Traffic Density as The Governing Parameter of Urban Roadway Performance in Mixed Traffic

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Abstract

Traffic density refers to the number of vehicles on a road at a given time. It is the most important element in how effectively motor traffic flows. In this study, traffic density is considered as the dependent variable, while traffic flow and space-mean speed are the measured variables. The density is derived from the basic traffic flow relationship and serves as the primary explanatory variable. This is done by leveraging data already collected in the field. To determine critical density, highway capacity, and congestion regimes, we use density-based flow-density and speed–density correlations. The findings suggest that density provides a more consistent and physically meaningful framework for assessing capacity and congestion than either speed or flow alone.

Keywords: Traffic density, independent variable, Critical density, Urban traffic

1. Introduction

Speed, flow, and density are usually studied together in urban traffic. People often talk about speed and flow, but these are not direct signs of how vehicles interact with one another. They are instead the result of the existing traffic conditions. Traffic density, which is the number of cars on a certain length of road, directly affects how cars interact with each other and how well they work.

In this research, traffic density is treated as the dependent variable, as it reflects the fundamental condition of traffic on a route. Variations in flow and speed are seen as reactions to variations in density. This density-focused viewpoint facilitates more precise identification of capacity conditions, the onset of congestion, and shifts in traffic regimes.

The aim of this research is to evaluate urban traffic behaviour by utilizing density as the controlling variable and to investigate its impact on flow and speed through empirical field data.

2. Data Description

The dataset consists of observed hourly traffic flow (veh/h) and corresponding space-mean speed (km/h) collected under varying traffic conditions, ranging from free flow to heavy congestion. The data reflect realistic urban traffic behaviour with wide fluctuations in both flow and speed.

Traffic density is not directly measured in the field; rather, it is analytically derived from observed traffic speed and flow data and subsequently used for further analysis.

3. Density as a Derived (Dependent) Variable

Traffic density k is computed using the fundamental traffic flow relationship:

$$k = \frac{q}{v}$$

where:

k = traffic density (veh/km) — derived dependent variable,

q= traffic flow (veh/h) — measured variable,

v= space mean speed (km/h) — measured variable.

Since density is computed from observed speed and flow data, it is treated as a dependent variable in this study. The derived density values are subsequently used to analyze traffic flow and speed characteristics and to develop flow–density and speed–density relationships.

Analytical Approach:

The following density-based relationships are analyzed:

- Flow–Density relationship to identify critical density.
- Speed–Density relationship to examine performance degradation with increasing density.

Critical density is the density at which the maximum sustainable flow occurs.

4. Results and Density-Based Analysis

4.1 Flow as a Function of Density

The flow–density relationship (Figure 1) illustrates how traffic flow responds to increasing density. At low density levels, flow increases with density, indicating efficient utilization of roadway space. In this regime, density increases primarily reflect higher demand without significant interference among vehicles.

As density increases, the flow rate increases and then diminishes, and a maximum flow rate is observed at a specific density, referred to as the critical density. Beyond this point, further increases in density result in a reduction in flow, even though more vehicles are present on the roadway. This behaviour highlights density as the governing factor behind capacity and congestion formation.

The maximum observed flow represents the highest short-term discharge recorded within a 5-minute interval. However, this peak flow does not necessarily correspond to optimal operating conditions, as it may occur during platoon discharge at low speeds.

4.2 Speed as a Function of Density

The speed–density relationship (Figure 2) shows a strong inverse relationship between speed and density. At low densities, vehicles operate at high speeds due to minimal interaction and ample manoeuvring space.

As density increases, speed decreases steadily as inter-vehicular spacing reduces and driver freedom becomes constrained. At high density levels, speed drops sharply, indicating congested conditions with frequent interruptions and unstable traffic flow. This result reinforces the idea that speed varies by density conditions.

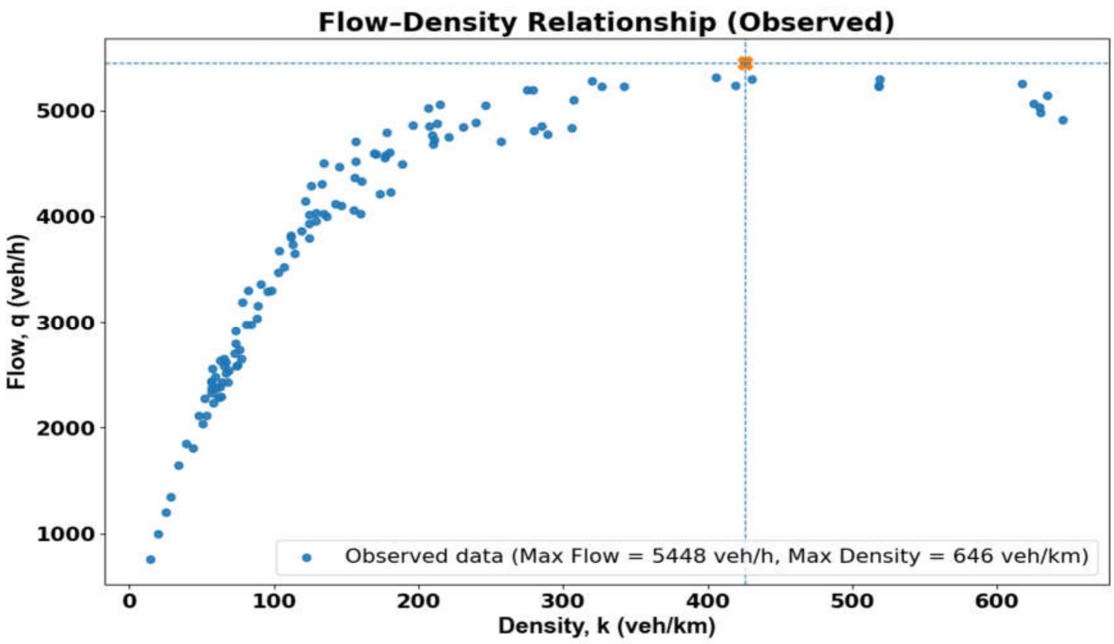

Figure 1: Flow-Density relationship of urban road.

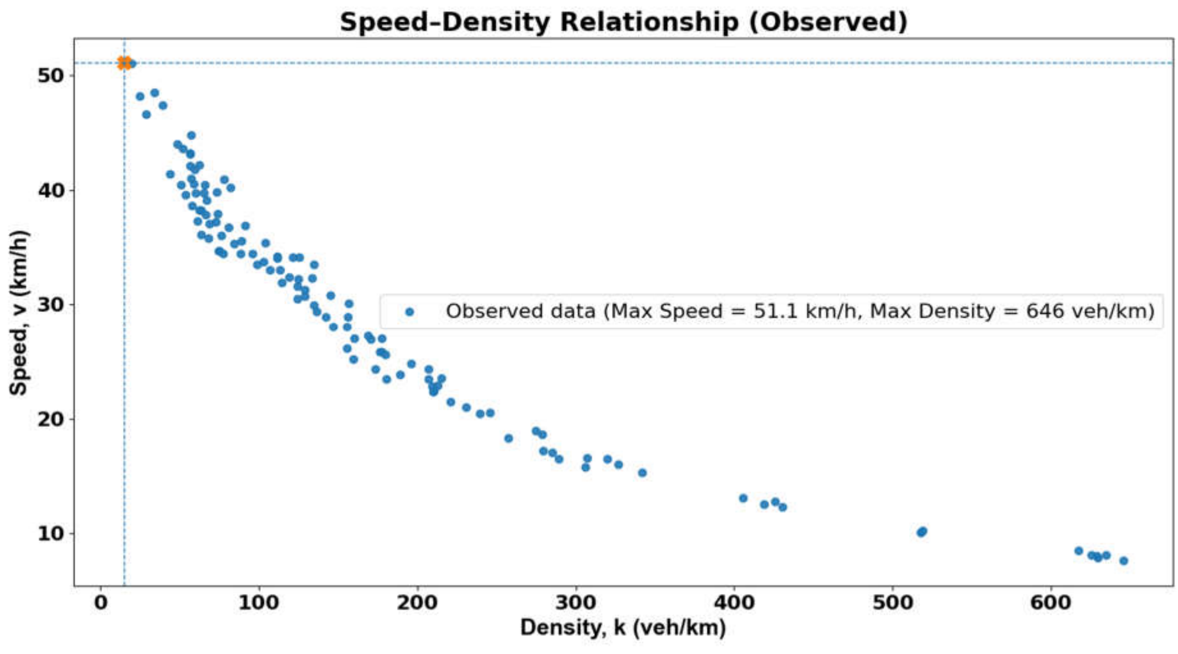

Figure 2: Speed-Density relationship of urban road.

4.3 Density-Based Traffic Regimes

Using density as the independent variable, three distinct traffic regimes can be identified:

- **Low-density regime:** High speed and increasing flow (stable traffic).
- **Critical-density regime:** Maximum flow and transition to instability.

- **High-density regime:** Low speed and declining flow (congested traffic).

These regimes demonstrate that density alone can effectively characterize traffic operational states.

5. Discussion

Treating density as the independent variable provides a clearer physical interpretation of traffic behavior. Unlike flow, which may remain high under queued conditions, density directly reflects congestion severity and space occupancy.

The results show that roadway capacity is more accurately associated with critical density than with peak observed flow alone. This is particularly important in urban environments where bottlenecks, signals, and interruptions can produce high flows at low speeds, potentially misleading capacity assessments if density is not considered.

6. Conclusions

This study adopted a density-centric framework, explicitly treating traffic density as the independent variable governing traffic performance. The key conclusions are:

1. Traffic density effectively explains variations in both flow and speed.
2. Speed degradation is primarily driven by increasing density.
3. Density-based analysis provides a robust basis for congestion identification and traffic regime classification.

The findings highlight the importance of explicitly incorporating density into traffic operational analysis and urban roadway planning.

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