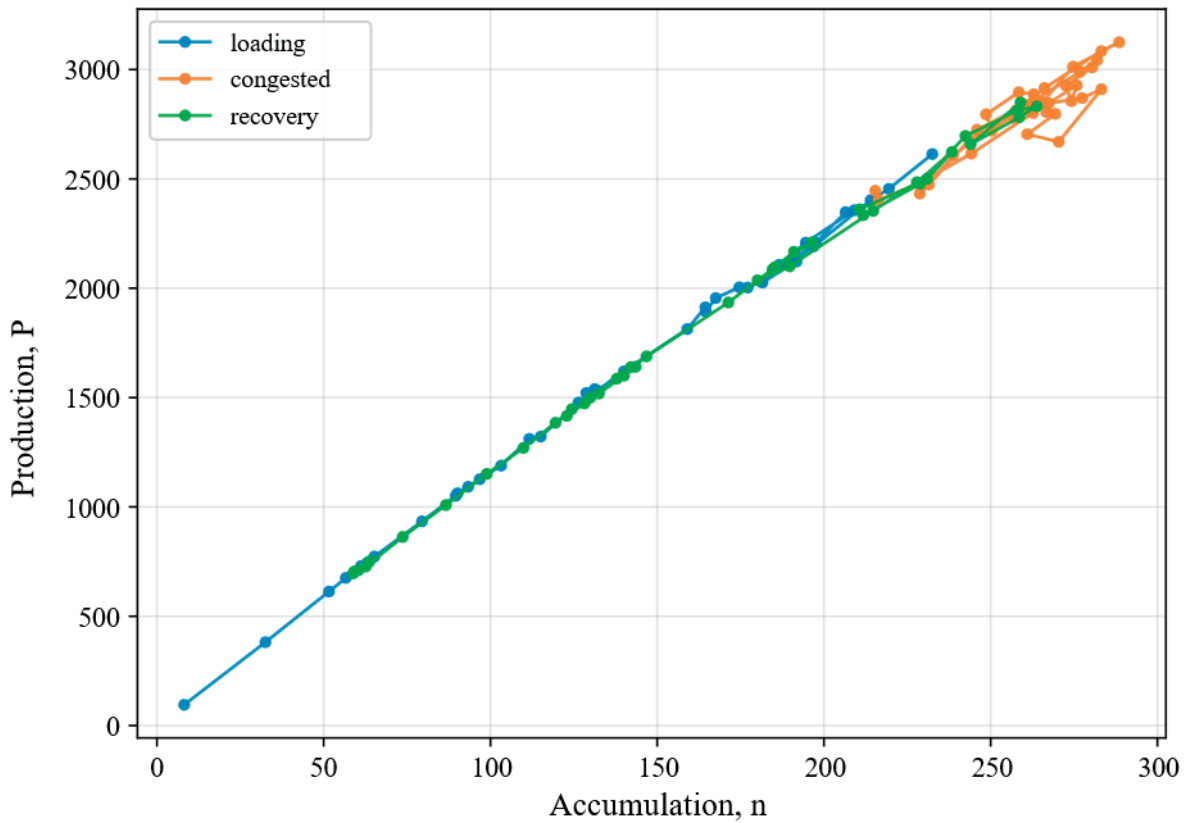


Figure 5 Loading-recovery trajectory in the accumulation-production plane; a supplementary visualization of phase-dependent movement in the simulated MFD is provided, illustrating why congested observations should not be interpreted solely through accumulation

basic MFD premise. The key finding is more specific: in congested regimes, the remaining production variation is systematically related to stopped fraction. Accumulation provides a strong first-order description, while stopped fraction captures an omitted immobilization dimension.

From an operational perspective, the value of stopped fraction lies in its simplicity. Unlike detailed spatial heterogeneity measures, it can be computed directly when vehicle speeds are observed for the relevant vehicle population, and it can be approximated from connected-vehicle monitoring or other speed-based diagnostics when the sample is sufficiently representative. This operational feature is important because the proposed variable is not intended as an abstract fitting device, but as a measurable indicator of the extent to which stored traffic is no longer producing movement.

This interpretation is consistent with the analytical representation in Equation (2). At a fixed accumulation, a higher stopped fraction reduces the effective moving component of traffic and may also reduce the productivity of moving vehicles. When such a variation is projected onto the accumulation-production plane, it appears as vertical scatter. Conditioning on stopped fraction does not necessarily yield complete closure, because other omitted dimensions such as spatial queue distribution, signal coordination and route concentration may also matter. The simulation results demonstrate that stopped

fraction captures a meaningful component of the omitted state information.

The loading-recovery trajectory in Figure 5 further shows that the omitted state information is not only cross-sectional but also dynamic. Similar accumulation values may appear during different phases of the simulated experiment, while stopped conditions and production need not coincide. This is consistent with the broader view that hysteresis-like patterns in congested MFDs can arise when the projected accumulation-production plane suppresses path-dependent immobilization.

The simulation design is intentionally stylized. The synthetic grid does not represent a calibrated real city, and the demand profile was selected to generate loading, congestion and recovery under controlled conditions. This is a limitation with respect to external validity and reproducibility from the manuscript alone, because the exact numerical trajectory also depends on simulation input files such as the demand realization, route assignment and signal program. The objective was not to provide a transferable calibrated benchmark, but to determine whether the proposed closure-failure mechanism can emerge under microscopic vehicle dynamics. Future work should examine whether the same pattern appears in calibrated urban networks and empirical trajectory datasets.

6 Conclusions

Stopped fraction was examined as a complementary macroscopic state variable for congested MFDs. The analytical argument is that accumulation measures traffic storage but not traffic immobilization. If states with similar accumulation differ in stopped fraction, production need not be fully determined by accumulation alone. Stopped fraction therefore provides a direct way to distinguish stored traffic that remains mobile from stored traffic that is effectively prevented from contributing to production.

A controlled SUMO simulation supported this mechanism quantitatively. Across all 120 observations, adding stopped fraction reduced in-sample RMSE from 41.32 to 18.79, a 54.5% reduction. In the congested regime defined by observations above the 60th percentile of accumulation, R^2 increased from 0.8777 to 0.9785 and RMSE fell from 55.84 to 23.40, a 58.1% reduction. The residuals of the accumulation-only model were strongly negatively correlated with stopped fraction in this regime ($r = -0.787$), showing that high-stopping states systematically produced less movement than accumulation alone would predict. The result was robust to alternative congestion thresholds: RMSE reductions ranged from 57.3% to 60.4% for the 50th-70th percentile definitions. These findings indicate that a part of the scatter in congested MFDs is a projection effect caused by omitted immobilization information rather than purely random noise.

The practical implication is that MFD-based monitoring and control may benefit from recording not only accumulation but also the proportion of vehicles that are nearly stopped. Such information can be derived

directly from microscopic simulation or full trajectory data, and can be approximated from connected-vehicle trajectories, probe-vehicle speeds or other speed-based sensing systems when their sampling coverage is adequate for estimating a stopped share. A principal limitation is the use of a synthetic grid network and a controlled demand profile rather than a calibrated real city. Future work should test the same relationship in empirical datasets, under alternative signal-control settings and across larger networks with spatially heterogeneous demand. By making immobilization observable at the macroscopic level, stopped fraction offers a compact way to extend accumulation-based MFD analysis in the regime where closure is most vulnerable. Thus, stopped fraction should be viewed not as a replacement for accumulation, but as a low-cost complementary state variable that helps diagnose when and why accumulation-only MFD representations lose closure under congestion.

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Conflicts of interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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