Hindawi
Journal of Advanced Transportation
Volume 2021, Article ID 8883068, 10 pages
https://doi.org/10.1155/2021/8883068

Research Article

Impact of Buses, Taxis, Passenger Cars, and Traffic Infrastructure on Average Travel Speed

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Received 18 August 2020; Revised 18 January 2021; Accepted 22 January 2021; Published 9 February 2021

Academic Editor: Yajie Zou

It is known that many variables influence traffic, yet very little is known about the weight of each factor in the dynamics of traffic in cities of developing countries, in many cases due to their peculiar traffic regulations. In this work, we search for the variables that have the most significant impact on the average travel speed of three distinct types of vehicles: passenger cars, taxis, and buses. First, we developed a tool featuring algorithms that simulate ordinary overtaking and car-following behaviors, along with controls for setting vehicles' actions, particularly buses' and taxis' stops. Then, we chose a particular zone to study, based on its common geometry and the particular traffic infrastructure (speed bumps, traffic lights, and bus stops) inside it. Later on, three experiments were carried out, with the following results. (1) Both the buses' arrival frequency and curbside bus stops affect the passenger cars' average travel speed. The buses' response was affected by the bus bay and curbside bus stops. The buses' speed tendency influenced neither the passenger cars' nor buses' response. (2) Taxis' arrival frequency, stopping frequency, and speed tendency were found to influence the passenger cars' response. Taxis' response was altered by taxis' speed tendency, while buses' response was affected by taxis' arrival frequencies. (3) The number of speed bumps, the arrival frequency of passenger cars, and their speed conditions (homogeneous and heterogeneous) affect the passenger cars' response. We expect that the findings presented in this study, along with the recommendations made from the results, may pave the way for better road design public policies.

1. Introduction

The main objective of the present study is to achieve a better understanding of low travel speed. We conducted all research in an area with compromised vehicle velocity. The zone under study possesses regular traffic infrastructure, such as speed bumps, traffic lights, and bus stops. It also has regular city traffic, i.e., buses, taxis, and passenger cars (hereafter just cars).

The appropriate combination of factors to sustain acceptable traffic speed (i.e., below but close to the speed limit) while avoiding undesirable traffic speed (i.e., far below the speed limit) is a functional problem under intense investigation in the field (e.g., references [1–8]). In the present investigation, we want to identify the variables that most affect the average travel speed. To do so, we will answer the following three questions:

(1) Are the buses' arrival frequency and speed tendency, bus bay, and curbside bus stops the variables that influence the average travel speed of cars and buses?

(2) Are the taxis' arrival frequency, stopping frequency, and speed tendency the variables that affect the average travel speed of cars, taxis, and buses?

(3) Are the number of speed bumps, cars' arrival frequency, and cars' speed conditions (homogeneous and heterogeneous) the variables influencing the cars' average travel speed?

Developing countries face serious traffic problems [9] and some of these not count with field traffic data to conduct investigations, so that new technologies as traffic simulations are a suitable (economic) choice. We employed an in-house developed simulator to model the interaction between cars, buses, and taxis. Such smart interactions, and reactions to traffic infrastructure, allowed our simulator to show which variables have stronger effects on the average travel speed. Henceforth, we performed a set of simulations to answer our research questions.

Some variables are associated with driver behavior (e.g., the speed tendency—see definition below), while others are related to traffic infrastructure (e.g., speed bumps). By detecting the variables that impact speed and how they affect it, we gain further understanding about what causes detrimental effects. Hence, we gain further understanding that may lead to better public policies.

The literature review that follows presents several well-proven models that, unfortunately, fall short in answering our specific research questions, yet it proves that such a task is possible. In addition, it presents references that investigated the effect of buses, taxis, and traffic infrastructure such as speed bumps. In our work, we investigate the effect of several factors on the vehicles' average travel speed that the literature suggests have an impact on traffic.

The rest of this work is organized as follows. In Section 2, we present the literature review. Section 3 deals with the method: avenue under study, design of the simulation tool, and experimental details. In Section 4, we present the statistical results of each experiment and compare the simulations' outcome (the average travel speed, also called response or output) in order to gain insight of the variables that affect it. Finally, in Section 5, we summarize the conclusions of our work and state the contributions we made.

2. Literature Review

2.1. Buses. The implications of improper bus stop locations in New Delhi, India, were investigated in [10]. In India in 2001, the percentage of fatal crashes that occurred near a bus stop was 6.2%, and in 2009, it was 7.0% [11]. In this study, it was observed a deficiency of sufficient space to stop and perform maneuvers and also pedestrian activity outside regulations. The effect of bus stops on traffic is analyzed in [12]. This paper correlated the traffic flow stability with bus stops and normalized density. The finding in a two-lane-30 km-long highway, where vehicles cannot overtake during buses' boarding/alighting periods, is that six or more bus stops affect the stability of traffic flow.

The relation between bus impact time and curb lane capacity of roadways in Beijing is presented in [13]. The bus impact time (without dwell time) is the amount of time since the bus starts to decelerate until it stops (in a bus bay stop), plus the time since accelerates to re-enter the road until it reaches another vehicle's speed. With data from 15 bus bay stops, it was found that the relation between average bus arrival frequency and average bus impact time is best explained with a power model.

The work described in [14] deals with simulations of non-lane-based heterogeneous traffic. Distinct flow measurements of the vehicles' average speed for a 400 m road length (200 m on each side of a bus stop) were done. The simulation considered curbside and bus bay bus stops and dwell times of 10 s, 20 s, and 30 s. The investigation in [15] analyzes the relationship between volume and speed in the presence of bus bay or curbside stops (using midblock location) with a bus arrival frequency of 10 min. In the case of vehicles per hour per lane = 480 and curbside stops, the speed difference between dwell times (20 s, 40 s, and 60 s) is quite small (about 2.5 mph between each other). Moreover, there is no significant speed difference for the bus bay stop case regardless of the dwell time.

In [16], simulations are used to establish the impact of the bus occupancy ratio (number of buses/number of vehicles) on traffic flow capacity. It was observed that traffic flow decreases as the occupancy ratio increases. The variables studied were speed and brake response time of cars and buses, safety following-distance, deceleration capabilities, and occupancy ratio. Reference [17] also utilizes simulations that consider the space occupation rate of buses (the sum of all circulating buses' length divided by the sum of the lanes' length) and the space occupation rate of cars, in order to analyze the influence of buses on other vehicles.

2.2. Taxis. Taxis have a significant effect on traffic, as shown in the following references. In [18], a study in Nanjing, China, identifies the percentage of taxis and cars that were involved in one of the following risk-taking behaviors: failure to yield the right-of-way, sudden lane change, inadequate stop, unnecessary passing, and failure to stay in lane. In these five situations, taxis' percentage was greater than that of cars.

In [19], the presence of taxis in a road section and its impact on vehicle dynamics was studied. Employing simulations, three taxi behaviors were explored: (1) a taxi makes a stop to pick up or drop off passengers, (2) a taxi slows down to inquire destination information, and (3) a taxi circulates at low speed seeking for customers. In another study [20], the time that taxis utilize to pick up or drop off passengers (blockage time) is investigated. Measurements were made in outlet legs of signalized intersections in Rasht City, Iran. From the observations of four intersections, the average parking maneuver was 7.37 s, and the average blockage time was 11.31 s (ranging from 8.85 s to 12.56 s).

Passenger car units per hour (PCU/h) and speed range regions were measured in the center of Patras, Greece [21]. An augmented Naïve Bayesian network was developed to associate variables. The results determine the order of importance of the relevant variables: travel speed, volume, taxis

%, motorcycles%, trucks%, cars%, and buses%. It was found that the taxis percentage (among all vehicles percentages) is the major contributor to the speed-volume relation.

2.3. Bumps and Speed-Calming Devices. In [22], the study centered on determining if speed bumps actually reduce the vehicles' speed. For this, speed observations were made in Cagliari, Italy, where the set speed limit was 50 km/h. The speed bump geometry was 30 mm high and 600 mm wide, and the speed bump was made of rubber. Their intended purpose is to protect crosswalk areas located about 20–25 m after them. In 30% of the cases, the 85th percentile speed (at the speed bump) was higher than the speed limit, 26% lied between 45 and 50 km/h, and for the remaining cases, the speed was under 45 km/h.

The social perspective towards the installation of speed bumps on Nigerian highways was studied in [23], via questionnaires. In one survey, 72% of persons answered that without bumps the vehicles' speed is very high, 14.57% responded just high, and the remaining percentages were 6.86% and 6.57%, corresponding to low and very low speeds, respectively. In another questionnaire, 52.86% answered that bump speed is low and 29.14% responded very low, while 3.14% and 14.86% corresponded to very high and high speeds, respectively.

In [24], the study centered on speed bumps and their effectiveness in reducing vehicles' speed in Nanjing, China. The mean speed at the bump position, 500 m after, and 500 m before (control locations) was measured. *T*-tests showed that the speed difference at the bump and at the control locations is significant.

Reference [25] presents a study of the effectiveness of three-dimensional speed markings (i.e., painted on the road) and speed bumps. This infrastructure was intended to reduce the speed on work zones with a speed limit of 40 km/h. The speed bump effectively reduced the average speed, which was 11 km/h behind the speed bump.

The average speed to traverse a 1400 m road (with speed limit = 50 km/h) before and after the installation of 3 sinusoidal speed humps and 2 chicanes was measured in [26]. Before the speed-calming measure installation, the overall mean speed was 53.5 km/h. After the installation, this value changed to 49.4 km/h, concluding that the speed-calming devices indeed have a speed-reduction effect.

In [27], modelling was done on the vehicles' speed profile in York, England. This was modelled on roads with the following traffic calming devices: speed tables, humps, cushions, and chicanes. To explain the speed profile, the following variables were considered: entry speed, distance to the next calming device, distance from the passed device, and calming device presence (absence).

3. Materials and Methods

3.1. Avenue Selection. We were interested in a place with low speed (see [28]). The selected avenue was Miguel Hidalgo, in Lerma (Mexico state), since its geometry (two lanes, same direction both), its traffic infrastructure, and the vehicle speed on it are common in Mexico state. Thus, the results in this work could apply to places with similar characteristics. Following [24], the avenue was divided into four segments, each of ~ 500 m length. Specific traffic conditions occur in each segment because each has different traffic infrastructure (see Table 1). The observations mentioned in this work were extracted from video recordings made in October 2017. Additionally, the traffic lights' cycle times were set in the simulator to match the real timings closely. The speed bumps on segments S_1, S_2, and S_4 force the vehicles to reduce the speed to ~10.8 km/h, a similar value as reported in [25].

Segment S_1 has two speed bumps at location 141 m (measured from the start of the segment) and 397 m. S_2 has two speed bumps at 85 m and 260 m, one curbside bus stop at 99 m, and one bus bay bus stop at 488 m. S_3 has one traffic light at 163 m and one bus bay bus stop at 220 m. S_4 has three speed bumps at 137 m, 211 m, and 440 m, two traffic lights at 46 m and 87 m, one bus bay bus stop at 65 m, and one curbside bus stop at 445 m.

3.2. Simulation Tool. We choose Unity Engine (used for traffic analysis in [29, 30]) to develop a simulation tool (scripts and scenario). In the simulator, variables related to vehicles can be set, such as the taxis' stopping frequency and the buses' dwell time. Also, it measures the vehicles' travel speed to traverse an avenue segment. The C# scripts to regulate the vehicles' behavior are presented as algorithms. For overtaking, see Algorithm 1. For accelerating, decelerating, and follow another vehicle, see Algorithm 2.

The overtaking algorithm was designed to be consistent with expected human behavior. The need for overtaking is triggered when a vehicle desires to attain a higher speed than the vehicle in front, which for some reason circulates slowly, or when in the proximity there is a static obstacle, as it can be a bus or a taxi that is completely stationary. Additionally, a vehicle overtakes only when it is safe to do so. In Algorithm 1, the *Overtaking()* function allows a vehicle to overtake if there is no collision risk, which depends on the speed of the vehicles located ahead and behind in the other lane of the current vehicle, and if there is no vehicle at its side. The first IF detects the need to overtake comparing the speed of the current vehicle (and the speed tendency) with the speed of the vehicle in front. It also accounts for the AD of the latter. The second IF detects the convenience to overtake comparing the speed of the vehicle in front with the speed of the vehicle in front in the other lane and the distances di_u and di_f. The speed tendency (or preferred speed, hereafter used interchangeably) is the top speed that a vehicle will try to reach without exceeding it. The distance between vehicles is measured from the front of the current vehicle to the back of the vehicle ahead.

In Algorithm 2, $ac = 2\,\text{m/s}^2$ for maximum acceleration and $ac = -4\,\text{m/s}^2$ for maximum deceleration, similar to the values presented in [31]. Variable se_{di} is defined in equation (1), br_{di} is defined in equation (2) (an analogue formula applies to br_{di_f}; just replace sp with sp_f), and ex_{di} is defined in equation (3). The constant re_{ti} is approximately the mean perception-brake response time observed

Table 1: Segment infrastructure.

Segment	Speed bumps	Traffic lights	Bus stops	Length (m)	Start GPS coordinate	End GPS coordinate
S_1	2	0	0	$l_1 = 501$	19.284512, −99.500927	19.285725, −99.505498
S_2	2	0	2	$l_2 = 500$	19.285725, −99.505498	19.286330, −99.510221
S_3	0	1	1	$l_3 = 500$	19.286330, −99.510221	19.286711, −99.514964
S_4	3	2	2	$l_4 = 501$	19.286711, −99.514964	19.286477, −99.519630

```
if ((Clause 1 AND Clause 2) OR (Clause 1 AND Clause 3))
{
   if ((Clause 4 AND Clause 5) OR (Clause 6 AND Clause 7) OR (Clause 8 AND Clause 9) {Overtaking();}
}
```

Clause 1 = $sp_f < sp_{\lim} * 0.8$ = the speed of the vehicle in front (sp_f) is less than the 80% of the speed tendency ($sp_{\lim} = 60$ kn/h).
Clause 2 = $ac_f \leq 0$ = the acceleration or deceleration (AD) of the vehicle in front (ac_f) is less than or equal to zero
Clause 3 = $sp_f < sp * 0.8$ = the speed of the vehicle in front is less than the 80% of the speed of the current vehicle (sp)
Clause 4 = $sp_f < sp_u * x_1$ = the speed of the vehicle in front is less than the $x_1 = 70\%$ of the speed of the vehicle in front in the other lane (sp_u)
Clause 5 = $di_u - x_2 > di_f$ = the distance between the current vehicle and the vehicle in front in the other lane (di_u) minus $x_2 = 0$ is greater than the distance between the current vehicle and the vehicle in front (di_f)
Clause 6 = same as *clause 4*, with $x_1 = 80\%$
Clause 7 = same as *clause 5*, with $x_2 = 2$
Clause 8 = same as *clause 4*, with $x_1 = 90\%$
Clause 9 = same as *clause 5*, with $x_2 = 4$

Algorithm 1: Overtaking.

```
if (se_di ≥ di_f){ac = −4}
else
{
   if (he ≥ de_he + 0.3){ac = 2}
   if (sp ≥ sp_lim * 1.1){ac = 0}
   if (he ≤ de_he − 0.3){ac = −4}
   if ((he ≤ de_he + 0.1)AND(he > de_he − 0.2)){ac = 0}
}
```

Notation:
ac =acceleration or deceleration of the current vehicle.
$de_{he} = 2$ s, headway tendency.
br_{di} =braking distance of the current vehicle.
br_{di_f} =braking distance of the vehicle in front.
ex_{di} =extra distance.
he =headway, the time needed by the current vehicle to reach the vehicle in front.
$p_{le} = 4.2$ m, car's length.
$re_{ti} = 0.5$ s, reaction time to brake.
se_{di} =safe distance between the current vehicle and the vehicle in front.

Algorithm 2: Driving.

in [32]. Constant de_{he} is in the headway mode range presented in [33], which is 1.8 to 2.2 s for densities between 20 and 80 PCU/km. If the distance between the current vehicle and the vehicle in front is less than or equal to the safe distance between the two, the current vehicle decelerates; otherwise, the algorithm applies the following rules: (1) if the headway is larger than or equal to the headway tendency plus 0.3 seconds, the current vehicle accelerates, (2) if the vehicle speed is larger than or equal to the 110% of the speed tendency, the current vehicle neither accelerates nor decelerates, (3) if the headway is less than or equal to the headway tendency minus 0.3 s, the current vehicle decelerates, and (4) if the headway is in the interval (1.8 s, 2.1 s], the current vehicle AD = 0. The speed is limited in case 2, and in case 4, a relaxation state is reached in which there is no need of taking AD actions.

$$se_{di} = \begin{cases} \left(br_{di} - br_{di_f}\right) + \left(p_{le} + ex_{di}\right) + \left(sp * re_{ti}\right), & \text{if } br_{di_f} \le br_{di}, \\ \left(p_{le} + ex_{di}\right) + \left(sp * re_{ti}\right), & \text{if } br_{di_f} > br_{di}, \end{cases} \quad (1)$$

$$br_{di} = \frac{-sp^2}{2 * (-4)}, \quad (2)$$

$$ex_{di} = \begin{cases} \frac{p_{le}}{2}, & \text{if the current vehicle is a bus,} \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Even though Algorithm 1 cannot include 100% of the human reaction possibilities to decide when and how to overtake and Algorithm 2 cannot do the same for the AD actions when following another vehicle, these cover common intuitive behaviors. The vehicles considered in the simulations of the experiments that follow are of three types: cars (width = 1.7 m and length = 4.2 m), taxis (same geometry as cars), and buses (width = 2.5 m and length = 10.3 m).

The variable flow for a certain vehicle type varies from one simulation to another around the observed value in the avenue under study in calm hours. Thus, the traffic dynamics of each simulation could be consistent with that of other avenues with equal number of lanes and comparable flow for each vehicle type. As random processes were not included in the traffic (out of the scope), there is no need to run multiple simulations per variable configuration to achieve output convergence. The simulation time of each simulation of the three experiments is 900 s.

3.2.1. Experiment 1: Buses' Related Variables.

Simulations in experiment 1 were configured as follows: the entrance speed of all vehicles is 40 km/h, and buses' dwell time is 30 s (the time they wait at bus stops), following the range from 8 to 35 s reported in [34]. After the dwell time, a bus in a bus bay stop tries to re-enter the circulation if possible. If not, after 10 s (by a programmed rule), a vehicle circulating in the lane adjacent to the bus stop, and behind the bus, decelerates to allow the bus to re-enter. For the curbside bus stop, the dwell time is also 30 s, during which the circulation of the vehicles behind is obstructed. Buses circulate only in the rightmost lane and therefore do not overtake. If a vehicle overtakes, it waits for 5 s to do it again in case it has to, imitating a driver who does not overtake immediately once it has; instead, it waits to understand the traffic around him before attempting to perform an overtaking maneuver once again. A car arrives per lane every 7.5 s (or per avenue each 3.75 s). The cars' speed tendency is 60 km/h. The average travel speed (ATS) is calculated with equation (4), the travel speed of the i_T-th vehicle is $v_{i_T} = l_j / t_{i_T}$, l_j is the length of the j-th segment, and t_{i_T} is the time that the i_T-th vehicle needs to traverse S_j. Subindex T indicates the vehicle type, $T = \{\text{car (c), bus (b), taxi (t)}\}$. N_T is the total number of vehicles of type T in the simulation.

$$\text{ATS}_T = \sum_{i_T=1}^{N_T} \frac{v_{i_T}}{N_T}. \quad (4)$$

Segment S_2 is the scenario of the simulations of experiment 1. We selected four variables (factors): time interval between buses arrival (TL_b), buses' speed tendency (SL_b), a bus stop obstructing the circulation (curbside stop, denoted as $BS1$), and a bus stop in a space designated to not interfere with circulation (bus bay stop, denoted as $BS2$). The time interval between buses per avenue takes values around 100 s (from observations each ~86 s a bus enters the avenue), and hence $TL_b = \{50\text{ s}, 100, 150, 200\}$. Buses' speed tendency ranges between 30 and 60 km/h; therefore, $SL_b = \{30\text{ km/h}, 40, 50, 60\}$. The presence of factor $BS1$ (or $BS2$) is set with 1 and absence with 0, and thus $BS1 = \{1, 0\}$ and $BS2 = \{1, 0\}$.

The variables' values of each simulation are presented in Table 2, along with the average travel speed of cars (ATS_c) and buses (ATS_b). An orthogonal experimental design was adopted, following the approach in [35]. In Table 2, columns 2 through 5 conform an orthogonal array.

The minimum number of simulations (NS) to obtain meaningful results is calculated with the following equation (see [36]):

$$\text{NS} = 1 + \sum_{i=1}^{i=k} \text{NF}_i \left(\text{NL}_i - 1\right). \quad (5)$$

Index $i = 1...k$ is used to enumerate cases. The i-th case corresponds with a number of levels and the number or factors with that many levels. NF_i = number of factors and NL_i = number of levels. In experiment 1, we have two factors with four levels and two factors with two levels, and hence NS = 9. Nevertheless, 16 simulations were performed for completeness.

3.2.2. Experiment 2: Taxis' Related Variables.

The simulation parameters from experiment 1 remain mostly the same for experiment 2, with the following differences: a bus arrives every 86 s, vehicles entrance speed is 30 km/h, and buses' and cars' speed tendency is fixed at 60 km/h. To perform simulations, we selected segment S_3 which has one bus bay stop and one traffic light (green time = 30 s, yellow = 3 s, and red = 27 s).

The objective is to determine which variables related to taxis have an impact on the average travel speed of cars

Table 2: Experiment 1 simulations.

Simulation	TL_b (s)	SL_b (km/h)	$BS1$	$BS2$	ATS_c (km/h)	ATS_b (km/h)
1	50	30	0	1	42.83244	17.73234
2	50	40	1	0	37.8702	19.87394
3	50	50	0	0	43.01352	36.49824
4	50	60	1	1	38.38968	15.36566
5	100	30	1	0	40.41936	17.90665
6	100	40	0	1	43.02828	19.8711
7	100	50	1	1	40.90032	14.75813
8	100	60	0	0	43.15932	39.47796
9	150	30	0	0	43.01604	26.59828
10	150	40	1	1	41.6052	14.26122
11	150	50	1	0	41.8032	21.44045
12	150	60	0	1	43.13556	21.44754
13	200	30	1	1	41.80536	13.33422
14	200	40	0	0	43.1352	31.6418
15	200	50	0	1	43.13196	21.31394
16	200	60	1	0	42.07248	22.67647

(ATS_c), buses (ATS_b), and taxis (ATS_t). The variables are speed tendency of taxis $SL_t = \{40\,\text{km/h}, 50, 60\}$, time interval between taxis per avenue (from observations each ~18 s a taxi enters in one of the two lanes) $TL_t = \{9\,\text{s}, 18, 27\}$, and the time interval between stops (i.e., when a taxi makes a stop to drop off or pick up customers and after 5 seconds, the time lapse until it decelerates to stop for the same reason) $TS = \{30\,\text{s}, 45, 60\}$. The taxi blockage time, to pick up or drop off passengers, is 5 s. This time is set relatively short as taxis stop at any lane. In the avenue under investigation, taxis have a defined route and collect and drop customers during their journey and transport as many clients as they can carry.

Table 3 shows the variables' values in an orthogonal array (columns 2 to 4) and the measured average travel speed of each vehicle type. The array has three factors with three levels each; therefore, NS = 7. Nonetheless, we perform two more simulations for completion.

3.2.3. Experiment 3: Cars' and Traffic Infrastructure Related Variables. The objective is to determine the impact of (1) speed bumps, (2) the time interval between cars, and (3) cars' preferred speed (heterogeneous and homogeneous speed cases), in the cars' average travel speed. For our simulations, we selected segment S_4, which has three speed bumps and two intersections with a traffic light in each one. Seven cars enter the avenue per intersection per traffic light cycle. The first traffic light, numbered in the traffic flow direction, has a green time = 42 s, yellow = 3 s, and red = 45 s. The second has a green time = 67 s, yellow = 3 s, and red = 20 s. The cars from upstream enter S_4 with a speed of 40 km/h and from the perpendicular streets at 15 km/h. A car decelerates to a speed of ~ 10.8 km/h to pass a speed bump (see [25]).

Speed bumps are denoted with $B = \{3, 2, 1, 0\}$. The value of B is associated with the number of speed bumps in the simulation, e.g., if $B = 2$, one speed bump is removed (from downstream to upstream) and two remain. The time interval between cars per avenue is $TL_c = \{4\,\text{s}, 6\,\text{s}\}$ or that per lane is $\{8\,\text{s}, 12\,\text{s}\}$. The cars' preferred speed is $SL_c = \{\text{HE}, \text{HO}\}$. In the heterogeneous (HE) case, the speed is uniformly and randomly assigned so that 50% of the cars' preferred speed = 60 km/h and that of the other half = 40 km/h. In the homogeneous (HO) case, the preferred speed = 50 km/h for all cars. ATS_c is calculated considering the cars traveling from the start of S_4, excluding the cars from perpendicular streets. Table 4 shows the variables' values and the output of each simulation. Columns 2 to 4 conform an orthogonal array, with $NS = 6$ (one factor with four levels and two factors with two levels) plus two more for completeness.

4. Results and Discussion

4.1. Experiment 1. ANOVA was conducted to determine the factors influencing a response (the average travel speed of a vehicle type). The analysis of variance results, with the data in Table 2, is presented in Table 5. In the following, considering 90% confidence intervals (unless otherwise mentioned), a factor with P value <0.1 influences the response, i.e., it is significant.

With ATS_c as the response, factors TL_b and $BS1$ are significant. Factor $BS2$ does not influence ATS_c, as a bus does not interrupt the circulation when it waits in a bus bay stop. Also, as cars are able to overtake slow buses most of the time, factor SL_b is not influencing the response.

If ATS_b is the response, factor SL_b is slightly significant (with 80% confidence intervals, 0.1866 < 0.2), while factors $BS1$ and $BS2$ (curbside and bus bay stops, respectively) both impact ATS_b, as a bus waits during the dwell time either if it is in a bus bay or a curbside stop. $BS2$ is impacting slightly more the response than $BS1$, mainly because a bus spends time to re-enter in the circulation lane if it is in a bus bay stop. Factor TL_b is not influencing ATS_b since buses (ideally) do not interfere with each other not even at the shortest time between buses' arrival (50 s).

Simulation 8 ($ATS_c = 43.1593$ km/h) is compared with a new simulation (numbered 17, not shown in the respective table), with factors $TL_b = 100$ s, $SL_b = 60$ km/h, $BS1 = 1$, $BS2 = 0$, and response $ATS_c = 40.9953$ km/h. Then, $BS1$ does change. The percentage (P) of ATS_c reduction, since buses stop at the curbside stop (simulation 17), is calculated with equation (6) (which calculates a loss, or a gain, in percentage). Thus, with $x_1 = 43.1593$ km/h and $x_2 = 40.9953$ km/h, there is an ATS_c loss of 5.01% from simulation 8 to simulation 17.

$$P = \left(\frac{|x_1 - x_2|}{x_1} \right) * 100\%. \tag{6}$$

ATS_c drops if there is a curbside stop. To measure the loss, we compare simulations in pairs, with same TL_b and different $BS1$ (the other influencing factor). Comparing simulation 3 vs 4, the response drops to 10.74%. From 8 vs 7, it drops to 5.23%. From 12 vs 11, it drops to 3.08%. From 15 vs 16, it drops to 2.45%. Then, the response's loss drops as TL_b of the compared simulations increases.

Also, ATS_c is influenced by TL_b. We compared simulations with same $BS1 = 1$ and different TL_b. By comparing simulation 7 vs. 4, the response drops to 6.13%. From 10 vs 7,

Table 3: Experiment 2 simulations.

Simulation	TL_t (s)	TS (s)	SL_t (km/h)	ATS_c (km/h)	ATS_t (km/h)	ATS_b (km/h)
1	9	30	60	39.57012	32.09062	21.02119
2	9	45	40	38.457	26.13989	21.1505
3	9	60	50	38.68164	32.36504	20.95096
4	18	30	40	38.03076	25.79638	21.46608
5	18	45	50	39.71952	32.36252	21.78511
6	18	60	60	41.634	38.59164	22.78577
7	27	30	50	41.14548	31.67957	22.07477
8	27	45	60	43.40268	38.38464	22.66538
9	27	60	40	41.50512	28.4391	22.84675

Table 4: Experiment 3 simulations.

Simulation	B	TL_c (s)	SL_c	ATS_c (km/h)
1	3	4	HO	26.60634
2	3	6	HE	26.80146
3	2	4	HE	27.050976
4	2	6	HO	30.208572
5	1	4	HO	32.271084
6	1	6	HE	31.658328
7	0	4	HE	32.325696
8	0	6	HO	37.74348

Table 5: ANOVA results (experiment 1).

Factor	P value (ATS_c)	P value (ATS_b)
TL_b	$0.0861 < 0.1$	$0.8643 > 0.1$
SL_b	$0.6937 > 0.1$	$0.1866 > 0.1$
$BS1$	$0.0018 < 0.1$	$0.0011 < 0.1$
$BS2$	$0.935 > 0.1$	$0.0009 < 0.1$

it drops to 2.15%, and from 16 vs 11, it drops to 0.64%. Again, we observe that the percentage becomes smaller as the compared TL_b values become larger. Yet, when comparing simulations with same $BS1 = 0$ and different TL_b, we notice almost the same response: the ATS_c of simulation 3 is 43.01 km/h, that of 6 is 43.02 km/h, and that of 12 and 15 is $\sim$ 43.13 km/h. Hence, without curbside stop, the buses' arrival time interval in the range 50 s to 200 s has no impact in the ATS_c.

With ATS_b being the response, ANOVA shows that both $BS1$ and $BS2$ significantly affect ATS_b. Comparing simulation 8 ($BS1 = 0$, $BS2 = 0$) with 4 ($BS1 = 1$, $BS2 = 1$), the response percentage loss is 61.07%. There is no evident response difference between simulation 12 (ATS_b = 21.44 km/h), with a bus bay stop ($BS2 = 1$), and simulation 16 (ATS_b = 22.67 km/h), with a curbside stop ($BS1 = 1$). Considering simulations 1, 6, 15, and 12, all with $BS1 = 0$ and $BS2 = 1$, ATS_b increases from simulation 1 to 12 in 20.95%, since variable SL_b also increases (from 30 to 60 km/h).

4.2. Experiment 2. ANOVA results (with data in Table 3) are presented in Table 6. All factors impact ATS_c, factor SL_t affects ATS_t, and factor TL_t affects ATS_b. In addition, considering 80% confidence intervals, TL_t and TS also have an effect in ATS_t, and TS also has an effect in ATS_b.

Table 6: ANOVA results (experiment 2).

Factor	P value (ATS_c)	P value (ATS_t)	P value (ATS_b)
TL_t	$0.0136 < 0.1$	$0.1992 > 0.1$	$0.0409 < 0.1$
TS	$0.0984 < 0.1$	$0.1413 > 0.1$	$0.1767 > 0.1$
SL_t	$0.026 < 0.1$	$0.0203 < 0.1$	$0.2384 > 0.1$

From Table 3, simulation 4 has the lowest ATS_c, with SL_t and TS at minimum values. Simulation 8 presents the highest ATS_c, with SL_t and TL_t at maximum values. Thus, the relevance of SL_t in ATS_c is made evident.

The ATS_c percentage gain between simulation 4 (minimum values of SL_t and TS) and simulation 6 (maximum values of SL_t and TS), both with TL_t = 18 s, is 9.47%.

We compare simulation 2, with TL_t and SL_t at minimum values, and simulation 8, with TL_t and SL_t at maximum values, both with TS = 45 s, finding an ATS_c gain of 12.86%.

We perform two more simulations: simulation 10, with TL_t = 9 s, TS = 30 s, SL_t = 50 km/h, resulting in ATS_c = 36.7081 km/h, ATS_t = 29.915, ATS_b = 20.0617; simulation 11, with TL_t = 27 s, TS = 60 s, SL_t = 50 km/h, resulting in ATS_c = 42.1927 km/h, ATS_t = 36.4168, ATS_b = 22.5704. Comparing simulation 10, with TL_t and TS minimum values, and simulation 11, with TL_t and TS maximum values, both with SL_t = 50 km/h, the ATS_c gain is 14.94%.

To evidence the significant impact of SL_t in ATS_t, we cluster simulations according to speed tendency in three groups (see Table 7). Notice that, by arranging data, first in subgroups of SL_t, then inside these subgroups by ascending TS, the table self-orders in ATS_t. Hence, TS is firstly affected by SL_t and secondly by TS.

The factor significantly influencing ATS_b is TL_t. In Table 3, simulations 1, 2, and 3, with TL_t = 9 s, present close values of ATS_b, with the average being 21.04 km/h. For simulations 4, 5, and 6, with TL_t = 18 s, the response is increasing along with TS, with the average being 22.01 km/h. The same occurs for simulations 7, 8, and 9, with TL_t = 27 s and average response of 22.52 km/h. Then, TL_t is firstly affecting ATS_b, followed by TS. Comparing simulation 3 (TL_t = 9 s) and 9 (TL_t = 27 s), both with TS = 60 s, the response gain is 9.04%.

4.3. Experiment 3. ANOVA results (with data in Table 4) are shown in Table 8. All factors impact ATS_c.

Table 7: Sorting TS in clusters of SL_t.

Simulation	Factor values	ATS_t (km/h)
4	$TL_t = 18, TS = 30, SL_t = 40$	25.7963
2	$TL_t = 9, TS = 45, SL_t = 40$	26.1398
9	$TL_t = 27, TS = 60, SL_t = 40$	28.4391
7	$TL_t = 27, TS = 30, SL_t = 50$	31.6795
5	$TL_t = 18, TS = 45, SL_t = 50$	32.3625
3	$TL_t = 9, TS = 60, SL_t = 50$	32.365
1	$TL_t = 9, TS = 30, SL_t = 60$	32.0906
8	$TL_t = 27, TS = 45, SL_t = 60$	38.3846
6	$TL_t = 18, TS = 60, SL_t = 60$	38.5916

Table 8: ANOVA results (experiment 3).

Factor	P value (ATS_c)
B	$0.026 < 0.1$
TL_c	$0.0767 < 0.1$
SL_c	$0.0644 < 0.1$

To compare simulations with different number of speed bumps and other factors at equal values, additional simulations were performed (see Table 9).

By reducing B, ATS_c increases. With $TL_c = 6$ s and SL_c = HE (likely for real traffic), we compare simulations with a different number of bumps. Comparing simulation 2 ($B = 3$) and simulation 12 ($B = 2$), there is a gain of 9.95%. Comparing simulation 2 vs 6 ($B = 1$), the gain is 18.12%. Comparing simulation 2 vs 16 ($B = 0$), the gain is 30.61%. Following this comparison logic, with $TL_c = 4$ s and SL_c = HE, we obtained gains of 6.84%, 19.0%, and 27.67%. With $TL_c = 6$ s and SL_c = HO, gains are 8.88%, 19.97%, and 36.04%. With $TL_c = 4$ s and SL_c = HO, gains are 9.23%, 21.29%, and 41.58%. Averaging the gain results with 3 speed bumps vs 2, the gain is 8.72%. The average gain of 3 speed bumps vs. 1 is 19.59%, and increases to 33.97% for the average gain of 3 speed bumps vs. no speed bumps. It is clear that regardless of the values of TL_c and SL_c, speed bumps harm the response.

The response in homogeneous traffic without speed bumps is approximately the same regarding TL_c, ATS_c = 37.6718 km/h for simulation 15 ($TL_c = 4$) and ATS_c = 37.74348 km/h for simulation 8 ($TL_c = 6$). Following this idea, we calculate the response gain comparing simulation 5 vs 14 (1 speed bumps each), simulation 11 vs 4 (2 speed bumps each), and simulation 1 vs 10 (3 speed bumps each). The average percentage gain of the four cases is 2.88%.

In heterogeneous traffic without speed bumps, there is a notorious response difference between a simulation with $TL_c = 4$ s and one with $TL_c = 6$ s, corresponding to simulation 7 (ATS_c = 32.3256 km/h) and simulation 16 (ATS_c = 35.0068 km/h), respectively. Following the idea, we compare simulation 13 vs 6 (1 speed bumps each), simulation 3 vs 12 (2 speed bumps each), and simulation 9 vs 2 (3 speed bumps each), to calculate the response gain. The average percentage gain of the four cases is 7.04%. Then, in heterogeneous traffic, the response changes because TL_c is more evident.

Table 9: Complementary simulations (experiment 3).

Simulation	B	TL_c (s)	SL_c	ATS_c (km/h)
9	3	4	HE	25.31797
10	3	6	HO	27.74362
11	2	4	HO	29.06255
12	2	6	HE	29.46848
13	1	4	HE	30.12912
14	1	6	HO	33.28459
15	0	4	HO	37.67184
16	0	6	HE	35.0068

The average speed tendency in heterogeneous traffic (SL_c = HE) is 50 km/h (50% of the cars' speed tendency = 40 km/h and 50% is 60 km/h), and the average speed tendency in homogeneous traffic (SL_c = HO) is also 50 km/h (100% of the cars' speed tendency = 50 km/h). Even though that in both traffic configurations (HE and HO) the average speed tendency is the same, the average travel speed is different. There is an ATS_c percentage gain of a simulation with SL_c = HO over one with SL_c = HE, both with $TL_c = 6$ s and same B. Simulation 10 vs 2 (with 3 speed bumps each) presents a gain of 3.51%. Simulation 4 vs 12 (with 2 speed bumps each) presents a gain of 2.51%. Simulation 14 vs 6 (with 1 speed bumps each) presents a gain of 5.13%. Simulation 8 vs 16 (with 0 speed bumps each) presents a gain of 7.81%. The average gain of the four cases is 4.74%. Also, there is an ATS_c percentage gain of a simulation with SL_c = HO over one with SL_c = HE, both with $TL_c = 4$ s and equal B. Simulation 1 vs 9 (with 3 speed bumps each) presents a gain of 5.08%. Simulation 11 vs 3 (with 2 speed bumps each) presents a gain of 7.43%. Simulation 5 vs 13 (with 1 speed bumps each) presents a gain of 7.1%. Simulation 15 vs 7 (with 0 speed bumps each) presents a gain of 16.53%. The average gain of the four cases is 9.04%. The advantage of homogeneous over heterogeneous traffic is evident.

4.4. Research Questions. The answers to our investigative questions are as follows:

(1) It was found that a curbside stop and the time interval between buses' arrival (in that order of relevance) modify the cars' average travel speed. Buses' average travel speed is affected by bus bay and curbside stops.

(2) The time lapse between taxis' arrival, speed tendency, and frequency to make a stop impact (in the order presented before) the cars' average travel speed. Taxis' average travel speed is influenced mainly by taxis' speed tendency. Taxis' arrival frequency influences buses' average travel speed.

(3) It was found that the three factors: speed bumps, speed tendency configuration, and time interval between cars arrival, significantly affect (in the order presented) the cars' average travel speed.

5. Conclusions

The ATS_c percentage loss (due to the curbside bus stop) of the compared simulations with same TL_b and different $BS1$ ranges from 2.45% to 10.74%. Then, from a traffic design perspective, it is preferable to avoid curbside stops, so that buses do not make stops in a way that obstructs circulation. Instead, bus bay stops are suitable, since $BS2$ has no significant effect on ATS_c. From the simulations compared with same $BS1 = 1$ and different TL_b (as this variable affects ATS_c), the ATS_c percentage loss is in the range 0.64% to 6.13%. Therefore, TL_b could be adjusted based on a supply and demand basis.

The ATS_b percentage gain, if a bus travels at the minimum preferred speed (30 km/h) compared with the maximum (60 km/h), is 20.95%. Thus, the connection between buses' preferred speed and ATS_b is evident.

As TS influences ATS_c, it could be beneficial that taxis had designated spots (similar to bus bay stops for buses, or even sharing these) to not obstruct the circulation when these pick up or drop off customers. In this way, a taxi is not motivated to travel at low speed (since SL_t is influencing ATS_c and ATS_t) trying to find customers along the way. As TL_t impacts ATS_c and ATS_b, if the number of taxis circulating do not match the number of customers (as it is likely in the avenue under study), it is recommended to find the TL_t values (considering time and day) that balance supply and demand.

In experiment 3, we found that B affects ATS_c, regardless of TL_c and SL_c. By gradually removing speed bumps, we noticed improvements in the response. For the avenue studied and other similar avenues, we suggest that if a speed bump is not in a space that actually benefits pedestrians, it should be removed. With $B = 0$ and SL_c = HO, there was no response improvement when extending TL_c. With $B \neq 0$, for both homogeneous and heterogeneous cases, ATS_c improves as cars arrive less frequently. As TL_c influences ATS_c and as TL_c is connected with the number of cars in circulation which in turn increases year after year, persons with transportation needs could be motivated, through better public transport services and adequate infrastructure, to use other means of transportation rather than private vehicles, such as public transport or bicycles (this poses the problem of a dedicated bicycle lane). As SL_c impacts ATS_c and as homogeneous speeds were proven convenient than heterogeneous, it is important to have suitable traffic infrastructure (quality streets with the right capacity, proper quantity, and location of speed bumps and traffic lights, among others) since drivers partly decide their driving speed considering that, so more drivers could be motivated to reach an acceptable speed (without exceeding the legal speed limit) and keep it.

The contributions are summarized as follows:

(1) The simulation tool: it allows for the manipulation of the driving behavior for cars, taxis, and buses. For the last two, the frequency and period of stops can be set. The simulator offers the option to measure the speed of each vehicle separately.

(2) As the scenario to perform simulations, it was selected a common two-lane one-way avenue with regular traffic infrastructure: speed bumps, traffic lights, and bus stops. The vehicles' interaction dynamic was designed to be intuitive and implemented with algorithms. Although the variables that influence speed in other locations might not be the same than those detected in this study, the method and analysis presented in this investigation are applicable to analogue situations.

(3) With the method presented, we identified among the selected variables related to each vehicle type, which most significantly affect the travel speed.

(4) The results may help to identify traffic problems and to propose solutions in the realm of public policies and infrastructure improvements, and consequently, people's quality of life could be improved. Even more importantly, traffic mitigation has the added benefit of decreasing the greenhouse emissions of vehicles.

Data Availability

The simulation data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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