DETERMINATION OF MOTORCYCLE PASSENGER CAR
EQUIVALENCE FOR UNINTERRUPTED FLOW IN AN URBAN
ROAD OF MEDELLIN, COLOMBIA

By

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Abstract

Motorcycle ridership has increased globally. Its high presence in traffic accidents has led to its study from the safety perspective. Its role in traffic congestion and road performance is, nevertheless, less known. Studies made in the latter aspect have shown divergent results, without leading to a general consensus. In Colombia, the annual rate of motorcycle ownership increase (15%) is the highest in South America, and to the year 2009 motorcycles already represented 45% of the national motorized fleet. The lack of knowledge of the effects of motorcycles on road performance and congestion leads to inaccuracies in road network planning and design in countries with high ridership of these vehicles. This work studies motorcycles impact in traffic congestion by determining its Passenger Car Equivalence (PCEm) in an urban road of three lanes, zero slope, uninterrupted flow and 3.2 m lane width. It was found that PCEm decreases as passenger cars density increases due to an increase in motorcycle filtering. During stable flow, the average PCEm was 0.29, whereas unstable flow showed an average PCEm of 0.05. Average PCEm observed for all regimes was 0.16. According to this, it is concluded that traditional PCEm used in Colombia (PCEm = 0.5) is not accurate and overestimates motorcycles impact on traffic. It is also concluded that the impact of motorcycles on congestion, for the observed traffic compositions, is negligible when filtering. Thus, from the traffic perspective, motorcycles can be beneficial to society for they, in certain conditions, allow people to dodge congestion and keep moving.

Keywords: Equivalence factor, passenger car equivalence, congestion, filtering, space mean speed, motorcycles.
1 BACKGROUND AND OBJECTIVE

1.1 Rise of Motorcycles

To begin with, it is necessary to mention that ‘motorcycles’ in this study refers to motorbikes, mopeds and motorscooters with cubic capacity of 50 cc or more and with seats provided to the rider. It does not include powered (electrical or gasoline) bicycles or standing-powered scooters. Having said that, several studies have shown that various nations around the world have experienced rapid growths in motorcycle ridership in the last 20 years, to the point of achieving significant proportions of their traffic being composed by motorcycles (1, 2, 3, 4, 5, 6, 7, 8, and 9), despite more recent downward trends due to the economic recession of 2008 – 2009 (1). Nevertheless, these recent downward trends are, in some countries, slow, with 0.3% annual decreases in UK, for example (1). On the other hand, nations like China are still experiencing growths (2.9% annually) in their motorcycle exports numbers (10), and regions like South America (SA) have still growing rates of registered motorcycles (11), see FIGURE 1.

![Figure 1: Annual growth of motorized vehicles](image)

Compared to Asian nations, motorcycle-motorization levels in the SA region are moderate. Despite this, growth tendencies in SA nations are significant. Colombia stands out among them with an explosive annual growth of 14.7% (11).

According to the Colombian national department of statistics (DANE by its acronym), between 2003 and 2009, the number of households with at least one motorcycle presented a cumulative growth of 77% (12). To the year 2011, it has been found that 18% of total Colombian households have at least one motorcycle (12). According to BBVA (2010), since the year 2005 motorcycles have had the biggest share of the Colombian national fleet, reaching 45% in the year 2009 (13).

FIGURE 2 shows growth trends of registered motorcycles in Colombia. It was constructed using data from (12, 13, 14, and 15).
FIGURE 2 Growth trends of the number of motorcycles in Colombia

The intensification in motorcycles growth rate after year 2009 may be explained by the lowering of acquisition prices due to the growth of Chinese brands, free trade agreements and easiness of financial opportunities related to motorcycle market.

In addition to ownership, motorcycle usage has also grown. Studies show that, between 2002 and 2010, the percentage of motorcycle users that ride one but do not own it, tripled. This suggests more motorcycles are been used also by the owner’s family and/or employees (14).

According to all this, it is reasonable to expect a significant growth of motorcycle’s presence in Colombian roads and thus, it becomes essential to expand the knowledge of their impact on congestion and road network performance.

1.2 Traditional PCEm value used in Colombia and its implications

Road performance is usually measured by its flow quality. However, flow is composed by various types of vehicles and agents that compete for road space (16). Because of this, passenger car equivalence (PCE) concept was created to a) represent the effect of lower performance and bigger vehicles (buses and heavy vehicles) on passenger cars and b) to convert heterogeneous flows into equivalent homogeneous flows, which facilitates the elaboration of level of service (17), capacity and performance assessments to road infrastructure and networks. Also, it facilitates new infrastructure designs. 2000 Highway Capacity Manual (HCM) defines PCE as the number of passenger cars that could use the same amount of road capacity that one heavy vehicle uses under prevalent traffic conditions (18).

According to this, buses and heavy vehicles PCEs are several times bigger than 1 and the basic unit of PCE are passenger cars, with other vehicles types defined in relation to them. In the case of motorcycles, HCM assumes motorcycles follow lane discipline and assigns an arbitrary PCE value of 0.5. In Colombia, this value is widely accepted and used. This may not be precise, for the mentioned HCM assumption is not valid in Colombian context, due to frequent filtering, and because motorcycles have a significant presence in traffic.

In addition to this, motorcycles high presence in traffic accidents has led, globally, to its study from the safety perspective. Its role in traffic congestion and road performance is, nevertheless, less known. Despite they constitute a significant share of total traffic in many countries, they are still poorly
represented by existing traffic flow theories, methodologies (6), such as PCE, and are mostly absent from traffic international studies.

It is clear, then, the necessity to determine motorcycles PCE with more precision, especially in countries like Colombia, where its ridership is becoming so relevant. Failure to do so will translate into road networks performance underestimation or overestimation and new infrastructure will continue to be designed with imprecisions that can be avoided. Section 2 describes methodologies that have been used to measure PCE of different types of vehicles, including motorcycles.

1.3 OBJECTIVE

To study motorcycles impact on traffic congestion, in a Colombian city, by measuring its Passenger Car Equivalence.

It’s worth mentioning that this study has the following hypothesis:

- Motorcycles are less affected by passenger cars congestion but generate additional delays to them.
- Motorcycles only affect traffic significantly when using lane discipline, that is to say, when they use spaces that passenger cars could also use.
- For a given lane-width, motorcycle’s filtering is governed mainly by traffic speed.

2 METHODOLOGICAL FRAMEWORK

At present, different approaches are been used to determine PCE for various kinds of vehicles, including motorcycles. Other places where motorcycle PCE has been measured include Greece (19), India (20), London, using a simulator (6, 21) and Vietnam (8), to name a few. The main differences resides in the performance parameter used, be it headway, delay, space mean speed, gap or vehicles-hour, among others (17).

In this section, some of the main approaches used to determine PCE for various kinds of vehicles, including motorcycles, are described.

2.1 Delay-based PCE

Rodriguez and Benekohal (2004) used delays to determine buses PCE at signalized intersections. Delay was defined as the additional time passenger cars take to cross the intersection, due to the presence of the bus. This approach takes into account delays caused to the whole queued vehicles for various positions of the bus in the queue. The expression to calculate PCE is:

\[ PCE_b = 1 + \frac{db}{do} \]
Where PCEb is buses PCE, \( \overline{db} \) is the average additional delay generated by buses and \( \overline{do} \) is the average delay for an only-car queue. The additional delay that the \( k \)th vehicle will experience equals the delay of the \( k \)th vehicle in a queue with bus minus the delay experienced by the \( k \)th vehicle in an only-car queue:

\[
dk = d_k^b - d_k^0
\]

The total additional delay caused by the bus to all queue is:

\[
d_0 = \sum_{k=b}^{n} d_k
\]

Where \( n \) is the number of vehicles in queue.

Inasmuch as the position of the bus in the queue, and the number of vehicles in queue affect PCEb, probabilities of the bus being in the \( K \)-ésima position and probabilities of having “n” number of vehicles in line, were calculated. PCEb were multiplied by those probabilities accordingly.

### 2.2 Space Mean Speed-based PCE

Rahman and Nakamura (2005) estimated PCE for rickshaws in road segments distant from signalized intersections. For this, they measured the effects of the proportion of rickshaws in traffic on average space mean speed of passenger cars. Thus, they defined PCE as:

\[
PCE_{cza} = 1 + \frac{S_b - S_m}{S_b}
\]

Where \( S_b \) is average space mean speed of passenger cars for 0% rickshaws in traffic and \( S_m \) is average space mean speed of passenger cars for \( 0 < \% \) rickshaws.

### 2.3 Density-based PCE

Tiwari et. al (2007) estimated PCE for various kinds of vehicles in heterogeneous traffic on Indian streets. The vehicles they measured included motorcycles, three wheelers and bicycles. Insomuch as Indian traffic is highly heterogeneous and does not follow lane discipline, they decided to modify the density method to establish density in terms of area.

To accomplish the above, the 85 \( \% \) percentile of road width that each vehicle uses, was determined. It is measured from one of the sides of the road. Thus, PCE (or PCU) for each type of vehicle is:
Where \( k \) is the type of Street, \( j \) is the type of vehicle analyzed; \( K_{pc} \) is the passenger car density; \( W_{85pc} \) is the 85\textsuperscript{th} percentile of road width used by passenger cars; \( q_j \) is the “\( j \)” type of vehicle flow; \( \bar{u}_j \) is the space mean speed of type “\( j \)” vehicle and \( W_{85j} \) is the 85\textsuperscript{th} percentile of road width used by the type “\( j \)” vehicle.

### 2.4 Motorcycle Car Unit (MCU)

In some Asian countries, due to the high prevalence of motorcycles, mixed traffic is converted to equivalent motorcycles, instead of equivalent passenger cars (8). One approach to determine the equivalence factor of a type “\( i \)” vehicle with respect to motorcycles, is given by the following expression:

\[
MCU_i = \frac{V_{mc}/V_i}{A_{mc}/A_i}
\]

Where \( MCU_i \): Motorcycle Car Unit for type “\( i \)” vehicle, \( V_{mc} \): Motorcycle space mean speed, \( V_i \): type “\( i \)” vehicle space mean speed (truck, bus, passenger car, etc.), \( A_{mc} \): Average road area occupied by a motorcycle, \( A_i \): Average road area occupied by type “\( i \)” vehicles.

### 2.5 Headway-based PCE

In Bangkok, passenger car equivalencies for motorcycles, at midblock roadway sections, where measured using three variations of the headway method (22):

<table>
<thead>
<tr>
<th>Approach</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( PCE_m = \frac{h_2}{h_1} \times 1 )</td>
</tr>
<tr>
<td>2</td>
<td>( PCE_m = \frac{1}{2} \times \left( \frac{h_3 - h_1}{h_1} \right) )</td>
</tr>
<tr>
<td>3</td>
<td>( PCE_m = \frac{h_4}{h_1} )</td>
</tr>
</tbody>
</table>

![FIGURE 3 Variations of headway method to measure motorcycle PCE](image)
Approach 1 is the PCE of motorcycles, given there is only one motorcycle between successive cars. Approach 2 is the average PCE of each motorcycle given two motorcycles are between two successive cars. Approach 3 is the expression of motorcycle PCE as the comparison between headway between two successive motorcycles and headway between two successive cars. In this particular study, PCE of filtering motorcycles will equal zero.

TABLE 1 summarizes main results of consulted studies:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Obtained values of passenger car equivalence for motorcycles (PCEm)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>$0.4 &lt; \text{PCE}m &lt; 0.8$</td>
<td>-When speed is lower, PCEm is lower and viceversa. -In conditions of free flow PCEm &gt; 0.5 due to reduced effects of filtering</td>
</tr>
<tr>
<td>8</td>
<td>PCEm = 0.26; PCEm = 0.28</td>
<td>Reports average dimensions of motorcycles as 1,87 m x 0.64 m.</td>
</tr>
<tr>
<td>16</td>
<td>PCEm = 0.32</td>
<td>No observations to be mentioned.</td>
</tr>
<tr>
<td>21</td>
<td>$0.16 &lt; \text{PCE}m &lt; 0.61$</td>
<td>PCEm decreases as lane width increases because it facilitates filtering.</td>
</tr>
<tr>
<td>22</td>
<td>$0.3 &lt; \text{PCE}m &lt; 0.8$</td>
<td>In this study PCEm for filtered motorcycles is not considered and would equal zero.</td>
</tr>
</tbody>
</table>

3 METHODOLOGY

3.1 PCEm Calculation

Based on previous methodologies shown, a modified motorcycle car unit approach (see section 2.4) is proposed to calculate motorcycles PCE for various traffic regimes. The proposed methodology is based on an existing method but modifies it by incorporating occupied road widths and probabilities of motorcycles following lane discipline (using passenger car lanes). These will be described later. This method was proposed taking into account the set of hypothesis mentioned in section 1.3, having in mind that filtering alters PCEm values in revised studies and considering that traffic compositions without significant (less than 5%) presence of motorcycles could not be obtained, therefore, limiting the possibility of using delay based methodologies. The Necessary information was collected using traffic videos (see section 3.2).
Having said that, Motorcycle PCE is defined by the following expression:

\[ PCEm = P_c \times \frac{V_{leq}/V_m}{W_{veq}/W_{vm}} \]

Where \( PCEm \) is motorcycle PCE. \( P_c \) is the probability of motorcycle using passenger car spaces (inside the lane). \( W_{veq} \) is the average road width that passenger cars use and \( W_{vm} \) is the average road width that motorcycles use.

\( P_c \) allows to consider that motorcycles effects on traffic differs when it competes for space (follows lane discipline or uses space inside the lane) or when it shares space (filters). Likewise, it takes into account that when motorcycle competes for space, it does it mainly with its width more than with its length. Because of this, widths are compared instead of areas. Comparing areas may lead to an underestimation of motorcycles impact on traffic.

### 3.2 Location and Field Information Processing

As mentioned previously, necessary information was collected from traffic videos. The study site (see FIGURE 4) was a one-way urban roadway of Medellin, Colombia with 3 lanes. Lane and roadway widths were 3.25m and 10m, respectively. The length of the study site was 60m and it was 250m away from any signalized intersection to comply with the un-interrupted flow condition. It is important to mention that at the end of the study site there is an incoming diagonal flow from the right. This site was chosen because it complies with the un-interrupted flow condition and existing videos of the road allowed good visual for the measurements made. Also, main roads of Colombian cities have three lane roadways.
123 minutes of video were processed. Travel times and percentage of travel time occupying passenger-car lanes of 615 motorcycles (5 per minute), were measured. Travel times of 1107 passenger cars (9 per minute or 3 per lane, per minute) were also measured. Speed can be determined using travel times and length of the study site.

Flows (Q) by type of vehicle (light-vehicles or passenger cars, buses, trucks and motorcycles) and travel times (T) by type of vehicle (light and motorcycles), were measured for each minute of video.

Other performance parameters measured were:

- **Density by type of vehicle (light vehicles and motorcycles):** measured every 12 seconds, to establish average densities per minute of video. This was accomplished by converting videos to pictures every 12 seconds. 5 pictures were studied per minute to determine equivalent vehicles densities per lane (veh/km) and motorcycles spatial densities (mot/km2).

- **Percentage of travel time a motorcycle occupies passenger cars lanes (not filtering):** measured for various traffic regimes. To accomplish this, besides measuring total travel times along the studied road section, the time a motorcycle occupies the passenger-car lane was also measured. The latter is measured when the motorcycle is located at a place inside the lane at which lane-sharing with passenger cars is not possible. The ratio between this two measured times gives the percentage of time a motorcycle occupies the passenger-car lane (Pc).

It is worth mentioning that for the density parameter buses and trucks were converted to equivalent passenger cars. For the flow parameter, buses and trucks were not converted to equivalent vehicles. This is because: Density refers to the space used by vehicles and it is easy to determine visually, for the prevalent traffic conditions, how many equivalent vehicles fit into the space a bus or a truck is using. With respect to flow, the conversion to equivalent vehicles implies a performance component (speed, acceleration, etc.). Plus, equivalence factors mostly used in Colombia come from HCM and were determined for USA conditions so using them would cause imprecisions. In addition to this, low presence of heavy vehicles in the road section studied (see TABLE 3) did not justify the effort of converting their flow to equivalent vehicles and it would be subject to the inaccuracies of using USA equivalence factors.

### 3.3 Occupied road-width (ORW) and Sensitivity analysis

As shown in the expression of section 3.1, average ORW by passenger cars and motorcycles is needed in order to compute PCEm. However, ORW per type of vehicle were not measured. Because of this, average ORW for each type of vehicle was established based on literature review (6, 23). After this, arbitrary variations of the average ORW were generated in order to perform a sensitivity analysis of how variations of ORW affect PCEm values.

It is worth clarifying that average ORW goes beyond the vehicle’s physical width. It also takes into account it’s lateral safety distances with respect to other vehicles. The lateral safety distances increase as traffic and vehicle speeds increase and, in the same way, can be very small for low speeds. Keeping this in mind, the arbitrary variations of ORW for the sensitivity analysis, were generated by varying the lateral safety distances from a minimum to a maximum, but leaving constant the vehicle’s (motorcycles and passenger cars) physical width.

Next, used values are listed.
The average physical widths established were:

Motorcycles: 0,8 m
Passenger cars: 2,0 m.

The minimum and maximum lateral safety distances were:
Motorcycles: 0,15m /side; 0,5m/ side
Passenger cars: 0,3m/side; 0,5m/side

Total minimum and maximum occupied road width:
Motorcycles: 1,1 m; 1,8 m
Passenger cars: 2,6 m; 3,0 m

4 RESULTS AND ANALYSIS

4.1 Basic results

First, it is worth noting that all tables and graphics presented here on refer to the set of all three lanes. As motorcycles are the objects of study, analyses where not performed for each lane, as usual. This is because they are able to transit outside passenger car-lanes, sometimes without ever using it through the whole study section. For this, doing analysis as usual would difficult (or in some cases prohibit) the inclusion of motorcycles in the measured parameters (density, flow, speed), for each lane.

TABLE 2 shows general conventions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Convention</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_e$</td>
<td>Spatial mixed flow – 3 lanes (Veh/h-km).</td>
</tr>
<tr>
<td>$\bar{P}_c$</td>
<td>Average percentage of travel time that the motorcycle uses passenger car lane. Probability that motorcycle uses passenger car lane (%).</td>
</tr>
<tr>
<td>$P_{CEm}$</td>
<td>Motorcycles passenger car equivalence</td>
</tr>
<tr>
<td>$K_e$</td>
<td>Spatial density passenger cars and motorcycles - 3 lanes (veh/km²).</td>
</tr>
<tr>
<td>$K_l$</td>
<td>Passenger car density - 3 lanes (veh/km).</td>
</tr>
<tr>
<td>$K_m$</td>
<td>Motorcycles spatial density (motocicletas/km²).</td>
</tr>
<tr>
<td>$V$</td>
<td>Traffic space mean speed (passenger cars and motorcycles) (km/h).</td>
</tr>
<tr>
<td>$V_l$</td>
<td>Passenger cars space mean speed – 3 lanes (km/h).</td>
</tr>
<tr>
<td>$V_m$</td>
<td>Motorcycles space mean speed (km/h).</td>
</tr>
<tr>
<td>$W_{ovl}$</td>
<td>Passenger cars average occupied road width (m).</td>
</tr>
<tr>
<td>$W_{om}$</td>
<td>Motorcycles average occupied road width (m)</td>
</tr>
</tbody>
</table>
TABLE 3 presents the characterization of traffic conditions, for the set of three lanes, during the time of study.

TABLE 3 Characterization of traffic conditions during the time of study for all three lanes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Stable flow (KI &lt; 60 veh/km/lane)</th>
<th>Unstable flow (120veh/km/lane &lt; KI)</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{V} ) [km/h]</td>
<td>50</td>
<td>8</td>
<td>29</td>
</tr>
<tr>
<td>( \bar{V}_m ) [km/h]</td>
<td>53</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>( \bar{V} ) [km/h]</td>
<td>51</td>
<td>12</td>
<td>31</td>
</tr>
<tr>
<td>Composition (buses; trucks; passenger cars; motorcycles) [%]</td>
<td>4; 8; 63; 25</td>
<td>2; 3; 53; 42</td>
<td>3; 5; 58; 34</td>
</tr>
<tr>
<td>KI min; KI max; ( k_l ) [Veh/km]</td>
<td>42; 155; 92</td>
<td>226; 561; 373</td>
<td>42; 561; 234</td>
</tr>
<tr>
<td>Ke min; ke max; ( k_e ) [Veh/km(^2)]</td>
<td>5806; 18710; 11861</td>
<td>31613; 64516; 44381</td>
<td>5806; 64516; 28253</td>
</tr>
<tr>
<td>Km min; km max; ( km ) [Veh/km(^2)]</td>
<td>0; 7742; 2660</td>
<td>1290; 16774; 7055</td>
<td>0; 16774; 4875</td>
</tr>
<tr>
<td>Q total min; Q total max; ( \bar{Q} ) total [veh/h]</td>
<td>2460; 6120; 4115</td>
<td>1020; 4680; 3024</td>
<td>1020; 6120; 3565</td>
</tr>
<tr>
<td>( P_c )</td>
<td>0,61</td>
<td>0,06</td>
<td>0,33</td>
</tr>
</tbody>
</table>

Finally, average \( P_{CEm} \) obtained for stable flow was 0,29. Average \( P_{CEm} \) obtained for unstable flow was 0,05 and average \( P_{CEm} \) obtained for both regimes was 0,16. It is worth reminding that \( P_c \) is the probability of motorcycle using passenger car spaces (inside the lane), whereas \( P_{CEm} \) is motorcycle PCE.

4.2 Fundamental Curves

Fundamental curves were obtained for the set of three lanes. Having in mind that motorcycles are the object of study, with their ability to use road width continuously (filtering), and not only discreetly (following lane discipline), analyses had to consider fundamental parameters of traffic as spatial variables (incorporating road-width). Thus, density is a spatial density “Ke” (veh/km\(^2\)). Flow is a spatial flow “Qe” (veh/h-km). Speed remains as a space mean speed (km/h).

FIGURE 5 presents the obtained relationship between Spatial Density “Ke” and Space Mean Speed “V”. The theoretical relationship is observed, this helps validate the data. All obtained information corresponds to low density, stable flow and high density, unstable flow. No middle density regimes were
obtained. The other two fundamental curves (Qe vs. V and Ke vs. Qe) also showed theoretical relationships, as expected.

![Graph showing Ke vs. Qe relationship](image)

**FIGURE 5** Observed relationship between spatial density and traffic space mean speed. As shown in previous figure and despite information gaps, extreme regimes (low and high density, or stable-unstable regimes) were obtained and so, they allow studying PCEm for a whole range of traffic regimes.

### 4.3 Other variable relationships

This section shows some analyses without contemplating fundamental parameters as spatial variables. FIGURE 6 presents the relationship between passenger car density “Kl” and motorcycles speed “Vm”, passenger cars speed “VL” and traffic average speed “V”. Both types of vehicles speed decreases as passenger car density increases. However, motorcycles are able to maintain higher speeds than passenger cars: between 10 to 20 km/h when passenger cars are almost in a full stop. This proves that motorcycle’s ability to filtrate allows them to dodge congestion and be less affected by passenger car congestion than other vehicles.
FIGURE 6 Passenger car density (KI) vs Passenger car speed (VI), motorcycles speed (Vm), traffic speed (V)

FIGURE 7 plots passenger car density “KI” against the probability of motorcycles using passenger car lanes “Pc”. It is observed that as passenger car density increases, the probability of motorcycles using passenger car lanes, decreases. When passenger car density is high enough (more than 450 veh/km for all three lanes) the mentioned probability is 0% for all cases; this means motorcycles were filtering 100% of the time on the observed length of road (60 m).

Based on the previous plot, it is possible to infer a direct relationship between V (km/h) and Pc:

At high KI (veh/km), V is low (see FIGURE 6) and Pc is low (see FIGURE 7), and at low KI, V is high and Pc is also high. In other words, motorcycles follow lane discipline more often as average traffic space mean speed increases. This is consistent with the wider lateral safety distances required by motorcyclists to filtrate when speed is high, as recognized by Lee in (6).
The relationship between speed and motorcycles use of passenger car lanes is explained by:

1. Filtering (or not using passenger car lanes) depends on lateral gaps between vehicles. As speed increases, motorcyclists need wider lateral gaps in order to filter (6).

2. Speed is high when vehicle density is low or moderate; low or moderate means less than 180 veh/km for all three lanes (or 60 veh/km/lane), according to FIGURE 6. In this situation filtering may not be very advantageous, because passenger cars may be circulating at similar speeds as motorcycles, and it may be more dangerous, as lateral gaps may not comply with needed lateral safety distances required by motorcyclists to filter.

3. In this low or moderate density regimes, there is more space inside passenger car lanes. Therefore, there is less need to filter.

In other words, at high speed-moderate or low density regimes, filtering is less attractive and more dangerous; passenger car lanes-spaces, on the other hand, are more attractive and have less competition for space.

FIGURE 8 shows how motorcycle’s equivalence factor PCEm (and hence impact on traffic congestion) rises as the percentage of travel time spent by motorcycles inside passenger car lanes (Pc) increases.

FIGURE 8 Motorcycle’s equivalence factor vs. Percentage of travel time spent by motorcycles occupying passenger car lanes

### 4.4 Sensitivity Analysis
TABLE 4 presents the set of occupied road width (ORW) combinations (for motorcycles and passenger cars) used for the sensitivity analysis.

TABLE 4 Combination of motorcycles and passenger cars ORW for computing PCEm

<table>
<thead>
<tr>
<th>$\bar{W}_{ol}$ (m)</th>
<th>$\bar{W}_{om}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,6</td>
<td>1,1</td>
</tr>
<tr>
<td>2,6</td>
<td>1,8</td>
</tr>
<tr>
<td>3,0</td>
<td>1,1</td>
</tr>
<tr>
<td>3,0</td>
<td>1,8</td>
</tr>
</tbody>
</table>

FIGURE 9 presents computed PCEm for the previously shown combinations of $\bar{W}_{ol}$, $\bar{W}_{om}$ and the average PCEm at different traffic regimes. From it, the obtained range of PCEm values can be extracted:

$$0 \leq \text{PCEm} \leq 0,60$$

Comparison of the obtained range of values for PCEm with values found in literature (see TABLE 1) shows a similarity, which validates both data collection and the methodology that was used. Zero PCEm values are found reasonable for they are obtained for traffic regimes so dense and unstable that motorcycles filter during the whole time. During these regimes, observed average space mean speeds for passenger cars were 8 km/h (which implies they were static for some periods of time) whereas observed average space mean speeds for motorcycles were 20 km/h. Therefore, during dense, unstable traffic regimes passenger are cause delays to motorcycles, not vice versa.

Also, based on the sensitivity analysis made, it was found that a variation of 1% in $\bar{W}_{om}$, produces a variation of 1% in PCEm. In the same way, a variation of 1% in $\bar{W}_{ol}$, produces a variation of -0.87% in PCEm. Therefore, variations on motorcycles occupied road width have the biggest effect on PCEm.
To conclude, the three hypothesis of this study were confirmed. Motorcycles are less affected by passenger cars congestion due to their ability to filtrate, which allow them to travel at higher average speeds than passenger cars, but generate additional delays to them during stable (less than 60 veh/km/lane) regimes. Motorcycles only affect traffic **significantly** when they use lane discipline.

It is also concluded that, for the conditions studied, $0 \leq \text{PCEm} \leq 0,60$. Nevertheless, average PCEm values for stable regimes ($0,29$) and for all regimes ($0,16$) are considerably smaller than values traditionally used in Colombia ($\text{PCEm} = 0,5$). This means that, for three lane roads, traditional analyses are overestimating motorcycles impact on traffic.

Finally, from the traffic perspective, and ignoring the congestion caused by motorcycles accidents, this type of vehicles are beneficial to society, for they allow people to dodge congestion and use spaces of the road that were previously underutilized. Further work remains to be done in order to evaluate motorcycles impact under different conditions, such as two lane roads, interrupted flow, non-zero slopes, among others.
6 References


