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The Higher Order Macroscopic Traffic Flow Models in Reproducing Stop-And-Go Phenomenon: Systematic Review

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Abstract: In large scale cities, traffic congestion is a common problem faced by drivers on the road especially during rush hour. Macroscopic traffic models are crucial in understanding the traffic phenomenon from an overall view. However, the first order Lighthill-Whitham-Richards (LWR) models are unable to capture a variety of real-world traffic patterns. This research aims to review the higher order LWR models in reproducing the stop-and-go phenomenon and assess their performance. A systematic review of the higher-order macroscopic traffic flow models was conducted to assess the models' performance and capability in reproducing stop-and-go phenomenon with the aid of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. There was a total of five papers selected for this review that fulfilled the inclusion criteria. Based on the findings of each paper, we concluded that the stop-and-go phenomenon was successfully reproduced by the improved macro models by considering different factors including road capacity, anticipation optimal velocity, the existence of ramps, moving, and static bottlenecks.

Keywords: Systematic Review, PRISMA, Macroscopic, Traffic Model, Stop-and-Go

1. Introduction

Currently, traffic problems are a severe issue in many countries because of the growing world population. When vehicles interact with one another, there is a rapid change in traffic which can lead to traffic congestion. Traffic flow modeling is carried out to study interactions between vehicles in order to produce efficient management of traffic [1]. Traffic flow model had been developed many years and it can be categorized into microscopic, mesoscopic, and macroscopic.

Microscopic models describe traffic flow from the point of individual vehicles and are capable of capturing the motion of and interaction among these vehicles [2]. Macroscopic models consider the traffic flow like a fluid and they are effective in describing the whole phenomena of the traffic flow since the models considered the aggregated quantities such as density, flow, or mean speed [3].

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Mesoscopic traffic flow models were developed to fill the gap between the microscopic models and the macroscopic models [4].

In traffic flow data, there can be noticed special patterns, known as phenomena. The goal of a traffic flow model is to reproduce or predict these patterns [4]. With the increased availability of detailed traffic data, numerous traffic flow phenomena which are complex and nonlinear have been identified and analyzed, including capacity drop, traffic hysteresis, or stop-and-go waves [5].

In this research, macroscopic models are considered since it has the highest aggregated level focusing on the average traffic flow characteristics. Although the first macroscopic traffic flow model namely Lighthill-Whitham-Richards (LWR) model [6] able to describe the formation, propagation, and evolution of shock [8], but the model is unable to reproduce the complex traffic phenomena. This research aims to review the higher order LWR models in reproducing the stop-and-go phenomenon and assess their performance. A systematic literature review of the higher order macroscopic traffic flow models in reproducing the stop-and-go phenomenon is conducted using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The quantitative synthesis of a meta-analysis is not included in this systematic review, we only focus on qualitative synthesis.

1.1 Stop-and-go phenomenon

During congestion, drivers may occasionally observe waves of traffic travelling with alternating slowdowns and speedups. These traffic instabilities are also known as stop-and-go waves, sometimes termed “oscillations” [4]. Predicting the formation and propagation of stop-and-go waves can be useful in some scenarios, such as warning drivers that a stop-and-go wave is approaching [4].

If the driver of the leading vehicle brakes slightly and continues to drive slowly, the driver of every following vehicle will also need to brake to avoid collision with the leading vehicle. As the following vehicle approaches the leading vehicle, the new distance gap to the leader may be smaller than the new safety gap. Hence, the following vehicle will have to reduce its speed further in order to regain its desired gap. This forces the next driver to brake more firmly. This mechanism continues until the drivers come to a temporary complete standstill. As a result, a stop-and-go wave has emerged [3].

1.2 Macroscopic traffic flow model

In 50’s, the first macroscopic model proposed independently by Lighthill and Whitham and Richards was LWR model [6]. This is a simple continuous traffic model that consists of a conservation equation and fundamental diagram as follows:

$$\begin{aligned} &\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=0 \\ &q=k\cdot v \end{aligned} , \qquad Eq.\ 1$$

where k is vehicle density, t is time, v is vehicle velocity, x is space, and q is flow. The main drawback of LWR model is that the vehicles are assumed to adjust their speeds to desired speeds instantaneously under equilibrium flow conditions [9].

In order to overcome the weaknesses of first order LWR models, higher order models were developed with an additional velocity dynamic equation. Payne and Whitham develop the first continuous second order model, known as Payne–Whitham (PW) model [9,10] and the velocity dynamic equation is

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+\frac{C_0^2}{k}\frac{\partial k}{\partial x}=\frac{v_e(k)-v}{\tau} , \qquad Eq.\ 2$$

that includes three terms which are convection, anticipation, and relaxation. The convection term

$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}$ describes the changes in speed due to the ingress and egress of vehicles while anticipation term $\frac{C_0^2}{k}\frac{\partial k}{\partial x}$ describes the driver spatial adjustment to traffic conditions. C_0^2 is the parameter of driver spatial adjustment. $\frac{v_e(k) - v}{\tau}$ is the relaxation term that describes speed adjustments due to forward conditions where $v_e(k)$ is the equilibrium velocity based on density and τ is the reaction time. PW model improved the LWR model considering the effects of acceleration and inertia and it is famous for capturing stop-and-go traffic in which vehicles oscillate between fast-moving and slow-moving states, rather than maintain a steady state [11].

However, Dagnzo [12] points out, the fluid kinematic theory applied in PW model cannot be applied to model vehicular flow because fluid flow is isotropic whereas vehicular flow is anisotropic. Another criticism of Payne model is the characteristic speed that is higher than the flow speed. As a limitation, the PW model may introduce negative velocities allowing the vehicles to drive backward. Aw and Rascle [13], Zhang [14,15], and Jiang, Wu, and Zhu [16] attempted to overcome the wrong-way travel problem by modifying the anticipation term in Payne model.

2. Materials and Methods

This systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.1 Review Protocol

Review protocols specified the things that researchers want to consider and include in their review. The scope in this study focused on the macroscopic traffic flow model in reproducing the stop-and-go phenomenon which has not been explored in other systematic reviews [17].

Once the research scope was determined, research question was formulated and should be answered in the final systematic review report [18]. The research question was developed based on PICOC criteria which include the components: population, intervention, comparison, outcomes, and context [19,20].

Table 1: PICOC for Research Questions

Population	Higher order
Intervention	Traffic flow model
Comparison	Model Performance
Outcomes	Stop-and-go phenomenon
Context	None

The defined research questions were:

Q1: What kind of higher order macroscopic traffic flow model is involved in reproducing the stop-and-go phenomenon?
Q2: How does the numerical simulation of macroscopic traffic flow model is carried out?
Q3: What is the performance of these macroscopic traffic models in reproducing the stop-and-go phenomenon?

2.2 Search Strategy

The search strategy from databases namely Scopus, IEEE Xplore, and Google Scholar were performed until December 2021. The search terms in title and abstract used for each database were ("macroscopic" OR "macro") AND ("traffic" OR "traffic flow" OR "traffic stream" OR "road traffic") AND ("model*") AND ("phenomen*" OR "stop and go" OR "traffic oscillations" OR "instability*"). The search strategy yielded 461 records from Scopus, 72 records from IEEE Xplore, and 100 records from Google.

2.3 Study Selection

The study selection involved screening of search results for selecting those papers that were relevant according to this review. For this process to be systematic and repeatable, a set of predetermined inclusion and exclusion criteria was used [21].

The inclusion criteria determined which of these studies should be included in the relevant research set. The inclusion criteria were as follows [22]:

1. The research work that has been selected is only those articles in which macroscopic traffic models that are capable of reproducing the stop-and-go phenomenon.
2. The range of publication years that has been chosen is from 2012 to 2021.
3. Studies published in English only were taken into deliberation.
4. Only research articles are selected instead of survey or review articles.

The exclusion criteria were applied to selected studies in order to identify those that do not fulfill further requirements. The exclusion criteria were as follows [22]:

1. The research articles with titles and abstracts that do not match the domain were rejected.
2. The research articles published before 2012 were rejected.

There is a possibility that the same research article can appear in multiple databases. Therefore, all papers obtained from the search strategy were filtered out by a free and open-source reference management software, Zotero to remove the duplicates. Out of the duplicated articles, only one was considered, and the others were excluded. Then, by screening the title and abstract, the potentially relevant papers were selected from the databases. Any papers that did not fit the inclusion criteria were excluded. The last step was to scan the full-text articles and assess the studies' eligibility [23].

2.4 Data Organization and Reporting

The information acquired from each study was arranged particularly according to the data about the research title, author’s name, year of publication, and objective of studies. The inclusion studies were reported according to PRISMA guidelines. Figure 1 shows the PRISMA flowchart of search strategy and selection process.

After searching three different databases, 633 papers were found. 540 articles were found after eliminating duplicates. Afterwards, 523 articles were rejected because they did not fulfill the inclusion criteria and 15 articles were downloaded and re-evaluated again for the qualification. Papers that lacked clear understanding of the macroscopic traffic model in reproducing the stop-and-go phenomenon were manually removed from main reading. Finally, only five of the papers were considered for this systematic review [23].

2.5 Data Analysis

In this stage, any data that assist in answering the research questions were extracted and classified to derive knowledge and conclusions. In this review, the performance of the macroscopic traffic flow model in reproducing the stop-and-go phenomenon was assessed based on the discussion on their findings, model structure, and numerical simulation [17].

2.6 Data Demonstration

The final phase of the systematic literature review process entailed writing up the results in a format suitable for the target audience. The results were documented in a systematic review report [24].

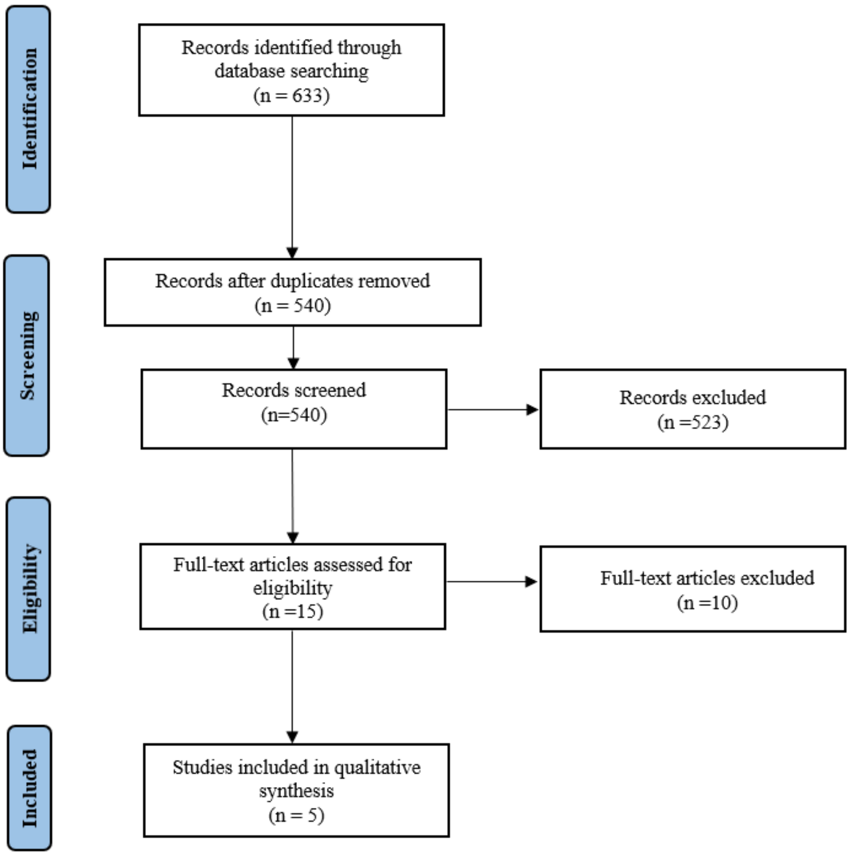

Figure 1: PRISMA flowchart of search strategy and selection process

3. Results and Discussion

3.1 Results

Table 2 indicates the studies selected in systematic literature review. Every study proposed the macroscopic models considering different effects such as road capacity, existence of ramps, anticipation optimal velocity, static and moving bottlenecks.

Table 2: Selected studies in systematic literature review

Studies	Author	Findings
A macro traffic flow model accounting for road capacity and reliability analysis	[25]	Road capacity destroyed the stability of uniform flow and produce stop-and-go traffic under the moderate density
A novel macro model of traffic flow with the consideration of anticipation optimal velocity	[26]	The higher initial densities produced multiple clusters which corresponding to the stop-and-go traffic
An Improved Macro Model of Traffic Flow with the consideration of ramps and numerical tests	[27]	The ramp produced stop-and-go traffic when the main road density is between two critical values

Impacts of moving bottlenecks on traffic flow	[28]	The moving bottleneck had negative influences on the evolution of uniform flow and small perturbation which leads to the occurrence of stop-and-go traffic under the moderate initial density
Effects of static bottlenecks on traffic flow in urban road network	[29]	The static road bottlenecks with various configurations produced stop-and-go traffic phenomenon under the moderate density

Table 3 shows the macroscopic traffic flow models for the studies selected in this systematic review. Shi et al. [27] proposed a macro model based on GK model which includes a viscous term while the models of another four studies [25, 26, 28, 29] were based on model proposed by Jiang [16].

Table 3: Macroscopic traffic flow models

Model Category	Macroscopic Traffic Flow Models		Author
Anisotropic–viscous models	$\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=s(x,t)$ $\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{1}{\tau}\cdot[v_e(k)-v]+\frac{1}{\tau}\cdot v_e{'}(k)[\frac{1}{2k}\frac{\partial k}{\partial x}+\frac{1}{6k^2}\frac{\partial^2 k}{\partial x^2}$ $-\frac{1}{2k^3}(\frac{\partial k}{\partial x})^2]-2\beta c(k)\frac{\partial v}{\partial x}$	*Eq.* 3	[27]
Anisotropic–inviscid models	$\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=0$ $\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_e(k)-v}{\tau}+c_0\frac{\partial v}{\partial x}+G_1$	*Eq.* 4	[25]
	$\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=0$ $\frac{\partial v}{\partial t}+(v-c_0)\frac{\partial v}{\partial x}=\frac{v_e(k)-v}{T}+\alpha v_e^{'}\frac{\partial k}{\partial t}+\frac{\tau}{T}\frac{c_0}{2}v_e^{'}\frac{\partial k}{\partial x}$	*Eq.* 5	[26]
	$\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=0$ $\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_e(k)-v}{\tau}+c_0\frac{\partial v}{\partial x}+G$	*Eq.* 6	[28]
	$\frac{\partial k}{\partial t}+\frac{\partial (kv)}{\partial x}=0$ $\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}=\frac{v_e(k)-v}{\tau}+c_0\frac{\partial v}{\partial x}+F$	*Eq.* 7	[29]

Shi et al. [27] proposed an improved macro model for traffic flow on a highway with ramps based on the Gupta–Katiyar (GK) model [30] as in Eq. 3. This model incorporated flow generation rate, $s(x,t)$ into the conservation equation to study the impact of ramps on the traffic dynamic as

$$s(x,t)=\begin{cases}\frac{q_{ramp}}{L_{ramp}} & \forall x\in\Omega_{ramp}, \\ 0 & \text{else}\end{cases} \qquad Eq.\ 8$$

where Ω_{ramp} is the region of the ramp, L_{ramp} is the length of the ramp, and q_{ramp} is the total ramp flow.

Tang [25], Ou and Tang [28], and Mahona et al. [29] developed the extended macro-model based on Speed Gradient (SG) model [16] by incorporating different factors into the velocity dynamic equation as shown in Eq. 4, Eq. 6 and Eq. 7 respectively. For instance, the factors added for Tang [25], Ou and Tang [28], and Mahona et al. [29] were friction effect resulted by a queue, G_1, friction effect caused by moving bottleneck, G and friction effect caused by static bottlenecks, F respectively. These three factors can be defined as

$$G_1 = -\varepsilon \frac{\max\{0, kv - C\}}{L} kv, \qquad Eq.\ 9$$

where L is the length of the range that the queue affects traffic flow, C is road capacity, and ε is the friction coefficient.

$$G = -\mu skv, \qquad Eq.\ 10$$

where μ is the frictional coefficient, $s = q / L_0$ (L_0 is the length of the moving bottleneck while q is the flow rate caused by the moving bottleneck).

$$F = \begin{cases} -b\Delta t k_{in} v_f (1 - \frac{k_{in}}{k_{jam}}) \\ \text{else} \\ 0 \end{cases}, \qquad Eq.\ 11$$

where b is impedance coefficient which indicates the disturbances to the vehicle flow caused by bottleneck, k_{in} is initial density, v_f is free-flow vehicle speed, k_{jam} is critical density at the road section and Δt is the change in time.

Peng et al. [26] developed a macro traffic model considering the anticipation effect of optimal velocity. This model employed an improved car-following model [16] with the anticipation optimal velocity [31]

$$\frac{dv_n(t)}{dt} = a[v_e(\Delta x_n(t + \alpha\tau)) - v_n(t)] + \lambda \Delta v_n, \qquad Eq.\ 12$$

where $\Delta x_n = x_{n+1} - x_n$ represents the distance headway and $\Delta v_n = v_{n+1} - v_n$ represents the velocity difference between the leading vehicle $n+1$ and the following vehicle n; $x_n(t)$ and $v_n(t)$ are the position and velocity of car n at time t respectively; τ is the delay time, α is the anticipation coefficient and $v_e(\Delta x_n(t + \alpha\tau))$ is the anticipation optimal velocity. According to Eq. 12, the driver adjusts driving acceleration not only based on his own running car velocity $v_n(t)$ and velocity difference Δv_n, but also based on anticipation optimal velocity at the time $t + \alpha\tau$ after delay. Then, the discrete variables of individual vehicles were transformed into the continuous flow variables [32]. The macro-model was developed as in Eq. 4.

All studies carried out the numerical test using the numerical method to discretize the model in order to get the analytical solution of it. The numerical method used in these studies was the finite difference method. Tang et al. [25], Shi et al. [27], and Mahona et al. [29] performed the numerical test by using the real traffic data while Peng et al. [26] and Ou and Tang [28] did not. The test sites considered in Tang et al. [25], Shi et al. [27], and Mahona et al. [29] were Beijing’s two roads, Xi’an-Baoji Highway and Bagamoyo road network respectively.

The performance in reproducing the stop-and-go phenomenon by different studies was evaluated by analyzing the phenomenon using different approaches. Tang et al. [25] compared the model's performance in a bad segment (Beitaipingzhuang) and a good segment (Weizikeng segment) with different initial densities. Peng et al. [26] considered different initial densities with constant anticipation coefficient under small perturbation situation. Shi et al. [27] analyed the phenomena of fixed vehicle generation rate but increasing initial density. Ou and Tang [28] studied in two typical traffic situations in the real traffic system: uniform flow and small perturbation. Mahona et al. [29] analyze by observing the variations of vehicle stream speed and density.

One of the similarities that can be found within these studies is the stop-and-go phenomenon occurred when the initial density is moderate. Tang et al. [25] found that the road capacity had great effects on uniform flow and prominent stop-and-go traffic will occur when the initial density is moderate. On the Weizikeng segment, less stop-and-go traffic was noted compared to the Beitaipingzhuang segment at the same density. Based on simulation results in Peng et al. [26], the perturbation was quickly dissipated at very low densities. Once the initial density reached the down-critical density, multiple clusters were formed, resulting in stop-and-go traffic. As the traffic density increased, the traffic became stable again since it was above the up-critical density.

The simulation results in Shi et al. [27] showed that the ramps can affect the stability of the main road traffic and forms the stop-and-go traffic eventually if the initial density is above the down-critical unstable density. The traffic was stable when the initial density is lower than the down-critical density or greater than the up-critical density. In Ou and Tang [28], the stop-and-go phenomenon occurred when the initial density is moderate in uniform flow and small perturbation. When the initial density is relatively small or relatively high, the moving bottleneck does not destroy the stability of traffic flow. In Mahona et al. [29], stop-and-go phenomenon was observed as the density became higher in both variations of vehicle stream speed and density.

3.2 Discussions

From the result, we noticed that there are different factors adopted in the models affect the stability of traffic flow which thus led to the occurrence of stop-and-go phenomena. The factors considered in these studies were road capacity, existence of ramps, anticipation optimal velocity, static and moving bottlenecks.

In this review, there are two types of models involved in reproducing the stop-and-go phenomenon, which are anisotropic–viscous model [27] and anisotropic–inviscid models [25, 26, 28, 29]. In order to obtain the analytical solution of the models, numerical method was implemented to discretize the model. The numerical method used in these studies was the finite difference method.

All of these models were simulated and validated to be capable to reproduce the phenomenon considering different factors. It can be noticed that the stop-and-go model was observed when the initial density is moderate, and the traffic flow become unstable. However, at a very low and very high initial density, the factors did not have prominent influence on the traffic flow and the traffic flow remained stable.

4. Conclusion

In this study, a total of five papers that fulfil the inclusion criteria are obtained. These five papers proposed macroscopic models considered different factors to reproduce the stop-and-go traffic such as road capacity, existence of ramps, anticipation optimal velocity, static and moving bottlenecks. The research questions formulated had been successfully answered as follows:

1. Two types of models are involved in this review, which are anisotropic–viscous model and anisotropic–inviscid models.

2. The numerical method used in these studies was the finite difference method.
3. The factors considered in these studies had prominent influence on the traffic flow and resulted in stop-and-go phenomenon when the initial densities were moderate.

The study of macroscopic traffic model on other complex phenomena such as hysteresis and capacity drop also can be further reviewed and investigated systematically.

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