Modeled Performance Characteristics of Heterogeneous Traffic Streams Containing Non-Motorized Vehicles

By
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Abstract:
Heterogeneous traffic streams containing motorized and non-motorized vehicles are becoming more common in urban areas all over the world. These streams contain both conventional vehicle types such as private cars, buses and trucks as well as non-conventional types namely, bicycles, motorcycles and other vehicular forms, some of which also exhibit peculiar traffic behavior. In order to plan for such traffic it is important to understand the roles the vehicle types plays either individually or collectively on the traffic performance. Using a special model developed by author and aspects of which have been previously published in the TRR series, this study investigates the effects of various non-conventional vehicles on stream performance including lane capacity and saturation flows.

It was found that such heterogeneous streams had reduced link capacities and lane saturation flows in comparison to homogenous flows with private cars only, although the trends were not always consistent. Moreover, it was found that the presence of some of these vehicles resulted in a highly scattered volume, speed density plots, which hardly corresponded with the known fundamental traffic relationships.

It was therefore concluded that such heterogeneous streams have peculiar flows that may not conform fully to the basic traffic theories and hence may require further research to characterize.

KEY WORDS: modeling, traffic, heterogeneous streams, non-motorized-vehicles

INTRODUCTION
Heterogeneous traffic streams containing various vehicular forms are becoming more common all over the world. For one, increased awareness to environmental concerns and greater emphasis on green planning approaches are gradually leading to shifting modal splits in favor of bicycles particularly in industrialized nations. In the less wealthy nations, the increase in mobility arising mainly from economic progress and wealth creation, has given rise to higher ownership of not only motorized vehicles but also non-motorized ones and other non-conventional vehicular forms (1).

In characterizing traffic streams containing such vehicles, two broad categories of vehicles can be defined as follows:

- **Standard vehicles** refer to conventional vehicles such as private cars, minibuses, buses, and light and heavy trucks that exhibit normal stream and queuing behavior usually assumed in traffic analysis.

- **Non-standard vehicles** refer to all those vehicles that exhibit or cause abnormal stream and queuing behavior. They include motorcycles, scooters, mopeds, bicycles and their derivatives. These derivatives come in different sizes, shapes and even names depending on the country of origin and can be motorized or non-motorized with two or more wheels. Examples of these vehicles include auto and cycle rickshaws, bemos, bajajs, tempos, and tuk-tuks and are widely used in developing cities.
In general, the presence of heavy and non-standard vehicles adversely affects the stream performance because of several factors. Firstly, they have poorer acceleration and speed capabilities and hence require more time to maneuver. The maximum speeds most of these vehicles can achieve are restricted and range from 4 to 6 km/h for pedestrian carts, 20 to 30 km/h for bicycles and pedal rickshaws and 40-70 km/h for motorized two wheeled vehicles like motorcycles and scooters and their three- or more-wheeled derivatives. Secondly, the bigger vehicles occupy more space and thereby limit the physical capacity of the roadway. In addition, some non-standard vehicles also exhibit or cause non-conventional behavior, which in most cases increase the tendency for lateral movements and thereby reduce average driving speeds and roadway capacity.

Understanding the characteristics of such heterogeneous streams containing these vehicle types therefore becomes imperative particularly in an attempt to analyze them and formulate appropriate traffic management for them. However, information on such streams is generally unavailable. It is not known if such streams can be adequately described by the existing theories and whether or not they would follow common fundamental traffic relationships.

The aim of this paper is therefore to present some basic characteristics of such streams so as to provide a better understanding of their performance. These characteristics were obtained by use of a special model that was drawn up specifically for heterogeneous traffic mixes containing both motorized and non-motorized vehicles. Detailed description of the model methodology and related aspects have been previously published by the author in the Transportation Research Record (2). In the current study, the model is used to study speed flow relationships and trends in capacity and saturation flows for traffic streams containing non-standard vehicles.

The paper is divided into five sections the first being the introduction. The second section briefly highlights aspects of the model that was used in the analysis. The experimental layout and the stream performance of heterogeneous traffic are presented and reviewed in the third section. Section four provides an overall discussion on the implications of the study findings and assesses their relevance to the theory and practice of traffic engineering. Finally, conclusions and recommendations are provided in the fifth section.

MODEL DESCRIPTION

In recognition that heterogeneous traffic poses specific challenges that may not be adequately addressed by most existing traffic analysis models, a special model covering their unique characteristics was developed. Detailed description of the model can be found in previous publications by the author (2,3). It adopts a microscopic traffic simulation approach and uses a deterministic car following rule developed in Gipp’s work (4) to depict the primary longitudinal movements. Some specific features of the model that make it suitable for heterogeneous traffic are briefly reviewed here.

The model uses a more encompassing definition of traffic heterogeneity to describe flows containing both standard and non-standard vehicles. The definition covers not only all the various vehicles types including motorized and non-motorized vehicles and taking into account their sizes and performance capabilities, but also the non-conventional behavior associated with some of them.

Overview of Vehicular Movements

The movement of a vehicle from origin to destination has been characterized as a complex process involving various maneuvers and decisions that can be taken at the strategic, tactical or operational levels (5). At the strategic or tactical levels, decisions on route choice may be taken whereas actual maneuvers a vehicle undertakes are considered to be on the operational level.

At the operational level, the maneuvers a vehicle can undertake as it travels can be summarized and categorized according to figure 1. Longitudinal movement is the primary maneuver as the vehicle travels towards its destination and can involve free flow or car following conditions. The vehicle may also encounter a queue on the way and be delayed until the queue eventually clears. Bicycles and motorcycles
may also creep slowly towards the stop line as opposed to waiting like other vehicles at the end of the queue. This action is referred to as **seepage action**. Moreover, bicycles and motorcycles can queue side by side on a single lane since the network definition in the model takes into consideration lane widths. Up to three vehicles can queue side by side on a single lane of about 3 meter width. Under normal circumstances, a vehicle will also move laterally and change lanes for a variety of reasons including those for directional requirements, need for overtaking or passing slower vehicles and even a desire to join a shorter queue. Evidently, some of these decisions are mandatory and have to be executed within a certain time or distance limitation whereas the rest are discretionary.

The model incorporates the above movements in order to depict heterogeneous traffic flows realistically. In addition, it specifically stresses on lateral movements since they do play the main role in the resultant stream performance.

**Detailed Lateral Movement Modeling**

Lateral movements play a pivotal role in the performance of heterogeneous streams. The complexities of their maneuvers in heterogeneous streams are analyzed and depicted in the model. Firstly it is recognized in the model that in heterogeneous streams, the faster vehicles always desire to overtake slower ones. It is therefore expected that such traffic will show high frequencies of lateral movements, which therefore requires detailed consideration. The approach used in the model is to identify several actions that a vehicle may actually undertake. These actions include normal overtaking of slower vehicles, changing of lane due to the desire to travel in a specific direction, avoidance of an imminent obstruction of the travel path, changing of lanes to a lane with a shorter queue and finally random changing. Each action is governed by specific rules and at any time in the simulation, the prevailing traffic conditions are assessed to identify viable alternatives.

Noting that there could be several viable options at any given instance, the model uses fuzzy analysis to assess the suitability of each option against exogenous factors such as distance to a critical point, the remaining time to reach that point, the magnitude of speed differences and the magnitude of the differences in queues on the different lanes, before verifying the availability of acceptable gaps in the target lane. At the end of the evaluation process, the vehicle may decide to go on with action or to abandon it altogether.

![Figure 1: Overview of movements a vehicle may execute under normal driving conditions. Lateral movement decisions could involve partial or complete lane changes. Other movements include driving under special conditions like with eye contact with another motorist.](image-url)
Should it decide to go on with it and given acceptable gaps, the vehicle executes the lateral movement using specific patterns that were drawn to closely depict what takes place in reality. The patterns recognize that lateral movements are not instantaneous but require various amounts of time to complete. During such maneuvers, vehicles can use two lanes simultaneously and thereby account for the effects such movements have on both lanes.

Lastly, it distinguishes between discretionary actions that can be abandoned depending on the prevailing traffic conditions and the mandatory ones that must be started and finished before the vehicle reaches the critical point. For example a vehicle must chose the correct travel lane before crossing the stop line. A vehicle wishing to carry out a mandatory action which cannot obtain acceptable gaps may adopt such driving behavior so as to ensure that it obtains an acceptable gap in time. Under such circumstances, the car following rules are overridden and the vehicle’s movement are described by special functions specifically drawn to depict such conditions.

**Lateral Movement Dynamics**

The model recognizes that lane changes and other lateral movements occur gradually and not instantaneously as has been traditionally modeled. It assumes that all lane widths are whole integers and, because lanes widths in urban areas are typically in the order of 2.50 to about 3.25 m, they are rounded off to 3.0m. Then using a lateral speed \( v_y \) of 1.0 m/s for each vehicle, a displacement of one meter is achieved discretely in steps of one second until the vehicle attains its desired lateral position. Consequently, depending on the width and number of individual lanes within an approach or link, a vehicle’s lateral position \( p_y \) can be represented as:

\[
\forall v : p_y \in \{0, 1, 2, \ldots, n\}
\]

\[
n = \sum_{i=1}^{NL} l_{wi} - 1
\]

where:

- \( l_{wi} \) is the width of lane \( i \);
- \( NL \) is the number of lanes in the approach;

The lateral position \( p_y \) represents the lateral displacement in meters of the vehicle from the far edge of the outermost lane in the link. In addition, the following simplifications apply:

1. All vehicles have the same lateral speed;
2. All lane widths are whole numbers or integers;
3. All vehicles have widths of one, two or three meters as below:
   - Bicycles and motorcycles 1m
   - All three wheelers 2m
   - Buses and heavy trucks 3m
   - Other vehicles 3m in motion but 2m at stand still

The widths are effective and include the safe clearance distance another vehicle wishing to overtake them would normally leave. Apart from the heavy vehicles which are somewhat wider than the rest, all standard vehicles are modeled with variable widths. Because vehicles generally travel in the middle of the lane, their widths are taken as three meters in motion but this is reduced to two meters at stand still.

At the start of lateral movement, a vehicle first determines the necessary displacement as follows:

\[
\Delta y = \begin{cases} 
  l_w, & \text{case 1} \\
  w_v, & \text{case 2}
\end{cases}
\]

where:

\( \Delta y \) is the desired lateral displacement.
lw is the lane width; and 
wv is the effective width of the vehicle being overtaken or obstruction ahead.

Cases 1 and 2 refer to situations where the vehicle changes lanes completely or returns to its original path respectively depending on the type of lateral movement maneuver being undertaken. When a vehicle is overtaking a narrow one like a motorcycle or a bicycle, or if it encounters a blockage on a lane, it may return to its original path after overtaking the slower one or after passing the obstacle. The displacement Δy can be either positive (+) or negative (-) depending on the direction of movement. The sign convention used treats Δy as positive for movements from the outermost lane to the faster inner lanes.

The lateral movement is then executed in accordance to the equations (3) and (4). For Case 1 where the vehicles changes lanes completely:

\[
yn(t + \Delta t) = \begin{cases} 
yn(t) + \Delta t \cdot vy, & y_n(t) < y_n(t_0) + \Delta y \\
y_n(t) + 0, & \text{else}
\end{cases}
\]

(3)

For the second case involving returning to the original lane of movement:

\[
yn(t + \Delta t) = \begin{cases} 
yn(t) + \Delta t \cdot vy, & y_n < y_n(t_0) + \Delta y \\
y_n(t) + 0, & y_n = y_n(t_0) + \Delta y \text{ and } x_n < x_{n+1} + \Delta x \\
y_n(t) - \Delta t \cdot vy, & y_n > y_n(t_0) + \Delta y \text{ and } x_n \geq x_{n+1} + \Delta x \\
y_n(t_0) + 0, & \text{else}
\end{cases}
\]

(4)

where:

- \(yn(t)\) is the lateral position of vehicle \(n\) at time \(t\)
- \(yn(t_0)\) is the lateral position of vehicle \(n\) at the start of movement
- \(\Delta y\) is the desired lateral displacement [m]
- \(\Delta x\) is a safety distance [m]
- \(\Delta t\) is the time for recalculation of lateral movement (taken as one second)
- \(x_n\) is the longitudinal position of vehicle \(n\)
- \(x_{n+1}\) is the longitudinal position of overtaken vehicle \((n+1)\)
- \(vy\) is the lateral speed of vehicle \(n\)

Validation of the Model

The model was calibrated and validated with data from Karlsruhe Germany and Nairobi, Kenya. Details of the validation exercise are covered in (2, 3). Firstly, a general verification was undertaken to ensure that the model yielded results that were plausible and consistent with the general traffic behavior. In addition, the model results were compared to field data and to some analytical solutions. In the former case, the model results were compared with the field data through visual and statistical analysis including goodness of fit tests and confidence analysis and they were found to be in close agreement. Table 1 provides a comparison of statistical descriptors of modeled results and field data from Nairobi, Kenya and shows that the two data sets matched each other acceptably well.
Table 1: Observed and modeled values of selected performance parameters. Modeled values are shown in parenthesis. 15% of vehicles were non-standard vehicles and vans. Modelled traffic composition was the same as for the observed data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (Standard Deviation)</th>
<th>Lower Quartile</th>
<th>Upper Quartile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle delay at intersection approach in [s]</td>
<td>88.6 (32.0)</td>
<td>62.5</td>
<td>89.0</td>
</tr>
<tr>
<td>Maximum number of vehicles queuing per cycle</td>
<td>38 (10.0)</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>Mid link speed between two intersections in [km/h]</td>
<td>59.8 (14.3)</td>
<td>56.3</td>
<td>60.0</td>
</tr>
<tr>
<td>Travel time between two intersections in [s]</td>
<td>96.2 (32.3)</td>
<td>74.0</td>
<td>96.0</td>
</tr>
</tbody>
</table>

* Observed and modeled delays for bicycles and motorcycles involved in seepage action were 44.8s and 46.9s respectively.

Additionally, the model results were also found to be in close agreement to some analytical solutions as shown in figure 2. In the first instance, the maximum queue lengths from the model were compared with the solution of the continuum model in part (a). The continuum model is shown as:

\[ Q_{\text{max}} = q \cdot r \]  \hspace{1cm} (5)

where:

- \( Q_{\text{max}} \) = maximum number of queuing vehicles per cycle;
- \( q \) = traffic flow in vehicles per second; and,
- \( r \) = effective duration of the red signal.

Secondly, the modeled delays were also compared against solutions obtained by use of the Highway Capacity Manual (6) and the Webster, (7), methods of calculating delays at signalized intersections (figure 2b). The general form of Webster solution is shown in equation 6.

\[ d = \frac{C(1 - \lambda)^2}{2(1 - \lambda x)} + \frac{x^2}{2q(1 - x)} - 0.65 \left( \frac{C}{q} \right)^{1/3} x^{(x + 5\lambda)} \]  \hspace{1cm} (6)

where:

- \( d \) = average delay per vehicle;
- \( C \) = cycle time;
- \( \lambda \) = the effective green to cycle time ratio;
- \( q \) = traffic flow;
- \( s \) = saturation flow; and
- \( x \) = degree of saturation \((q/\lambda s)\);

The first term in the expression is the delay due to a uniform rate of vehicle arrivals; the second term is the delay due to randomness of vehicle arrivals whereas the third term was empirically derived from the simulation of traffic flow. Under normal circumstances, the calculations can be simplified by ignoring the third part and multiplying the sum of the first two terms by 0.9, that is:
\[ d = 0.9 \left[ \frac{C(1 - \lambda)^2}{2(1 - \lambda x)} + \frac{x^2}{2q(1 - x)} \right] \] (7)

On the other hand, the expression for delay according to the HCM method is as follows:

\[ d = 0.38C \frac{[1 - \lambda]^2}{2[1 - x\lambda]} + 173x^2 \left[ (x - 1) + \sqrt{(x - 1)^2 + \frac{16x}{c}} \right] \] (8)

where:
- \( d \) = average stopped delay per vehicle;
- \( C \) = cycle time;
- \( \lambda \) = the effective green to cycle time ratio;
- \( c \) = capacity of lane group; and
- \( x \) = degree of saturation \((q/c)\);

**Figure 2**: Comparison of model predictions of delay (a) and maximum queues (b) with analytical solutions for homogenous traffic mix on a single lane with capacity of 660 vph and cycle time and green time of 60 and 20 seconds respectively.

Although the comparison of the model results with analytical solutions was done for only homogenous streams with standard vehicles only, it is nevertheless crucial in demonstrating that the model predictions are also reliable in the traditional context as would be encountered in typical traffic flows in western cities.

In summary, the validation process indicated that the model predictions were comparable to field data and to analytical solutions to acceptable levels. There was therefore enough confidence in the model to warrant its use to study the overall performance of heterogeneous traffic containing both standard and non-standard vehicles.
STREAM PERFORMANCE

Experimental Layout

In general, analysis in this section was done for simple network sections shown in figure 3. Whereas capacities and speed density relationships were analyzed for an uninterrupted stretch of a two lane road as in part (a), link travel times and speeds, saturation flows, delays and queues were analyzed on the basis of the simple section consisting of two intersections as shown in (b). Generally the flow considered for the latter case was 1000 vehicles per hour.

Streams containing various proportions of non-standard vehicles in addition to private cars were considered in the analysis and are denoted by the percentage of the non-standard vehicles they contain. For example, streams denoted as 25% bicycles stand for a stream composed of 75% private cars and 25% bicycles. Similarly streams denoted as 25% motorcycles contain 75% private cars and 25% motorcycles. The same definition applies for other streams. Mixed stream are composed of various non-standard vehicles, usually in the same proportion, in addition to private cars and a stream denoted as 25% mixed contains 75% private cars and about 5% each of the various non-standard vehicles. The sizes and performance characteristics of these vehicles are given in table 2.

Stream Characteristics and Capacities

Examination of fundamental relationships between traffic flow parameters (speed, volume and density) is important in verifying that model results are in agreement with the traffic theory. Despite some doubts on the issue (8), it is the general belief that under free flow conditions, speeds on a section of the road reduces as the traffic volume increases. This reduction in speed continues gradually until volumes approach capacity when it becomes precipitous. Flows with lower speeds can also be obtained but these fall under forced flow conditions.

Capacity is the maximum sustained flow that can traverse a section of the road. It is expected to occur at or near the place where the speed reduces precipitously on a volume speed curve. That is also the point where the parts of the curve representing free flow and forced flow conditions meet. Since traffic flow is stochastic and varies with time, it is common to specify a time over which such flows can be sustained. It is clear that if observations were to be made over a very short duration, higher flows could be observed but
such flows would not be sustainable over longer periods of time. In the general traffic engineering practice, an interval of 15 minutes is normally used as the period over which such flows must be sustained.

Table 2: Vehicle characteristics for mixed traffic streams

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Length [m]</th>
<th>Width [m]</th>
<th>Acceleration [m/s²]</th>
<th>Deceleration [m/s²]</th>
<th>Max Speed [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private car</td>
<td>4.5</td>
<td>3</td>
<td>2.50</td>
<td>3.00</td>
<td>n.g.</td>
</tr>
<tr>
<td>Vans</td>
<td>4.5</td>
<td>3</td>
<td>2.00</td>
<td>2.50</td>
<td>n.g.</td>
</tr>
<tr>
<td>Light vehicles</td>
<td>7.0</td>
<td>3</td>
<td>1.10</td>
<td>1.80</td>
<td>n.g.</td>
</tr>
<tr>
<td>Heavy vehicles</td>
<td>11.0</td>
<td>3</td>
<td>0.60</td>
<td>1.50</td>
<td>n.g.</td>
</tr>
<tr>
<td>Motor cycles</td>
<td>2.5</td>
<td>1</td>
<td>3.50</td>
<td>3.00</td>
<td>n.g.</td>
</tr>
<tr>
<td>Motorized 3 wheelers</td>
<td>3.0</td>
<td>2</td>
<td>1.20</td>
<td>1.50</td>
<td>60.0</td>
</tr>
<tr>
<td>Non motorized 3 wheelers</td>
<td>3.0</td>
<td>2</td>
<td>0.80</td>
<td>1.50</td>
<td>25.0</td>
</tr>
<tr>
<td>Bicycle</td>
<td>2.0</td>
<td>1</td>
<td>0.90</td>
<td>2.10</td>
<td>30.0</td>
</tr>
<tr>
<td>Carts</td>
<td>3.0</td>
<td>2</td>
<td>0.50</td>
<td>1.00</td>
<td>6.0</td>
</tr>
<tr>
<td>Pedestrians</td>
<td>1.0</td>
<td>1</td>
<td>0.50</td>
<td>1.00</td>
<td>6.0</td>
</tr>
</tbody>
</table>

a Width of vehicles is 3m in motion but 2m at still stand to allow for seepage action
b n.g.: network governed: speeds are governed by restrictions in network
c Accelerations and decelerations are maximum attainable rates for the respective vehicle type.

Figure 4: Modeled volume, speed and density relationships for a two lane road with homogenous stream containing private cars only having an average desired speed of 80 km/h.
The capacities reported in this paper were obtained based on the definition discussed in the preceding paragraphs. They represent the maximum flows modeled over 15 minute periods on the uninterrupted flow section shown in figure 3. In these flows, each vehicle is considered individually and is not converted to passenger car equivalents for the reasons discussed later in the paper.

The volume speed and density relationships for a two-lane road with only private cars is shown figure in 4. These curves represent the free flow state with high speeds at low volumes but these speeds reduce as volumes increase and approach capacity. They exclude forced flow conditions and were obtained by using the characteristics for private cars as given in table 1. The general shapes of the curves are in accordance with fundamental traffic theories: As the volume increases from zero, the traffic density increases but the mean travel speed reduces. This trend continues up to capacity flows where optimum values for speeds and density are attained. Any further increase in density results in unstable traffic conditions characterized with lower speeds and flows.

The model predicts a maximum capacity of about 3600 vehicles per hour [vph] for the two lanes or about 1800 vph per lane. Although this capacity is lower than for highways for which higher values of up to 2200 vph/lane have been reported (9, 10), it nevertheless looks reasonable under the modeled conditions with limited speeds, since it known that capacities generally reduce as the maximum attainable speeds decrease (6, 8). The maximum speed allowed was 90 km/h and the average desired speed in the network was about 80 km/h. These limitations were necessary to produce results that correspond to driving conditions on urban arterials and do ultimately reduce achievable capacities.

![Graphs showing volume and speed relationships for different traffic compositions](image)

Figure 5: Volume and speed relationships for a two lane road with a desired speed of 80 km/h for flows with non-standard vehicles. The mixed stream had 5% each of heavy vehicles, motorcycles, bicycles, 3 wheeled vehicles and carts.
Stream analysis was also carried out for mixed streams containing non-standard vehicles with the characteristics shown in Table 2. As expected, the presence of non-standard vehicles influences the capacity and the general shapes of the relationships. Figure 5 presents the stream relationships obtained for the same road but with traffic containing 25% of various non-standard vehicles. An explanation of the notation used in describing the various mixed streams was provided under the experimental layout subheading.

A significant observation from figure 5 is the general shape of the speed and volume relationships in the presence of the non-motorized vehicles. It is apparent that the relationships for streams containing motorized vehicles like motorcycles and the like generally follow the expected fundamental relationships and compare well with the trends for private vehicles. However, where the streams contain non-motorized vehicles like bicycles [parts (c) and (d)], the expected shape of the fundamental diagram in no longer discernible and it doubtful whether or not macroscopic models relating speeds and volumes can adequately represent them. These trends could be attributed to the general speed disparity between the faster private cars and the slower non-standard vehicles.

With the exception of motorcycles for which no noticeable differences were observed, the presence of the other non-standard vehicles resulted in significant capacity reductions. The maximum flows obtained on the two-lane road were about 3000, 2300 and 2400 vph (that is 1500, 1150 and 1200 vph/lane) for streams with 25% of 3-wheeled vehicles, bicycles and for all-non-standard vehicles respectively. It can also be seen that the optimum speeds reduce somewhat in the presence of these vehicles.

A summary of these results is provided in Table 3 for streams with 25% of the various non-standard vehicles. It also shows the corresponding lane saturation flows for the same streams. Flows with 25% pedestrian carts caused the greatest reductions of 45% and 52% to the saturation flows and mid block capacities respectively. On the contrary, the presence of motorcycles had a positive effect and resulted in about 40% increase in saturation flows but without any effects on capacity. In mixed streams, bicycles and motorcycles creep towards the stop line bypassing the other stopped vehicles and thereby resulting in higher saturation flows and less delays.

Table 3: Effects of various vehicle types on lane capacity and saturation flows. Capacities are for all vehicles in the stream and are NOT converted to passenger car equivalents.

<table>
<thead>
<tr>
<th>Stream Composition</th>
<th>Lane Capacity at mid-block [veh/h]</th>
<th>% change</th>
<th>Lane Saturation Flow [veh/h]</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private Cars Only</td>
<td>1800</td>
<td>0%</td>
<td>1980</td>
<td>0%</td>
</tr>
<tr>
<td>25% Motorcycles</td>
<td>1800</td>
<td>0%</td>
<td>2430</td>
<td>23%</td>
</tr>
<tr>
<td>25% Trucks and buses</td>
<td>1300</td>
<td>-28%</td>
<td>1350</td>
<td>-32%</td>
</tr>
<tr>
<td>25% Motorized 3 Wheelers</td>
<td>1500</td>
<td>-17%</td>
<td>1530</td>
<td>-23%</td>
</tr>
<tr>
<td>25% Non-motorized 3 Wheelers</td>
<td>980</td>
<td>-46%</td>
<td>1170</td>
<td>-41%</td>
</tr>
<tr>
<td>25% Bicycle</td>
<td>1150</td>
<td>-36%</td>
<td>2300</td>
<td>16%</td>
</tr>
<tr>
<td>25% Pedestrian carts</td>
<td>860</td>
<td>-52%</td>
<td>1080</td>
<td>-45%</td>
</tr>
<tr>
<td>Mixed Flow with various types</td>
<td>1200</td>
<td>-33%</td>
<td>1600</td>
<td>-19%</td>
</tr>
</tbody>
</table>

Since capacity flows on actual networks are generally observed after bottleneck conditions (8), one may expect that saturation flows at a stop signal would be comparable to mid-block capacities where flows are uninterrupted. Whereas this was found to be true for the streams with standard vehicles, it was not so for streams with non-standard vehicles. Streams with private cars only had a mid-block capacity and a saturation flow of 1800 and 1980 vph per lane respectively and that with 25% heavy vehicles also had flows of 1300 and 1350 vph per lane respectively. In both cases the flows were comparable. On the contrary, saturation flows for streams with 25% bicycles and 25% motorcycles were evidently higher than the mid-block capacities (2300/1150 and 2430/1850 vph/lane respectively).

This apparent anomaly is attributed first and foremost to the occurrence of seepage action. Seepage action occurs only where vehicles have stopped as they wait for their right of way. Although bottleneck situations are somewhat similar, seepage action hardly occurs there because the speeds of vehicles hardly reach zero.
Rather, the vehicles move at reduced speeds, which are usually in the same order of magnitude as speeds of vehicles undertaking seepage action, and thereby exclude the latter from taking place. In addition, what should be considered as saturation flows in heterogeneous streams occur over relatively short intervals of time and the traffic conditions enabling them can not be sustained over longer time periods. In such streams, vehicles can queue side by side on one lane but when they start moving and clear off the stop line, they quickly realign themselves and return to normal travel (figure 6). Thus the flows observed crossing the stop line are much higher than what would be observed at a point a short distance downstream. These factors make saturation flows for streams with non-standard vehicles, and especially the narrow ones, significantly higher than the mid-block capacities. But in the absence of non-standard vehicles, the pattern of flow is relatively uniform throughout and saturation flows and capacities are expectedly similar as was the case for streams with private cars and heavy vehicles.

![Queuing and crossing stop line](image1)

![Normal flow after realignment downstream](image2)

**Figure 6: Comparison of queuing pattern and normal flow for heterogeneous stream containing narrow vehicles.**

To better understand how the presence of non-standard vehicles affects capacities and stream performance in general, relationships were drawn for capacity and saturation flows based on the proportion of these vehicles in the stream. Figure 7 shows trends in link mid-block capacities and lane saturation flows as the proportion of various non-standard vehicles increases. The trends were determined for the link sections shown in figure 3. The curves were obtained by regression analysis and show the best fit for the various individual points simulated. The correlation coefficients were generally high and ranged from 0.65 to 0.91 with the majority being above 0.8.

Except for the stream containing motorcycles that remains relatively unchanged, the capacities generally reduce as the proportion of the non-standard vehicles increases. The results for motorcycles are not surprising since motorcycles have performance capabilities comparable to those of private cars. The stream with non-motorized 3-wheeled vehicles had the greatest reduction in capacities as the level of heterogeneity increased because of their size and poorer performance capabilities. Although there is hardly any prior work to which most of these results can be compared, the trends for heavy vehicles are generally similar to what has been reported for highways. The results of a function proposed in (10) relating highway capacities and the proportion of heavy vehicles compares well with the observed trends. In (11) similar findings at motorway roadwork sites were also reported.

These trends can be attributed first and foremost to the reduction in speeds resulting from the presence of the slower vehicles. As the number of slower vehicles increases, the overall desired speed of the stream reduces thereby causing a corresponding decrease in capacities. In addition, the size of the vehicle also plays a role in the modeled capacities. It can be seen that although the bicycles and non-motorized three wheeled vehicles have similar speed capabilities, capacities for the former are somewhat higher. Moreover, the motorized three wheeled vehicles also possess comparable speed capabilities to the heavy vehicles but...
they do show marginally higher capacities. The smaller vehicles occupy less space and can achieve higher densities at any speed level and consequently higher capacities.

Saturation flows of heterogeneous traffic also vary depending on the proportion of non-standard vehicles in the stream. On the one hand, saturation flows for streams containing motorcycles and bicycles increased linearly with the proportion of these vehicles. In addition, the saturation flows of these streams are significantly higher than their corresponding mid-block capacities. This is attributed to seepage action which results in a temporal surge in flow immediately after the signal turns green and thereby increasing the average number of vehicles actually discharged from the stop line. But as the vehicles travel further downstream, realignment occurs and flow patterns return to normal. This has been discussed in the preceding paragraphs. Over the modeled range of heterogeneity, saturation flows for the two vehicles types increased from slightly less than 2000 to well over 2500 vehicles per hour per lane, amounting to about 40% increase. However, for streams with standard vehicles (that with private cars and heavy vehicles only), saturation flows and capacities are comparable as expected.

![Regression curves for (a) capacities and (b) saturation flows for heterogeneous traffic containing various proportions of non-standard vehicles.](image)

**Figure 7:** Regression curves for (a) capacities and (b) saturation flows for heterogeneous traffic containing various proportions of non-standard vehicles.
In contrast to those with bicycles and motorcycles, streams with other vehicle types generally show reduced saturation flows as the proportion of the other vehicles types increases. Streams with three wheeled vehicles and heavy vehicles showed consistent reductions with increasing heterogeneity and typical values drop to about 1400 and 1150 vph/lane respectively at 35% proportion. The mixed stream containing various vehicle types showed somewhat less pronounced reductions than the other streams and the minimum saturation flow obtained was about 1500 vph/lane at a composition of about 40%. This is because the would be gains from the presence of motorcycles and bicycles are counteracted by the presence of the other vehicles, thus giving values somewhere midway between the two extremes.

It is known that saturation flow of any stream is largely affected by the maximum attainable acceleration of the vehicles in it \(^3\). As the acceleration capabilities reduce, so does the saturation flow. In addition, it is also affected by the ability of vehicles to engage in seepage action and finally by the size of the vehicle. The size factor partly explains why streams with three wheeled vehicles attain higher saturation flows than the heavy vehicles, although their speed and acceleration capabilities are comparable.

**Lateral Movement Frequencies**

Streams containing non-standard vehicles are also characterized by higher frequencies of lateral movements as the faster vehicles try to overtake the slower ones. This is portrayed in figure 8 that shows the variation in lateral movement frequencies for various traffic streams. It is clear that the mixed stream have the highest frequencies of lateral movements reaching up to 2.5 movements per vehicle per km. In comparison, streams with private cars only and those with heavy vehicles show only 0.25 and 0.7 movements per vehicle per km respectively. The trend for other heterogeneous streams are generally similar and fall somewhere between that of the mixed stream and the private cars.

![Figure 8: Variation of lateral movement frequencies with flow for different stream compositions.](image)

The trends of lateral movements generally follow an inverted U-shape: as the traffic volume increases, so does the frequency of lateral movements. This trend continues up to volumes roughly equal to half the capacities of the streams and thereafter reduces gradually towards zero at capacities. The trends are in agreement to what has been observed on German highways \((12, 13, 14)\) and are expected because as the flow increases, the number of vehicles wishing to overtake also increases, but the availability of acceptable gaps diminishes concurrently. The two factors reach a point of equilibrium at volumes about half of the respective capacities thereby resulting in highest lateral movement frequencies. As flows increase further
and approach capacities, the speeds become more uniform and availability of gaps diminishes thereby reducing the potential for lateral movements. As expected, under such conditions, lateral movements are primarily caused by the desire of faster vehicles to overtake the slower ones. Consequently, the resulting movements predominantly fall in the two classes of overtaking and random maneuvers. The latter represent lanes changes from the inner to the outer ones, either randomly or when forced to do so by faster vehicles wishing to overtake.

**DISCUSSIONS**

It has been shown in this paper that non-standard vehicles affect traffic performance mainly by their performance capabilities, their dimensions and their ability to engage in some maneuvers such as seepage. The presence of slow moving vehicles causes the faster vehicles to try to overtake and thereby resulting into significantly higher frequencies of lateral movements. With the exception of those containing motorcycles, streams with non-standard vehicles types are generally associated with lower performance parameters than the homogenous streams with private cars only. Streams containing bicycles, motorized and non motorized three wheeled vehicles as well those with pedestrian carts and heavy vehicles show reduced capacities, reduced saturation flows and reduced link speeds as the proportion of these vehicles increase. The superior capabilities of motorcycles generally result in improved performance as their proportion in the traffic stream increases. Streams containing up to 40% non standard vehicles were considered and the results are considered reliable within that range.

However, the effects of non-standard vehicle types on various performance parameters are not always consistent. In certain cases, the presence of a vehicle type in a stream can affect various performance measures in completely opposite ways. An example is streams with bicycles. The bicycle is a bit peculiar because its ability to engage in seepage action and its small size make it have somewhat higher saturation flows but its lower speed capabilities result in lower capacities and average travel speeds. However, the trend observed most was that the degree to which each vehicle type affected the various performance parameters varied greatly depending on the vehicle type and the measure of performance considered. It follows, therefore, that assignment of general equivalency factors (or passenger car unit values) for non-standard vehicles applicable in all circumstances may not always yield reliable results. Rather, where such values must be used, it would be more appropriate to specify them for each performance measure separately.

The broad characteristics of these vehicles also result in scattered speed and volume relationships for which the expected shape of the fundamental diagram is hardly discernible. This is of paramount importance since it raises doubts on whether the streams with some of these vehicle types can be adequately represented and analyzed by macroscopic models relating speed and volume.

These findings raise important questions on the type of traffic management strategies suitable for controlling and optimizing performances of such streams. Since even the non-standard vehicles play an integral part in the overall urban mobility, their usage cannot be simply banned without negative ramifications to the flow of persons, goods and services in a given jurisdiction. In addition, the capital investment required to provide separate auxiliary lanes and carriageways to these vehicles is hardly available especially in the short term.

Noting that there can also be some benefit in having some of these vehicles in the traffic stream, perhaps the most suitable strategies would be those that can harness their advantages while minimizing their apparent disadvantages. Since saturation flows generally increase for streams with bicycles and motorcycles, it is apparent that they would result in a more efficient use of the road space, particularly where their average occupancy is comparable to that for private cars. Consequently, policies encouraging the safe usage of such vehicle types in the traffic stream, such as provision of special lanes and queuing spaces, should be explored. If well included in the design of urban roads, as has been widely done in the Netherlands for example, it can result in enhanced intersection capacity and safety.
CONCLUSIONS

This paper has presented theoretical performance characteristics of heterogeneous traffic including non-motorized vehicles, which were obtained by use of a special model. It also provided a brief overview of the model used in the study. It has shown that such heterogeneous traffic streams generally have lower capacities and saturation flows. However, those streams with bicycles and motorcycles better performances mainly because of the ability of these vehicles to engage in seepage action and the better speed and acceleration capabilities of the latter. In addition, heterogeneous flows are generally associated with higher incidences of lateral movements as the faster vehicles try to overtake the slower ones.

On the whole, these findings are important to the overall understanding of the characteristics of such heterogeneous streams and for selection of appropriate operational policy options in managing them. The study has clearly demonstrated that the stream behavior in some heterogeneous flows may not be consistent with the fundamental relationships on which most macroscopic analysis are based. In particular the scatter associated with the speed volume relationships and the inconsistent influence they have on the performance parameters seem to challenge the traditional fundamental relationships and the application of the private car equivalency factors. Better understanding and characterization of such streams may therefore necessitate further research. Moreover, further model validation with more heterogeneous traffic streams may also be necessary to provide greater confidence in the results.

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