Modeling Lane-Changing Behavior of Vehicles at Merge Section under Mixed Traffic Conditions

Bhargav Naidu Matcha1; Sivakumar Sivanesan, Ph.D.2; and K. C. Ng, Ph.D.3

Abstract: The lane-changing behavior of different types of vehicles at the merging section of an urban road is assessed by using a new lane-changing model proposed in the current work. The lane-changing model known as MOBIL (minimizing overall braking induced by lane changes) is modified and combined with the intelligent driver model (IDM) to implement the lane-changing rules for different vehicle classes by applying the politeness and vehicle-type factors. It is noted that the heterogeneity of surrounding vehicles during lane-changing, which is common in developing countries, is not considered in most of the existing lane-changing models. The preceding problem is addressed by incorporating the vehicle-type dependent factor in the proposed lane-changing model. This new model considers the effect of motorcycle movement on the lane-changing decision and evaluates the aggressiveness of motorcyclists during lane-changing. The merging maneuver data from video recording is utilized to calibrate and validate the models. The lane changing rate is the highest for motorcycles and the least for trucks (at a given politeness factor). Motorcycles exhibit lower lane changing durations for politeness factors \( p = 0 \) and \( p = 1 \), showing integrated movements due to their pushy or erratic maneuverability. DOI: 10.1061/JTEPBS.0000502, © 2021 American Society of Civil Engineers.

Author keywords: Lane changing; Mixed traffic; Merge section; MOBIL model; Intelligent driver model.

Introduction

The nature of traffic conditions in southeast Asian countries is different from that in developed countries. The traffic stream in developed countries consists predominantly of cars giving rise to homogeneous traffic conditions. However, the traffic in developing Southeast Asian countries consists of a wide variety of vehicles with different physical and dynamic characteristics. The vehicular composition in these countries consists of two-wheelers, cars/vans, trucks, buses, and light commercial vehicles, giving rise to nonlane disciplined movements. Small vehicles often filter through the traffic giving rise to integrated movement, complex maneuvers, and interaction in mixed-traffic situations. These complex behaviors intensify at merging and diverging sections of highways. Therefore, the evaluation of realistic mixed-traffic flow is feasible by performing a multilane simulation framework, incorporating various vehicle types at merging sections. The simulation study helps to perceive the impact of symmetric lane-changing on capacity, stability, and breakdown of traffic flow, especially at onramp and offramp regions.

In this study, we present a modified minimizing overall braking induced by lane changes (MOBIL) lane-changing model that incorporates vehicle-type dependent factors to evaluate the symmetric lane-changing behavior of different vehicle types. This modified model is calibrated and validated with the observed field data collected from an urban merge section. This updated model presents the aggressiveness of drivers during lane changing (subjected to the influence of vehicle types) at an urban merging section under mixed-traffic conditions.

Background

Many studies have been performed in evaluating the merging behavior of vehicles under car-following situations. Gipps (1986) and Wagner et al. (1997) developed the homogeneous lane-changing and merging models under normal conditions in order to simulate various lane-changing characteristics under different flow categories. For mixed-traffic streams, Arasan and Koshy (2005) reproduced highly heterogeneous traffic flow by presuming acceptable lateral longitudinal spacing during lane changing. Lee et al. (2009) laid forward a new method to simulate mixed traffic flow by focusing on the movements of motorcycles. Matcha and Chhabra (2018) determined the mixed-traffic flow conditions involving vehicles (especially motorcycles) that interact both laterally and longitudinally, even on a straight road section. Therefore, it can be inferred that these complex interactions increase rapidly at merging sections.

Matcha et al. (2020) have recently concluded that a large collection of field parameters is necessary for calibrating and validating the developed models for mixed-traffic flow conditions. Hence, in order to understand the behavior of lane-changing at merging sections, accurate vehicle trajectory data is required. Treiber and Kesting (2007) introduced the MOBIL model to extract lane-changing directives for car-following models. A parameter named the politeness factor, which distinguishes between egoistic and
cooperative driving behaviors, was introduced. However, the MOBIL lane-changing model was not thoroughly tested or calibrated in real-time mixed-traffic conditions, as highlighted by Xie et al. (2019).

Monteil et al. (2014) implemented the MOBIL model as an underlying lane-changing model along with a full-velocity difference car-following model to simulate cooperative traffic flow to investigate the vehicle-to-vehicle cooperation during traffic congestion. They studied the impact of vehicle heterogeneity and aggressive or egoistic lane-changing behavior of vehicles in triggering congestion. However, their work is limited to automated or semi-automated vehicles under homogeneous traffic conditions, which is not feasible in the case of developing countries where the traffic flow is heterogeneous with a good number of aggressive drivers, especially motorcyclists. Khan et al. (2014) suggested that the MOBIL lane-changing model is an optimal model as it considers the lane-changing decision on the immediate surrounding vehicles. They evaluated parameters, such as the number of lane changes, fuel consumption, and overall braking, under the influence of surrounding vehicles for a connected vehicle network. Again, their work is limited to connected autonomous vehicles under homogeneous traffic conditions.

Lazar et al. (2018) and Lazar (2019) proposed a new car-following model called the modified velocity separation difference model (MVDSD), which is an extension of the velocity separation difference model (VSDM), by implementing an optimal velocity function and integrating it with the MOBIL lane-changing model to evaluate the lane-changing behavior. This proposed model is able to minimize unrealistic braking and deceleration in the existing car-following model. However, this model does not consider the vehicle heterogeneity of surrounding vehicles during lane changing. Song et al. (2019) developed a microscopic traffic tracking algorithm that models the lateral and longitudinal movement of vehicles simultaneously. The proposed model integrates the intelligent driver model (IDM) car-following and MOBIL lane-changing model to evaluate the lateral and longitudinal interactions between the vehicles. However, their model does not take into consideration the movement of motorcycles and their influence on the traffic stream.

Zheng et al. (2019) developed a simulation framework for connected and autonomous vehicles by modifying and integrating the IDM car-following model and the MOBIL lane-changing model to evaluate the lane changing strategy of these vehicles at highway onramp sections consisting of diverging traffic flow. This proposed framework does not consider the presence of manually driven vehicles and heterogeneity in evaluating the lane-changing behavior in diverging areas. Taguïam et al. (2019) calibrated the politeness factor of the MOBIL model for Philippine vehicle drivers and derived four new classifications based on politeness factors, such as advantageous, altruistic, egoistic, and thwart drivers. However, their work does not present the classification of drivers based on vehicle type. The rule-based models, especially the MOBIL lane-changing model, specifies an identical gap acceptance threshold for all vehicle types, thus leading to an unrealistic driving scenario [Kusuma et al. (2020)]. In fact, under mixed-traffic conditions, different drivers have different gap acceptance preferences depending on the vehicle type and road section. Table 1 summarizes the related open literature.

Although the MOBIL lane-changing model has been implemented to study the lane-changing behavior of vehicles for more than a decade, there still exists some open questions. This work attempts to bridge some of these gaps:

• Most of the existing MOBIL lane-changing models do not consider the vehicle heterogeneity of surrounding vehicles during lane changing;

• For developing countries where the traffic flow is heterogeneous, the developed MOBIL lane-changing models are not thoroughly tested or calibrated in real-time mixed-traffic conditions; and

• Most of the MOBIL lane-changing models are implemented for homogeneous traffic conditions and do not take into consideration the movement of motorcycles and their influence on the traffic stream.

In order to address the aforementioned issues and to model the lane-changing behavior of different vehicle types in a more accurate manner under mixed-traffic conditions, this work attempts to present a modified MOBIL lane-changing model that takes vehicle heterogeneity into account by implementing the so-called vehicle type-dependent factor. The motivations and contributions of this study are the following:

• The proposed lane-changing model takes into consideration the driver heterogeneity of immediate surrounding vehicles during lane changing by implementing the vehicle-type dependent factor. This helps in understanding the lane-changing decisions under mixed-traffic conditions.

• The proposed lane-changing model considers the effect of motorcycle movements on lane-changing decisions of other vehicle types and evaluates the aggressiveness of motorcyclists during lane changing.

• The modified MOBIL lane-changing model is calibrated using real-time data extracted from the urban merging section under mixed-traffic conditions.

The rest of the paper is organized in the following manner. The “Traffic Composition” section presents the field traffic characteristics of the study location. The “Model Calibration” section deals with the updated model calibration. The simulation results are presented in “Analysis of Simulation Model” section. Validation of these results is highlighted in the “Validation” section. Finally, “Limitation and Future Work” section and “Conclusion” section presents the conclusions and future work of this study.

### Modified Mobil Lane-Changing Model

All time-continuous microscopic car-following models characterize the motion of individual vehicle unit $\alpha$ as a function of their velocity $v_\alpha$, the bumper-to-bumper distance of the lead car $(\alpha-1)$ to the following car $\alpha$ denoted as $s_\alpha$, and their relative velocity $\Delta v_\alpha = v_\alpha - v_{\alpha-1}$. The general form of the acceleration function $a_\alpha$ in these microscopic models is

$$ a_\alpha = \frac{dv_\alpha}{dt} = a(s_\alpha, v_\alpha, \Delta v_\alpha) \quad (1) $$

The Gipps (1986) model and the intelligent driver model (Treiber et al. 2000) present two common examples of the time-continuous car-following model.

The preceding acceleration function has been modified to consider vehicle-type dependent lane-changing behavior under mixed-traffic conditions. The modified acceleration function of the subject vehicle $j$ to the leading vehicle $i$ by considering the vehicle-type dependent factor is expressed

$$ a^{ij} = \frac{dv^{ij}}{dt} = a(s^{ij}, v^{ij}, \Delta v^{ij}) \quad (2) $$

For a distinct lane-change of a vehicle from the center lane to the side lane, as shown in Fig. 1, the lane-changing vehicle relies upon the following vehicles on the present lane and the chosen lane, respectively. The following notations are used to denote the lane-changing criteria: vehicle $x$ is going for a lane change, and the
<table>
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<th>Type of study</th>
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<th>Parameters</th>
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<td>Development of integrated model to simulate motorcycles flow pattern</td>
<td>Cars, motorcycles</td>
<td>Speed, density, flow, lateral headway, longitudinal headway, lateral clearance</td>
<td>Java-based simulation</td>
<td>Traffic simulator capable of simulating motorcycle movement for traffic management and planning</td>
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<td>Lane-change model based on deep learning</td>
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<td>Cars</td>
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<td>MOBIL</td>
<td>Simulation of cooperative traffic flow to investigate the vehicle to vehicle cooperation during traffic congestion</td>
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<td>MOBIL</td>
<td>To evaluate the result of lane changing decisions on immediate surrounding vehicles</td>
<td>Cars</td>
<td>Politeness factor, speed, longitudinal headway, safe braking speed</td>
<td>SUMO</td>
<td>Number of lane changes, CO₂ emissions, overall braking influence for connected vehicles</td>
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<tr>
<td>MOBIL</td>
<td>A new car-following model MVSDM, which was integrated with MOBIL to evaluate the lane-changing behavior</td>
<td>Cars, trucks</td>
<td>Desired speed, time headway, minimum gap, politeness factor</td>
<td>Java based open source traffic simulator</td>
<td>Headway and relative speed during lane-change operations</td>
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<td>MOBIL</td>
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<td>Cars, trucks</td>
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</table>
following vehicles on the present and target lanes are denoted
by \( m \) and \( n \), respectively. The acceleration of vehicle \( x \) is denoted
by \( a_x \) in the present lane, and \( \bar{a}_x \) represents the acceleration of
vehicle \( x \) in the target lane after the lane change. Likewise, the accel-
erations of the following vehicles in the present and chosen lanes
are denoted by \( \bar{a}_m \) and \( \bar{a}_n \), respectively, after the lane change of
vehicle \( x \).

**Modified Safety Factor**

The safety criterion evaluates the need for a safe lane change for
different vehicle types. This safety factor is responsible for a safe lane change by examining its consequence on the vehicles present
on the chosen lane. After a lane change, the safety criterion assures
that the deceleration of the new follower vehicle \( \bar{a}_j \) on the chosen lane does not surpass the safety limit \( b_{\text{safe}} \), or in other words

\[
\bar{a}_j \geq -b_{\text{safe}}
\]  

The preceding safety criterion has been modified to consider the
vehicle-type dependent safe lane-changing behavior under mixed-
traffic conditions. The modified safety criterion assures that after a lane change, the deceleration of the new follower vehicle type \( \bar{a}_j \) on
the chosen lane does not surpass its safety limit \( b_{\text{safe}}^{j} \), or in other words

\[
\bar{a}_j^{j} \geq -b_{\text{safe}}^{j}
\]  

where \( j \) represents the vehicle type.

This formulated inequality bears the information from the lon-
gitudinal car-following model, which depends upon the velocity,
gap, and approach rate, as shown in Eq. (2). Therefore, if the speed of the following vehicle type in the chosen lane is higher than the
subject vehicle type, then more significant gaps are required be-
tween them to satisfy the safety check. In the same way, if the
following vehicle type speed in the chosen lane is lower than the
subject vehicle type speed, then smaller gaps are allowed. The in-
clusion of safe braking deceleration of different vehicle types in this
safety criterion using car-following models excludes conflicts and
-crashes during lane changes under mixed traffic conditions. In this
model, the safe braking deceleration \( b_{\text{safe}}^{j} \), for different vehicle types
should be well below the maximum possible deceleration \( b_{\text{max}} \),
which is \( 9 \, \text{m/s}^2 \) on dry surface roads (Kudaraukas 2007). This
\( b_{\text{safe}}^{j} \) value prevents accidents even in the case of extreme egoistic
drivers if its value is below \( b_{\text{max}} \) for different vehicle types (Bokare
and Maurya 2017). However, the \( b_{\text{safe}}^{j} \) value always limits the brake
reaction time of the following vehicle on the chosen lane. This is
because the lane changing operation induces a disruption in the
input parameters of the new follower’s acceleration function, which
is relevant in traffic simulations.

**Modified Incentive Factor**

The lane changing execution in the MOBIL model takes place after
satisfying the safety factor, along with the incentive factor. This
incentive factor typically determines the initiated lane change that
enhances the traffic surrounding the subject vehicle. The incentive
factor has been modified to consider vehicle-type dependent safe
lane-changing behavior under the influence of different surround-
ring vehicles. A politeness factor \( p \) determines the influence of the
nearby vehicle types on the subject vehicle lane change initiation.
For a lane-changing action of a driver of vehicle type \( x \), the modified
incentive criterion is

\[
\bar{a}_x^{i} - a_x^{i} + p(\bar{a}_m^{j} - a_m^{j} + \bar{a}_n^{j} - a_n^{j}) > \Delta a_{\text{th}}
\]  

where \( \bar{a}_x^{i} - a_x^{i} \) denotes the old follower vehicle-type; and \( \bar{a}_m^{j} - a_m^{j} \)
denotes the new follower vehicle-type.

From the equation, the first two terms indicate the possible lane
change advantage of the subject vehicle type \( i \), where \( \bar{a}_x^{i} \) signifies
the acceleration of vehicle \( x \) on the chosen lane after the lane
change, and \( a_x^{i} \) is the acceleration of vehicle \( x \) on the existing lane.
The third term, along with prefactor \( p \), indicates the rise or fall in
the acceleration of the immediate surrounding vehicle types on the
present and chosen lane, which is weighted based on the politeness
factor \( p \). The final term on the right-hand side is the switching
threshold \( \Delta a_{\text{th}} \), which restricts the lane change if its advantage
is marginal to the keep lane situation. Finally, this incentive factor
gets satisfied if the subject vehicle lane change acceleration gain is
far greater than the weighted sum of the acceleration losses of the
following vehicles on the present and the chosen lane by the

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Fig. 1. Lane-change process of a vehicle.

Fig. 2. Overall plan of the study section.
threshold $\Delta a_{ij}$. The politeness factor $p$ influences the lane-changing behavior of the subject vehicle with the next nearby vehicles. In contrast, the threshold $\Delta a_{ij}$ influences the lane-changing behavior globally, i.e., all the vehicles present at the lane-changing section.

The politeness factor $p$ represents the degree of altruism, varying from $p = 0$ (selfish lane changers) to $p > 1$ (selfless drivers) whose lane-change behavior does not interrupt the traffic flow situation of the surrounding vehicles. Even the harsh lane changing vehicles can be modeled by setting $p < 0$ because such drivers do not care about the surrounding vehicles. From past simulation studies, the realistic lane-changing behavior of traffic is modeled when the politeness factor is in the range of $0.2 < p < 0.5$ (Treiber and Kesting 2007). In some special circumstances when $p = 1$ and $\Delta a_{ij} = 0$, the incentive factor becomes

$$\bar{a}_{ij} + \bar{a}_{ij} + \bar{a}_{ij} > a_{ij} + a_{ij} + a_{ij}$$

Hence, when there is an increase in the sum of the weighted acceleration of surrounding vehicle types, then lane change operations are performed.

### Implementation of Multilane Traffic Merging Simulation

The modified lane-changing MOBIL model is implemented to model three-lane highway traffic merging with a two-lane road. The formulation of the rules in the MOBIL model is independent of longitudinal acceleration modeling. Therefore, the specification of the underlying car-following model is required. We implement the IDM (Treiber et al. 2000), which is a simple microscopic model, to model longitudinal acceleration. In the IDM model, the acceleration of each vehicle $\alpha$ of vehicle type $j$ depends upon their velocity $v_{ij}$, the velocity difference $\alpha_{ij}$ with leader vehicle $i$, and the remaining gap between the vehicles $s_{ij}$

$$a_{ij} = a \left[ 1 - \left( \frac{v_{ij}}{v_{ij}^0} \right)^{\delta} - \left( \frac{s_i^a \Delta v_{ij}}{s_i^a} \right)^2 \right]$$

where $\delta = \text{acceleration exponent}$.

The safe-distance $s_o$ + $T$ in this model should be greater than the equilibrium distance between the follower and leader vehicle type. In this study, $s_o$ is the desired minimum distance, and $T$ is the safe time gap to the leader vehicle type. The position and velocity of the subject vehicle are denoted by $x_i$ and $v_i$, respectively. The subject vehicle length is indicated by $l_i$. The net distance between the subject vehicle type $j$ and leading vehicle type $i$ is

$$s_{ij} = x_{ij} - x_{ij} - l_i$$

where $\alpha - 1$ represents the leader vehicle in front. The relative velocity between the follower vehicle type $j$ and the leading vehicle type $i$ is denoted

$$\Delta v_{ij} = v_i - v_{ij}$$

The desired gap is $s^*$ between different leader-follower pairs, is defined

$$s^*(v_{ij}, \Delta v_{ij}) = s_{ij} + \max \left[ 0, \left( \frac{v_{ij}^0 \cdot T + \frac{v_{ij}^0 \cdot \Delta v_{ij}}{2\sqrt{a_b}}}{s_{ij}} - \bar{a}_{ij} \right) \right]$$

In the preceding equation, the acceleration is classified into desired acceleration denoted by $1 - (v_{ij}^0/v_{ij})^\delta$ for free flow and braking acceleration $s^*(v_{ij}^0, \Delta v_{ij}^0)$ due to the leader vehicle type $i$. When the next vehicle type approaches the preceding vehicle type moving with the desired speed $v_{ij}^0$, then the acceleration during the free-flow condition decreases from $a$ to $0$.

For each simulation step, the incentive criterion is evaluated because drivers inspect their incentives continuously. The lane change action is performed immediately if it is termed safe and sound, thereby omitting the transition phase from the present lane to the chosen lane. This multilane mixed traffic flow merging model combining the IDM car-following and MOBIL lane-changing model is consistent in terms of the numerical simulation for a limited time step in the limit $\Delta t \rightarrow 0$ by considering the vehicle-type dependent factor.

### Data Collection

For the collection of field data, a merging section on a five-lane divided multilane urban road in Selangor, Malaysia, is selected. Based on the reconnaissance survey conducted over the entire stretch of the Persiaran Kewajipan highway of 10 km in Subang Jaya, the location is chosen as a representative section. This final selection is chosen from several other merging sections visited during the field survey. The choice of this location is based on the availability of the vantage point for camera recording to capture the traffic flow at the merging site. The study section plan is reported in Fig. 2, showing the overall five-lane road segment in one direction. Fig. 3 shows the map view of the study location:

- **The upstream side of the merging section**. This section lies 30 m upstream from the merging section. Time headway data is studied to understand vehicle behavior before the merging location.
- **The merging section**. A 60-m long stretch at the verge of merging. The traffic flow parameters of speed, density, flow rate, headways, and overtaking behavior are studied.

![Fig. 3. Google map view of study location. (Map data © 2019 Google.)](image-url)
• The downstream side of the merging section. Traffic data is also collected at the location 500 m away from the merging section to compare the effect of merging on traffic flow parameters. The five-lane divided urban road has a carriageway width of 17.5 m (3.5 m × five lanes) on each side. Traffic flow was recorded by placing a camera at a vantage point. The traffic recording duration was selected to capture both peak and offpeak hour traffic.

Traffic Composition

The composition of the traffic analyzed for the entire duration of 1 h (evening peak hour flow) is shown in Fig. 5. The section consists of cars occupying more than half of the traffic composition (55%). It is followed by motorcycles occupying nearly 30%, followed by heavy vehicles (buses and trucks) occupying around 15% of the traffic. The characteristics of the vehicles (speed, acceleration, and vehicle width) analyzed from the samples are shown in Table 2.

Model Calibration

The model proposed is a combination of the IDM and modified MOBIL model considering the vehicle-type dependent factor kept in a single framework. The combined models must be calibrated separately, and the calibrated parameters must be checked for synchronization. In diverse traffic conditions, the lane-changing and car-following behavior depends upon the vehicle types or vehicle heterogeneity. In our study, we considered three vehicle types to implement vehicle heterogeneity. The vehicle types consisting of slow-moving trucks with the desired velocity $v_o = 80$ km/h, fast-moving cars ($v_o = 80$ km/h), and erratic two-wheeler motorcycles ($v_o = 80$ km/h). To increase the influence of vehicle heterogeneity, we considered a variation of ±20% in the desired velocity of each vehicle type. The initial parameters used in the IDM model are shown in Table 3.

The modified MOBIL model parameter values used in simulations are shown in Table 4.

Analysis of Simulation Model

The modified lane-changing model is applied to simulate lane changes at an urban merge section. This modified MOBIL model models the lane changes induced by different vehicle types based on the politeness factor. The inflow traffic from the main highway and the merging section is shown in Table 1. The field survey provides the initial input parameters for the simulation model. The road section assessed in the proposed model is shown in Fig. 2, where the lane-changing process of different vehicles is analyzed throughout the section. The simulation time step size of 0.1 s is adopted to analyze in detail the lane-changing behavior of different vehicles. The merge section prompts a lot of discretionary lane changes from the left to the right lane, where lane changes from the right to the left lane are less when compared to the previous. Because different vehicles merge to the left lane of the highway, the left lane becomes less fetching for these vehicles on the highway upstream of the merging section.

Table 2. Traffic characteristics

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Sample size</th>
<th>Speed, $\mu_v(\sigma_v)$ (m/s)</th>
<th>Acceleration, $\mu_a(\sigma_a)$ (m/s²)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>3,234 (62%)</td>
<td>11.11 (1.93)</td>
<td>1.67 (1.56)</td>
<td>1.50–2.50</td>
</tr>
<tr>
<td>Heavy vehicle</td>
<td>1,656 (28%)</td>
<td>9.78 (1.28)</td>
<td>1.43 (0.61)</td>
<td>2.50–3.00</td>
</tr>
<tr>
<td>Motorcycle</td>
<td>986 (10%)</td>
<td>13.30 (2.67)</td>
<td>2.59 (1.85)</td>
<td>0.50–0.75</td>
</tr>
</tbody>
</table>

Note: $\mu$ = mean value; and $\sigma$ = standard deviation.

Table 3. Parameters used in IDM model (field observations)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Car</th>
<th>Truck</th>
<th>Motorcycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration ($a$) (m/s²)</td>
<td>1.5</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Deceleration ($b$) (m/s²)</td>
<td>1.67</td>
<td>2.66</td>
<td>2.57</td>
</tr>
<tr>
<td>Desired speed ($v_o$) (km/h)</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Desired time headway ($T_o$) (s)</td>
<td>1.8</td>
<td>2.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Desired safe distance ($x_o$) (m)</td>
<td>2.0</td>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Acceleration exponent ($\delta$)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Vehicle length ($l$) (m)</td>
<td>4.5</td>
<td>8.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 4. MOBIL parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Politeness factor ($p$)</td>
<td>0–1</td>
</tr>
<tr>
<td>Switching threshold ($\Delta x_{zh}$)</td>
<td>0.1 m/s²</td>
</tr>
<tr>
<td>Maximum deceleration for cars ($b_{max}^{car}$)</td>
<td>4 m/s²</td>
</tr>
<tr>
<td>Maximum deceleration for trucks ($b_{max}^{truck}$)</td>
<td>1 m/s²</td>
</tr>
<tr>
<td>Maximum deceleration for motorcycles ($b_{max}^{motorcycle}$)</td>
<td>1.5 m/s²</td>
</tr>
</tbody>
</table>
Fig. 4. Lane-changing rates of cars to traffic density: (a) politeness factor $p = 0$; and (b) politeness factor $p = 1$.

Fig. 5. Lane-changing rates of trucks to traffic density: (a) politeness factor $p = 0$; and (b) politeness factor $p = 1$.

Fig. 6. Lane-changing rates of two-wheelers to traffic density: (a) politeness factor $p = 0$; and (b) politeness factor $p = 1$. 
lane-change rate reduces drastically to \( \sim 800/\text{h}/\text{km} \). As \( p \) is further increased, the rate of lane-changes is reduced significantly.

- The maximum lane-changing rates for trucks reduce by approximately 50% from 140/\text{h}/\text{km} to 75/\text{h}/\text{km} for politeness factors \( p = 0 \) and \( p = 1 \). Also, for the given traffic density, the lane-change rate of trucks reach the minimum value even though the traffic density is well below the road capacity due to their large static yet low dynamic capabilities.
- The maximum lane-changing movement for a motorcycle or two-wheeler ranges from 500/\text{h}/\text{km} to 160/\text{h}/\text{km} for politeness factors \( p = 0 \) and \( p = 1 \). However, from several simulations, the lane-changing actions of motorcycles do not come to a halt even when traffic density exceeds the road capacity. This seems to suggest the integrated or no-lane movements of motorcycles while filtering through traffic, a phenomenon commonly known as porous flow.
- Flow-through available gaps or filtering through traffic is the nature of a two-wheeler. This gives rise to integrated movements within a lane, exhibiting no-lane behavior, which is vigorous, especially at merging sections. This behavior is evident from various simulation runs. When the politeness factor \( p = 0 \) is employed, the lane-change rates are quite high, evidently showing the egoistic or selfish nature of two-wheeler drivers.
- With an increase in traffic density, the difference in mean velocity of all types of vehicles on different lanes decreases, thus giving rise to a reduction in lane change movement. However, due to the presence of more selfish drivers (e.g., two-wheelers), the lane-change rates do not diminish even though the road capacity is exceeded.
- The results show that with an increase in the traffic density, the lane-changing rates of all vehicle types increase. The presence of an increased number of vehicles for a given length of road reduces the headway and lane-changing spacing intervals of vehicles, which in turn might influence road safety.
- The lane changing rates of all vehicle types from the left to right lane (or the slow to fast-moving lane) are more compared to the right to the left lane, implying vehicles tend to shift to the fast-moving lanes once they exit the merge section.
- The presence of an increased number of trucks at a merge section reduces the overall lane changing rates of vehicles due to their maximum lane changing durations owing to their large static and low dynamic properties compared to other vehicle types, which in turn cause disturbances in the overall flow.
- The presence of erratic or selfish drivers influence the lane-changing spacing intervals affecting the flow of through vehicles and causing delays for rear vehicles, thereby causing disturbances in the overall flow affecting the road safety and capacity, leading to traffic conflicts and congestion.
- Overall, for a given traffic density, two-wheelers tend to be more aggressive, erratic, and not follow lane discipline owing to their

![Fig. 7. Lane-changing duration to traffic density for (a) cars; (b) heavy vehicles; and (c) motorcycles.](image-url)
smaller size and high maneuverability, followed by cars, which are less aggressive compared to two-wheelers and follow lane-discipline, which is then followed by trucks due to their large static and low dynamic properties.

**Lane-Changing Duration**

Politeness factor $p$ plays a crucial role in determining the lane-change durations of various drivers ranging from egoistic or selfish to altruistic ones. This factor is further modified to include the driver behavior of varying vehicle types when they behave selfishly and altruistically. The lane-changing duration of different vehicle types for $p = 0$ and $p = 1$ to traffic density is shown in Figs. 7(a–c). In these simulations, the density of traffic $\rho$ is calculated using the hydrodynamic equation $Q = \rho V$, using the traffic flow equations for each lane $Q = \sum_{i=1}^{L} Q_i$ and $V = \frac{\sum_{i=1}^{L} (Q_i V_i)}{Q}$ multilane roads.

- **Lane-changing durations for all vehicles increased with an increase in traffic density.** In the case of cars, the maximum lane-change duration ranged between 4.5 and 5.5 s for $p = 0$ and $p = 1$. From Fig. 4(a), when the politeness factor was $p = 0$, drivers were selfish and made quick lane changes without considering surrounding vehicles.
- **The maximum lane-changing duration of heavy vehicles for $p = 0$ and $p = 1$ is 8.5 and 7.1 s, respectively.** This shows little difference in lane changing durations between a selfish and selfless driver due to the broad static and low dynamic capabilities.
- **The maximum lane-changing duration for motorcycles at $p = 0$ and $p = 1$ is 4.4 and 3.4 s, respectively.** They have the least lane-change durations compared to other vehicles due to their smaller size and more excellent maneuvering capabilities, giving rise to erratic and integrated driving behavior. They are continuously making lateral shifts while moving longitudinally, giving rise to within the lane movements, which have not been recorded in this modified model.

**Headway and Velocity during Lane-Change**

A lane-changing simulation scenario of a merging section consisting of mixed traffic to determine different vehicle headways and velocities during lane change operations using the MOBIL lane-changing model was established. The vehicles (cars, trucks, and motorcycles) were generated at random in each and every simulation to evaluate the lane changing behavior under different leader-follower pairs. This simulation scenario evaluates the lane-changing behavior of 10 mixed vehicles from Lane 1 to Lane 2, as shown in Fig. 8. The responses of various vehicles during the lane-change process were evaluated, and their headway to time during a lane change was plotted, as shown in Fig. 9.

Different vehicles maintained different headways with their leader vehicles on the present and target lanes due to different static and dynamic characteristics. The variation of velocity versus time from this simulation scenario is shown in Fig. 10.

Compared to cars and trucks, motorcycles maintained smaller headways for higher velocities due to their high maneuvering capabilities and smaller dimensions, concluding swerving and filtering behavior. This nonlane behavior and within lane movements of motorcycles need to be further investigated. The summary of headway maintenance of different vehicles for the given velocities during the lane-change process after running different simulation runs are shown in Table 5.

The mean velocity of all the vehicles during the lane-change process from left to right and vice versa for the politeness factors $p = 0$ and $p = 1$ to traffic density is shown in Fig. 11.
The mean velocity of the vehicles for politeness factor $p = 0$ during a lane change from the left to the right lane, and vice versa, remained high for a given density. This is because most of the lane changes are due to egoistic or selfish drivers who do not care about the smooth and safe flow of the traffic stream resulting in high travel times. However, for the $p = 1$, the mean velocity of vehicles during lane change reduced to a minimum due to an altruistic nature of drivers paving the way for the smooth passage of surrounding vehicles improving the overall performance.

**Validation**

To assess the execution of the proposed model, real-time vehicle trajectories are used extracted from collected traffic data and then compared with the simulation trajectories under a similar scenario. Nearly 30% of the real-time data that was not utilized in model calibration was used for model validation. This data is used in the original calibrated model and then collated against a model explicitly estimated based on this data for obtaining the goodness-of-fit ($\rho^2$). The validation and forecasting ability of the calibrated model is found reasonable based on the corresponding $\rho^2$ values.

### Table 5. Headway and velocities of different vehicles during lane change

<table>
<thead>
<tr>
<th>Cars</th>
<th>Trucks</th>
<th>Motorcycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (km/h)</td>
<td>Headway (m)</td>
<td>Velocity (km/h)</td>
</tr>
<tr>
<td>70</td>
<td>11–15</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>5–9</td>
<td>30</td>
</tr>
<tr>
<td>30</td>
<td>2–4</td>
<td>—</td>
</tr>
<tr>
<td>20</td>
<td>1–3</td>
<td>—</td>
</tr>
</tbody>
</table>

**Fig. 11.** Mean velocity to traffic density.

### Table 6. Lane changing speeds statistics (goodness-of-fit)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Proposed lane change model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root mean square error (m/s)</td>
<td>2.84</td>
</tr>
<tr>
<td>Root mean square percent error (%)</td>
<td>10.87</td>
</tr>
<tr>
<td>Mean error (m/s)</td>
<td>-0.61</td>
</tr>
<tr>
<td>Mean percent error (%)</td>
<td>-3.17</td>
</tr>
</tbody>
</table>
Lane Changing Speeds of Vehicles

The observed speeds of vehicles during a lane change from the field trajectory data are compared with the simulated speeds of vehicles during a lane change using the proposed lane change model, and the goodness-of-fit statistics are recorded, as shown in Table 6. The proposed model showed good results with very little error in terms of the mean error and mean percent error.

Number of Lane Changes

The simulated number of lane changes of the vehicles at the merge section using the proposed lane change model are compared with the field trajectory data. The results show a reasonable match in the number of lane changes between the simulated and observed data, as shown in Fig. 12. The RMSE for a fraction of vehicles undergoing a lane change from left to right and right to left in the proposed model is 0.027 and 0.018.

Vehicle Headways during Lane change

The simulated longitudinal headway maintained by different vehicle types during a lane change as a function of the velocity is compared with the field trajectory data, as shown in Figs. 13(a–c). The results lay forward a reasonable match between the simulated and observed headways for the given velocity values. The RMSE values for the vehicle longitudinal headway maintenance as a function of velocity for cars, trucks, and motorcycles are 0.380, 0.389, and 0.255, respectively.

Fig. 12. Comparison of lane changes between observed trajectory data and simulated data.

Fig. 13. Vehicles headway as a function of velocity during lane change: (a) cars; (b) trucks; and (c) motorcycles.
Limitations and Future Work

The present work has certain limitations. Firstly, the modified model neglects the differences between the lanes, i.e., it is applicable only for symmetric lane changing. Secondly, the data used in this study is extracted from video recordings for a particular merging location. More data collection and extraction from other locations to improve the quality of the model is subjected to future research. Thirdly, the modified model was evaluated using data collected from moderately congested traffic conditions, which cannot be applied directly to oversaturated flow conditions. Further research will be conducted to test the performance of the modified model under congested traffic conditions. Finally, the present work is investigated using the intelligent driver model (IDM) as the underlying car-following model. The applicability of other car-following models for the modified MOBIL model to evaluate the lane-changing behavior is yet to be explored and is subjected to future research.

Conclusion

Lane-changing models form a significant part in a microscopic simulation of the mixed traffic stream due to their varying traffic composition and continuous lateral movements, especially at merging sections.

In this article, we have put forward a modified MOBIL lane-changing model in combination with an IDM car-following model by considering a vehicle-type dependent factor under mixed-traffic conditions. This modified model analyzes and classifies the behaviors of aggressive and passive drivers during lane change operations for each vehicle type. We have analyzed the attractiveness of a given lane for each vehicle type and the risk associated with a lane change in terms of acceleration. The acceleration function of the IDM car-following model is utilized to determine the incentive criterion and safety limit. This modified MOBIL model takes into consideration the drivers’ politeness factor $p$, i.e., a selfless or selfish driver, and differentiates these characteristics based on the vehicle type. The lane changing rate is higher in the case of motorcycles for a given politeness factor due to their erratic dynamic characteristics, resulting in a high number of pushy or selfish motorcycle drivers. The least erratic lane changing is recorded in the case of trucks due to their heavy static and low dynamic capabilities, showing a good number of altruistic drivers. Motorcycles exhibit lower lane changing durations for politeness factors $p = 0$ and $p = 1$, showing integrated movements due to their pushy or erratic maneuverability. The headway maintenance at higher velocities with the surrounding vehicles during the lane-change process is lower in the case of motorcycles due to their higher maneuverable capabilities resulting in swerving and filtering actions.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The data regarding the model validation in this study will be available upon request.

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