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Evaluation of the Minimum Number of Local Driving Cycles Required to Represent the Traffic of Distinct Cities: A Case Study of Two Brazilian Metropolises

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Abstract

This study aimed to determine whether a single local driving cycle (LDC) can effectively represent different cities in the same country, in both urban and highway routes, and for cars and motorcycles. To achieve this, experienced drivers drove different monitored vehicles (five cars and three motorcycles) on seven selected routes in two Brazilian states (Pernambuco and São Paulo State), collecting 170 h of speed data in urban and highway routes during peak and off-peak hours. Using the micro-trip and Markov chain methods, LDCs were then developed based on the collected real-world data. The kinematic and energy parameters of different route groupings were compared, revealing that two LDCs, one for cars and one for motorcycles, could be used to represent all urban routes. However, each highway route required a unique LDC. When compared with standard driving cycles adopted in Brazil, the created LDCs presented a coefficient of variation of 13%–46% in kinematic characteristic parameters, highlighting the need for developing LDCs to better represent Brazilian traffic.

Keywords

data and data science, urban transportation data and information systems, GPS data, speed data, sustainability and resilience, transportation and sustainability, transportation energy, fuel economy technologies and test cycles

Governments use standard driving cycles (SDCs) to evaluate and regulate consumption and emission levels (*1*, *2*). In the U.S., several driving cycles have been employed. For example, the Federal Test Procedure driving cycle (FTP-75) is used to represent urban driving conditions, the Highway Fuel Economy Driving Cycle (HWFET) is used to test vehicles in highway driving conditions, the New York City Cycle is used to represent low-speed and stop-and-go traffic conditions, and the US06 driving cycle is used to represent aggressive driving behavior (*3*). In Europe, there is the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), which is currently used for passenger cars and light commercial vehicles (*4*). For motorcycles in Europe and China, the World Motorcycle Test Cycle (WMTC) is used, and for some Latin American countries the former driving cycle adopted in Europe, the New European Driving Cycle (NEDC), is still active (*4*, *5*).

In Brazil, the country of this study, the adopted SDCs were not developed from local traffic speed data, as occurred in the U.S. and Europe. The Brazilian legislation establishes the use of the FTP-75/HWFET cycles to assess the fuel consumption of cars and motorcycles in urban (FTP-75) and highway (HWFET) scenarios (*6*). To assess pollutant emissions, Brazil adopts the FTP-75/

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HWFET for cars and the WMTC cycle for motorcycles (*6*, *7*). The traffic in Brazil and the U.S. differs, as in Brazil the traffic is characterized by a higher proportion of motorcycles. Therefore, driving cycles employed to represent local traffic in different countries exhibit significant differences, as concluded in the study conducted by de Andrade et al., comparing cycles in the U.S., Europe, Brazil, and other countries (*8*).

Moreover, the literature presents that there is a significant discrepancy between the fuel consumption and emissions measured using driving cycles and those observed under real-world driving traffic (*9*). To address this problem, in Europe the old NEDC was replaced by the newer WLTC in 2018, and China is currently transitioning from NEDC to WLTC until 2025 (*10*, *11*). Another approach to mitigate this problem is the development of a specific driving cycle for the traffic characteristics of a given location, which is called a "local driving cycle" (LDC) (*12*). Recent studies with driving cycles demonstrate that there is an average difference in consumption and emissions levels between SDC and LDC in cities around the world, from values below 5% up to values above 40% (*1*, *3*, *13–15*)

In the literature, the two prevalent methods for developing driving cycles based on real-world traffic data are the micro-trip and the Markov chain method. In the micro-trip method, the speed-time data is processed to identify individual micro-trips. These micro-trips are then recombined to create a driving cycle candidate for statistically representing the original data. This iterative process continues until certain predetermined quality criteria is achieved. Some relevant SDCs have been developed based on this approach, such as WLTC for cars and WMTC for motorcycles (*4*). Additionally, the micro-trip method has been employed to develop LDCs for motorcycles, cars, and trucks (*16–21*). The second method, the Markov chain method, is a mathematical approach to model the probability of the vehicle changing from one state (i.e., speed, acceleration, headway) to another. This method has already been applied to develop driving cycles for different vehicles, such as cars, motorcycles, buses, and even scooters (*22–25*).

The research question of this study is whether a single driving cycle can be used to represent the traffic condition across different cities, road types, and vehicle types. To this end, the traffic of two major Brazilian cities, Recife and São Paulo City, was analyzed, considering their urban and highway road scenarios, and two of the most commonly used vehicle types, motorcycles and passenger cars. In total, 170 h of speed data were recorded, in seven routes. Various combinations of routes were tested to find the minimum number of LDCs needed to represent their characteristics. This study provides the observations that each type of vehicle requires its unique driving cycle, the same driving cycle can simultaneously represent two distinct metropolitan cities, and each distinct highway needs its own driving cycle. Additionally, this study presents several novel analyses of the traffic characteristics in two distinct cities, considering different road and vehicle types, providing insights into the differences and similarities. Results from this study can be useful for policymakers, researchers, and practitioners.

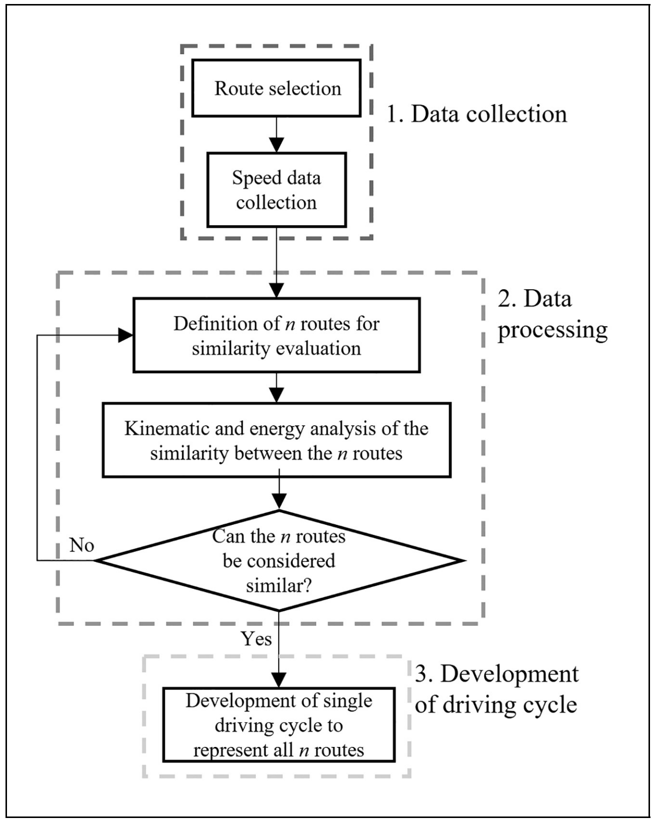

Figure 1. Framework for developing local driving cycles (LDCs).

Methodology

This section explains the methodological framework applied to evaluate the minimum required number of driving cycles to represent the traffic of different cities, vehicles, and types of road. In general, the development of LDCs requires three stages (see Figure 1): 1) test route selection and speed data collection; 2) selection of group of routes and subsequent kinematic/energy similarity analysis; and 3) development of the driving cycles.

Test Routes Selection

In this study, seven test routes were selected using urban and highway sections of the capitals of two important Brazilian states (Pernambuco State and São Paulo State), one in the northeast (Recife in Pernambuco) and other in

Figure 2. Brazilian states and cities selected to define test routes.

the southeast (São Paulo City in São Paulo State) (see Figure 2). Recife, the capital of Pernambuco State, is one of the oldest cities in the Americas (founded in 1537) and is an economic, tourist, and medical center in the northeast region. This city has 1.6 million inhabitants (the metropolitan area has a population of 4.1 million people), with an area of 218 km^2, an average elevation of 4 m, and a fleet of approximately 400,000 passenger cars and 170,000 motorcycles (*26*). The second city selected, São Paulo City, the capital of São Paulo State, is the largest capital in Latin America, and the main commercial center in Brazil, with 12.4 million inhabitants (the metropolitan area has a population of 22 million people), with an area of 1,521 km^2, average elevation of 760 m, and a fleet of 5.9 million passenger cars and 1.4 million motorcycles (*27*).

In Recife City, three urban routes were defined (PE-Urb-S, PE-Urb-E, PE-Urb-N, see Figure 3*a*) to assess whether more than one route was needed to characterize a city. The definition of three urban routes in Recife was made to encompass most of the city's traffic, considering avenues with high traffic flow, intersections, and traffic lights. Initially, the origin-destination matrix of the city of Recife was used to identify the streets with the highest traffic volume based on the analysis of trip data (*28*). Subsequently, the routes were defined with the researchers' experience of the local traffic in such a way as to be composed of main avenues, local roads, and collector roads. In addition, the chosen route should have the characteristic of connecting different regions of the city (north, south, and east) and total length similar to FTP-75. For São Paulo City, only one route was selected (SP-Urb, see Figure 3*b*) with the objective of comparing it with Recife, that is, to study whether only one driving cycle could represent two distinct cities (i.e., Recife City and São Paulo City). The SP-Urb route was selected in the central region of São Paulo City to include roads with multiple lanes and congested traffic, roads with multiple lanes and free flow traffic, and roads with fewer lanes.

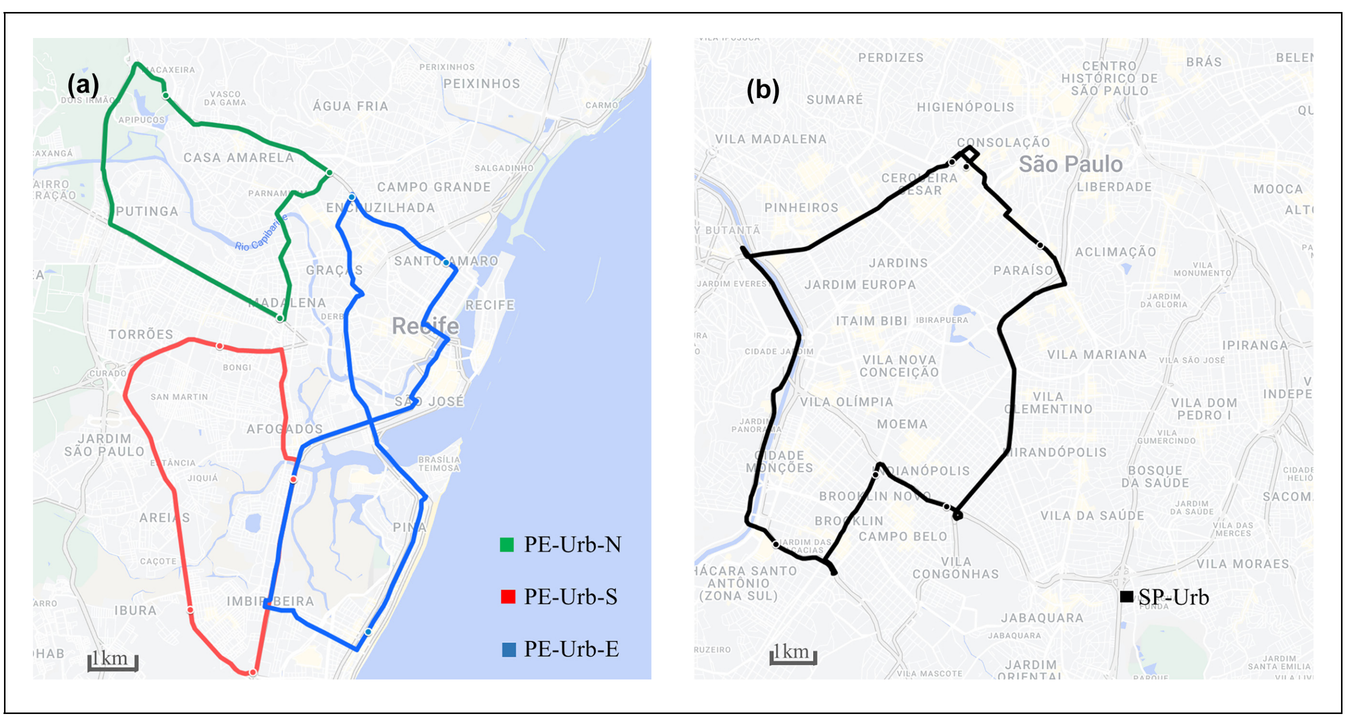

Figure 3. Urban test routes in (*a*) Recife City and (*b*) São Paulo City.

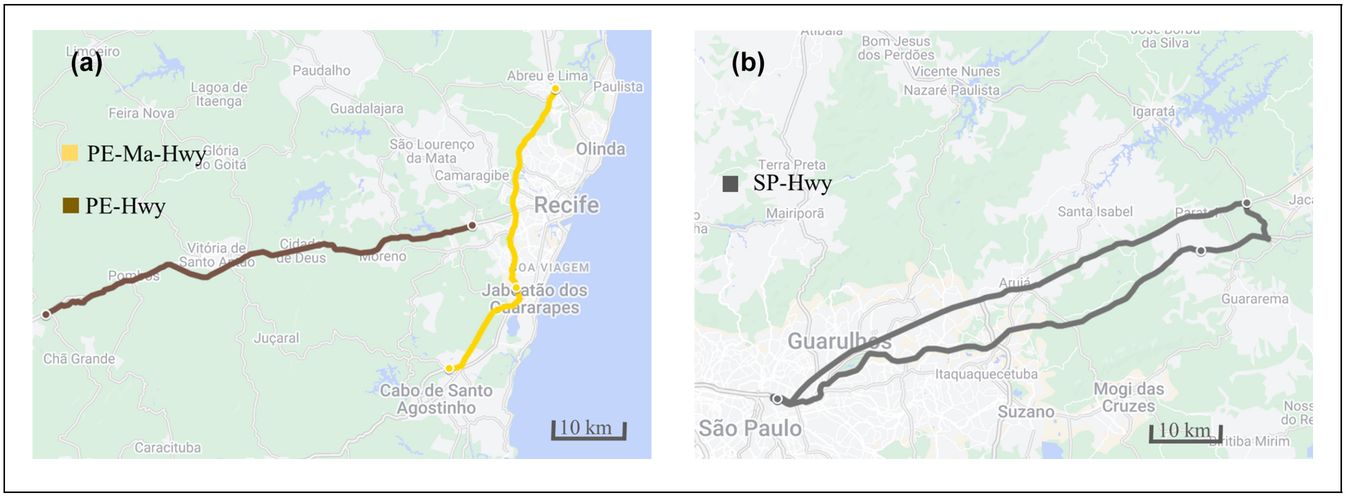

Figure 4. Highway routes in (*a*) Pernambuco State and (*b*) São Paulo State.

In addition to urban routes, there was a selection of highway routes in both states (see Figure 4). For this, highways that connected each capital to nearby small cities were selected. In Pernambuco, two routes were defined to compare two different highways scenarios: 1) PE-Ma-Hwy is a trajectory between cities inside the metropolitan area of Recife, in which the vehicle drives the peripheral regions of the city (composed of traffic lights, intersections and heavy traffic); and 2) PE-Hwy is a highway trajectory from the capital to a small city, Gravatá. In the state of São Paulo, a highway route, SP-Hwy, connecting the capital to a medium-sized city, Jacareí, was selected.

Speed Data Collection

In the data collection, five different car models and three different motorcycles models were used. In addition, experienced drivers were hired and instructed to respect the speed limit, follow the behavior of the other drivers on the roads, and drive without aggressive action in relation to lane changing, acceleration, and braking. In the experiments, GPS receivers of smartphones (capture frequency of 1 Hz) to register the vehicles' speed were employed, as conducted by de Andrade et al. (*12*). A filtering step is required to eliminate gross errors such as signal losses (null speeds) and unrealistic accelerations (*12*).

The number of tests executed in each route was defined as displayed in Table 1. The data collection was carried out in the morning, afternoon, and evening periods during January 2022 by drivers with experience of local traffic. In addition, the tests were equally distributed during peak and off-peak hours for urban routes, PE-Ma-Hwy, and SP-Hwy. In the PE-Hwy route, it was assumed the period did not affect the traffic volume the same way as in the urban routes, because they are classified as express highways. Each route was tested by different drivers, in different vehicles, on different days, and considering the peak and off-peak conditions, to verify the influence of those variables.

Table 1. Definition of Number of Tests

Route	Number of tests for cars	Number of tests for motorcycles	Route length (km)
PE-Urb-S	20	18	17.3
PE-Urb-N	20	18	15.3
PE-Urb-E	20	18	25.7
PE-Ma-Hwy	6	6	93.4
PE-Hwy	8	4	71.4
SP-Urb	28	28	28.3
SP-Hwy	5	4	146.1

Selection of Group of Routes for Similarity Analysis

The minimum number of driving cycles required to represent the traffic of a studied region is determined following the process indicated in Figure 1. To answer the research question, seven groupings of routes were predefined: 1) all selected routes together, 2) all highway routes together, 3) PE-Hwy and SP-Hwy together, 4) all urban routes together, 5) all urban routes from Recife City and PE-Ma-Hwy together, 6) all urban routes from Recife together, and 7) all routes separately. The process starts with all routes (group 1) and, if necessary, proceeds to smaller and different groupings until a configuration in which the analyzed routes can be considered statistically similar is found (the criteria are presented in the Kinematic and Energy Analysis subsection). In addition, it is important to point out that the process was applied separately for the speed datasets collected for

Table 2. Definition of Kinematics Characteristics Parameters (CP_i) as Defined by Barlow et al. (*29*)

Kinematic characterization of speed-time data	
Average running speed (km/h)	$CP_1 = v_{avg,\,run} = 3.6\frac{L}{T_{drive}}$
Average speed (km/h)	$CP_2 = v_{avg} = 3.6\frac{L}{T_{total}}$
Average positive acceleration (m/s^2)	$CP_3 = a_{pos} = \left(\sum_{i=0}^{T_{total}}\begin{cases} a_i & (a_i>0) \\ 0 & (else)\end{cases}\right) / \left(\sum_{i=0}^{T_{total}}\begin{cases} 1 & (a_i>0) \\ 0 & (else)\end{cases}\right)$
Average deceleration (m/s^2)	$CP_4 = a_{neg} = \left(\sum_{i=0}^{T_{total}}\begin{cases} a_i & (a_i<0) \\ 0 & (else)\end{cases}\right) / \left(\sum_{i=0}^{T_{total}}\begin{cases} 1 & (a_i<0) \\ 0 & (else)\end{cases}\right)$
Time spent idling (%)	$CP_5 = \%idling = \frac{T_{stop}}{T_{total}}$
Time spent cruising (%)	$CP_6 = \%cruise = \frac{T_{cruise}}{T_{total}}$
Time spent accelerating (%)	$CP_7 = \%accelerating = \frac{T_{acc}}{T_{total}}$
Time spent decelerating (%)	$CP_8 = \%decelerating = \frac{T_{dec}}{T_{total}}$
Standard deviation of speed (km/h)	$CP_9 = \sigma_s = \sqrt{\frac{1}{T_{total}-1}\sum_{t=0}^{T_{total}}(v-\bar{v})^2}$

Note: L = total distance traveled; T_{acc} = drive time spent accelerating; T_{cruise} = time spent with constant non-zero speed; T_{dec} = drive time spent decelerating; T_{drive} = time spent with speed greater than zero; T_{stop} = time spent stopped; T_{total} = total time traveling.

cars and for motorcycles. Later, the developed driving cycles, for cars and motorcycles, are compared to analyze whether the same driving cycle could be used simultaneously both for cars and for motorcycles.

Kinematic and Energy Analysis

In this section, the kinematic and energy parameters are presented. Based on that, the criteria used to consider whether two or more routes are statistically similar were defined.

Kinematic Parameters. Nine kinematic characteristic parameters (CP_i) are used in this study for the numerical characterization of the routes and driving cycles (see Table 2).

Equation 1 evaluates the deviation CV_i between the kinematic parameters $CP_{i,j}$ of each route that composes the grouping. If CV_i is low, it indicates that those routes are similar in respect to the kinematic parameter i. Then, Equation 2 calculates the mean of the coefficient of variation for all the nine kinematic parameters. If $\overline{CV}_{kin}$ is less than or equal to 0.1, the grouping is considered satisfactory, that is, only one driving cycle is necessary to represent all the composing routes. If $\overline{CV}_{kin}$ is greater than 0.1, then the group is discarded.

$$CV_i = \frac{\sqrt{\frac{1}{n_r-1}\sum_{j=1}^{n_r}\left(CP_{i,j}-\overline{CP}_i\right)^2}}{\overline{CP}_i} \tag{1}$$

$$\overline{CV}_{kin} = \frac{\sum_{i=1}^{n_{cp}} CV_i}{n_{cp}} \tag{2}$$

where

CV_i = coefficient of variation of CP_i considering analyzed routes (n_r),

$\overline{CP}_i$ = average of CP_i considering analyzed routes (n_r),

$\overline{CV}_{kin}$ = average coefficient of variation of analyzed routes or driving cycles,

j = route or driving cycle,

i = kinematic characteristic parameter,

n_r = number of routes or driving cycles being analyzed, and

n_{cp} = number of analyzed CP_i.

Energy Parameter. Kinematics characteristics parameters are not the absolute way to characterize a driving cycle, as it is possible that routes can have similar $\overline{CV}_{kin}$ and different energy demand. The results of the analysis of 40 driving cycles made by de Andrade et al. are in agreement with the last statement (*8*). From their results, 15% of the cycles presented $\overline{CV}_{kin}$ less than 10%, although energy demand variation greater than 10%, while 27% presented $\overline{CV}_{kin}$ greater than 10% and a coefficient of variation from the energy demand less than 10%. Thus, it can be inferred that similar kinematic characteristic parameters do not imply similar energy demands.

The evaluation of the energy demand is made through the calculation of the mechanical power demanded on the tires (Equation 3) and its consequent demanded energy (integrated over the whole trajectory, Equation 4). In this analysis, among all the vehicles used in the tests (as references for the energy comparisons), the Chevrolet Onix 1.0 car and the Honda CB300 motorcycle were chosen, the parameters of which are described in Table 3. The vehicle

Table 3. Physical Parameters of the Simulated Vehicles

Physical parameter	Chevrolet Onix car	Honda CB300 motorcycle
m (kg)	1,086	227
K_A (kg/m)	0.49	0.37
C_R	0.01	0.009

Note: C_R = rolling coefficient; K_A = aerodynamic resistance factor; m = vehicle mass.

masses were obtained from the respective user manuals, added to the driver/rider mass, and adjusted by a factor of 1.015 to account for the effects of the rotating mass of the vehicle, as defined in Brazilian norm for coastdown test (*30*).

For the car, the aerodynamic resistance factor (K_A) and the rolling coefficient (C_R) were obtained from the Coast Down test for existing vehicles in Brazil using data shared by the Brazilian National Institute of Metrology, Standardization and Industrial Quality. For motorcycles, there is no official public data available in Brazil. The value of K_A and C_R used were the same obtained by de Andrade et al. for the Honda CB 300 (*12*).

The mechanical power (P_{tire}), defined in Equation 3, refers to the instantaneous mechanical power required in the tire for the vehicle to travel on the studied route. Its value is null when the vehicle is idling or when the inertial force is negative and greater than the resistant forces of the movement (gravity, rolling, and aerodynamics). In the results section, there will be a brief evaluation of both the impact of the road slope as well as what would the vehicular demanded energy (VDE) be if a regenerative propulsion system was used.

$$P_{tire}(t) = \left\{ma(t) + mg\sin\theta \quad + C_r mg\cos\theta \quad + K_A[V(t)]^2\right\}V(t) \tag{3}$$

where
P_{tire} = instantaneous mechanical power on the tire (W),
g = acceleration of the gravity (m/s^2),
m = corrected vehicle's mass (kg) (*30*),
$a(t)$ = instantaneous acceleration (m/s^2),
$V(t)$ = instantaneous speed (m/s), and
θ = road slope (rad).

The VDE is defined by the division between the total mechanical energy used in the route by the total distance traveled, Equation 4:

$$VDE = \frac{1}{L}\int P_{tire}dt \tag{4}$$

where
L = total distance traveled.

For a set of routes to be considered similar in energy demand, it was defined that the coefficient of variation of VDE, CV_{energy} (Equation 5), must be up to 10% (*21*). It is important to highlight that test routes are only counted as similar in this study if they respect both the kinematic and energy criteria. This analysis of similarity is the foundation stone for the development of LDCs in this study because for each set of similar routes an LDC will be developed.

$$CV_{energy} = \frac{\sqrt{\frac{1}{n_r - 1}\sum_{j=1}^{n_r}\left(VDE_j - \overline{\mathrm{VDE}}\right)^2}}{\overline{VDE}} \tag{5}$$

Methodology for the Development of Driving Cycles

The main objective of the development of a driving cycle is obtaining compact speed vectors that reproduce the vehicle behavior in real traffic, maintaining the kinematic parameters of the speed data collected experimentally. In this study, regardless of the method used (see Figure 5), the developed cycle is considered valid if its duration time is between 10 and 40 min (as stated by Arun et al.) and its $\overline{CV}_{kin}$ (in relation to the original grouped collected data) is up to 10% (*20*). Otherwise, the driving cycle developed is discarded, and another is developed until the required specifications are met.

For the development of driving cycles, two of the main methods employed and accepted in the literature were adopted, following the recommendation of Santos et al: 1) the micro-trip method for urban driving cycles and 2) the Markov chain method for highway driving cycles (*16–24*, *31–41*).

In the micro-trip method, the speed dataset is divided into micro-trips (defined as segments that start and finish when the speed is zero). Then, the segments obtained are recombined randomly (see Figure 5*a*). The developed cycle is considered valid only when all established criteria are met. Otherwise, the driving cycle is discarded, and another one is developed. Therefore, the driving cycle developed by the micro-trip method preserves segments of the collected speed data, being formed by micro trajectories that a vehicle has actually traveled before (*12*). The micro-trip method is suitable for the development of urban driving cycles, in which there are frequent stops owing to congestion, traffic lights, and intersections.

The development of driving cycles using data collected on highways is not suitable for the micro-trip method owing to the low occurrence of zero speed, which makes the Markov chain method an alternative. Although the Markov chain method can be used for urban and highway scenarios, Huertas et al. warn that this method produces fewer developed cycles compared with the micro-trip method (*24*). Furthermore, Santos et al. and Zhang et al. observed that the use of the Markov chain method generated segments

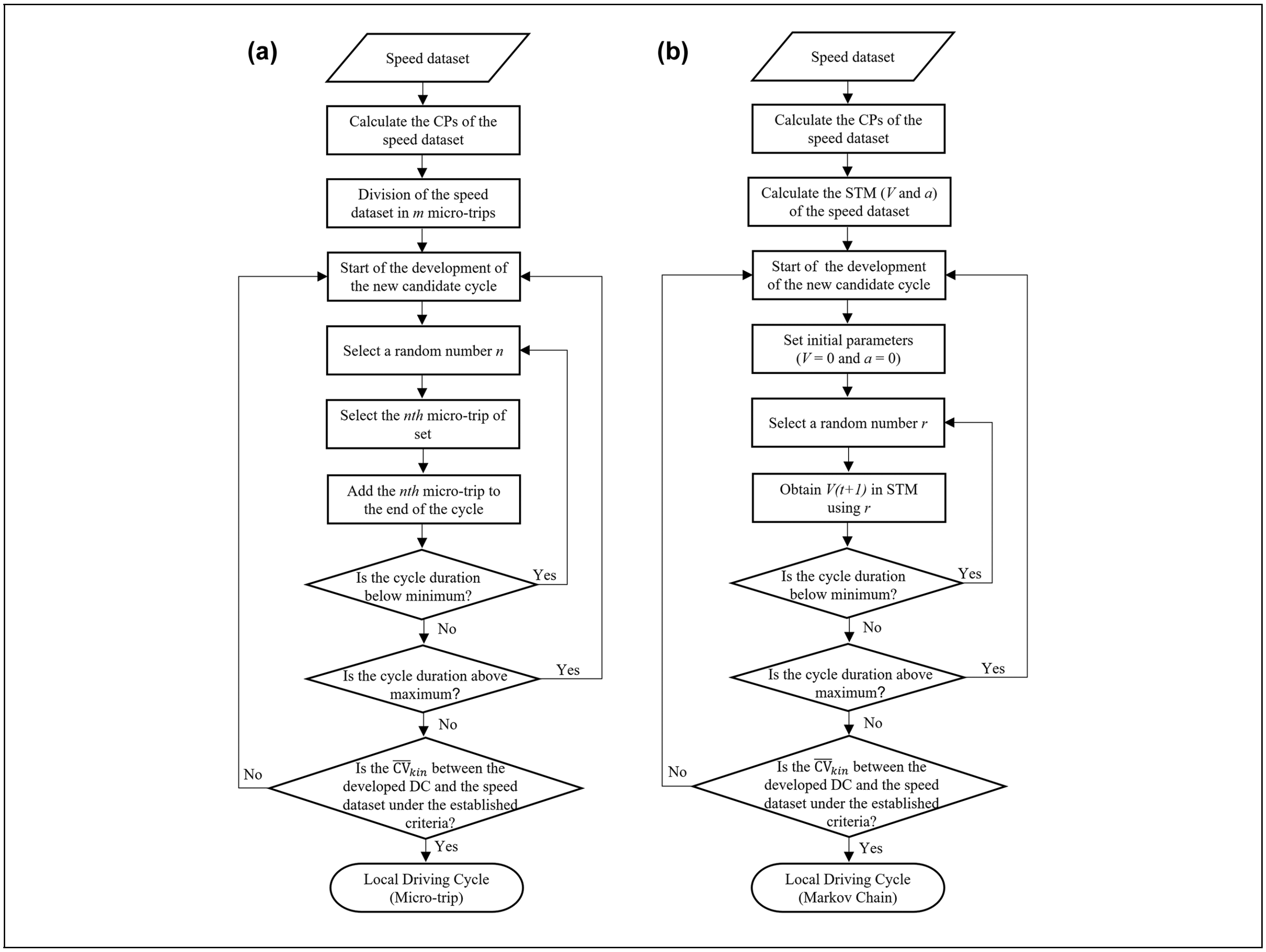

Figure 5. Flowchart for the development of driving cycle: (*a*) micro-trip method and (*b*) Markov chain method.
Note: CP = Kinematic Characteristics Parameters; DC = driving cycle; STM = state transition matrix.

with longer duration compared with the micro-trip method when applied to the same set of urban speed data (*32*, *40*).

In the Markov chain method, the driving cycle is created to statistically represent the kinematic information of the evaluated routes using one or more variables. This mathematical approach operates under the assumption that, in a given time, the state depends only on what happened in the immediately previous time (*40*). The transition of a variable from one state to another is computed using a matrix called the "state transition matrix" (STM), which records the probability for all possible transitions to occur. In this study, two variables (speed and acceleration) are evaluated with the STM (see Figure 5*b*). For the developed cycle to be approved, it is necessary, as with the micro-trip method, that the duration time is between 10 and 40 min and its $\overline{CV}_{kin}$ (in relation to the original grouped collected data) is up to 10%.

Concerning the codes used in this study, all of them were developed by the authors: the kinematic parameters, the energy parameter, and the driving cycles (micro-trip method) were calculated using Scilab codes; the coefficients of variation were calculated using an Excel datasheet; and the driving cycles (Markov chain method) were calculated using a C++ code.

Results and Analysis

In this section, the test routes selected in Pernambuco and São Paulo states are characterized by kinematic and energy parameters. Afterwards, LDCs are developed to represent the traffic behavior of cars and motorcycles in the studied regions. Finally, the LDCs created are compared with the SDCs established by the Brazilian legislation (i.e., FTP-75, HWFET, and WMTC).

Collected Data on the Test Routes

Cars and motorcycles were used on the seven test routes (described in Test Routes Selection subsection) defined for the states of Pernambuco and São Paulo on urban

Table 4. Summary of the Collected Speed Dataset

Vehicle type	Route	Number of tests	Time (s)	Average speed (km/h)	Route length (km)
Car	PE-Urb-S	20	70,585	22	17.3
	PE-Urb-N	20	51,044	23	15.3
	PE-Urb-E	2	8,231	26	25.7
	PE-Ma-Hwy	6	39,619	52	93.4
	PE-Hwy	8	27,867	86	71.4
	SP-Urb	28	115,449	24	28.3
	SP-Hwy	4	29,458	71	146.1
Motorcycle	PE-Urb-S	18	30,569	37	17.3
	PE-Urb-N	18	31,374	34	15.3
	PE-Urb-E	18	57,676	29	25.7
	PE-Ma-Hwy	6	31,542	64	93.4
	PE-Hwy	4	8,549	82	71.4
	SP-Urb	28	81,471	33	28.3
	SP-Hwy	5	30,107	77	146.1

and highway routes. In these experiments, 95 h of data were recorded using cars and 75 h of data were recorded using motorcycles (see Table 4). The discrepancy between the number of hours spent with cars and motorcycles is because cars take more time to cover the test routes. This occurs because local traffic conditions have a great impact on the movement of the cars, while the motorcycles can travel between traffic lanes in Brazil, allowing them to be quicker. It should be noticed that, in the case of Brazilian motorcycles (65% of them are above 12 HP, and 95% above 7 HP), the motorcycles are very fast in urban traffic, which cannot be true in other countries where the majority of motorcycles are scooters and cubs. The discrepancy between the number of tests for cars on the PE-Urb-E route and the other urban routes of Recife City (PE-Urb-N and PE-Urb-S) occurred owing to the discard of 18 tests, caused by the excessively aggressive behavior of the test driver, observed by the occurrence of speeds 40% higher than the value allowed by law. In addition, one test with cars on the SP-Hwy route was discarded owing to technical problems with the GPS.

Kinematic and Energy Analysis of Urban and Highway Routes

In this subsection, the kinematic parameters and VDE on the test routes are compared to analyze the possibility of combining the data collected (see Table 4) for the purpose of creating driving cycles.

To assess whether only one LDC can represent the urban and highway traffic in the two Brazilian states, Pernambuco and São Paulo, the kinematics characteristics parameters (CP_i) and VDE from the speed data collected in all selected the test routes were evaluated (see Figures 6 and 7). Average coefficients of variation of 42% for cars and 42% for motorcyclesin relation to the kinematic parameters were obtained. The results of the energy analysis confirm what was verified in the kinematic analysis, obtaining a coefficient of variation of 13% for cars and 25% for motorcycles. Therefore, a single driving cycle cannot adequately represent the diversity of traffic patterns observed across all the routes analyzed for each type of vehicle.

It is important to highlight that the impact of road slopes was evaluated before estimating the demand energy of the cars and motorcycles using the data collected by the GPS. In all routes studied, the impact on the VDE was less than 4%, except for the SP-Urb route, on which there was an impact of approximately 10%. In addition, it is important to point out that it is possible to disregard the influence of the incline in the routes, since the Brazilian national fleet is capable of carrying out these tests without affecting its performance (the highest engine power used by the cars on the route was 56% of the engine peak power and the highest engine power used by the motorcycles was 64% of the engine peak power). Thus, as the main interest of this study is in the characterization of the traffic, for simplicity and to facilitate the comparison between the traffic between the various regions, the slope of the roads was considered as zero on the energy demand calculations.

Subsequently, another analysis was carried out between the cycles of Pernambuco and São Paulo States to assess the possibility of the development of a single highway driving cycle to represent the recorded data of both states (i.e., PE-Hwy, PE-Ma-Hwy, and SP-Hwy). An analysis of kinematic characteristics parameters (CPs) revealed an average coefficient of variation ($\overline{CV}_{kin}$) between the highway routes of 38% for cars and 34% for motorcycles, a value considerably greater than the 10% threshold. This indicates that a single highway driving cycle is not sufficient to adequately represent the wide variability of driving patterns observed across the two states of Pernambuco

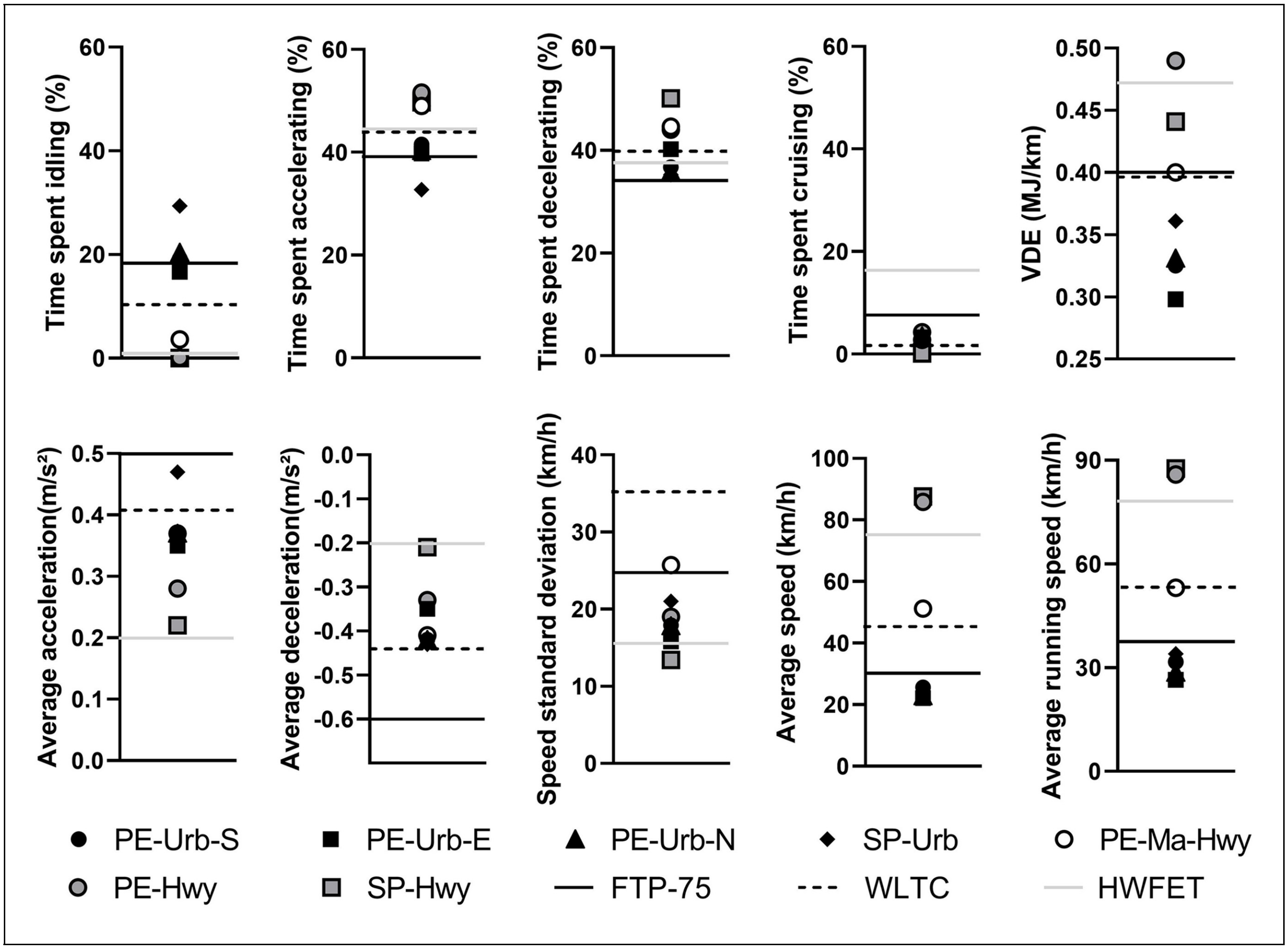

Figure 6. Kinematics characteristics parameters (*CPi*) and vehicular demanded energy (VDE) collected with cars.
Note: FTP = Federal Test Procedure; HWFET = Highway Fuel Economy Driving Cycle; WLTC = Worldwide Harmonized Light Vehicles Test Cycle.

and São Paulo. One hypothesis for this difference is that PE-Ma-Hwy is composed of stretches with urban characteristics (e.g., the presence of traffic lights and intersections), whereas PE-Hwy and SP-Hwy are composed only of highway sections.

A complementary analysis of the kinematics parameters was carried out only with the PE-Hwy and SP-Hwy cycles to eliminate the effects of the urban stretches of the PE-Ma-Hwy route. A $\overline{CV}_{kin}$ of 28% for cars and 36% for motorcycles was found. Therefore, the use of a single highway driving cycle is not appropriate. This kinematic conclusion is in accord with the energy analysis. The VDE analysis exhibited a coefficient of variation (CV_{energy}) of 13% for cars and 16% for motorcycles.

The subsequent step was the evaluation of urban routes. The data collected on the urban routes in Recife City (PE-Urb-S, PE-Urb-E, PE-Urb-N) and São Paulo City (SP-Urb) were compared. It was found that there is a $\overline{CV}_{kin}$ of 10% (for cars) and 9% (for motorcycles). This result is within the limit of 10% and indicates the possibility of applying a single local urban driving cycle for Recife and for São Paulo City from a kinematic point of view. From an energy perspective, there is a CV_{energy} of variation of 8% for cars and 9% for motorcycles, confirming the possibility of creating a single driving cycle for each type of vehicle to represent the urban traffic of both cities.

In addition, all urban routes from Recife City were compared with the PE-Ma-Hwy. This comparison was performed to verify if the metropolitan highway route (PE-Ma-Hwy) has similar characteristics to the urban routes, as it passes through peripheral areas of the city with traffic lights. It was found that PE-Ma-Hwy cannot be considered similar to the urban route of Recife, because the average coefficient of variation of the kinematics parameters are greater than 25% for both types of vehicle.

As a complementary analysis, the impact that regenerative braking would have on the VDE was evaluated. For this specific analysis, it was considered that the net power (negative in the case of deceleration) transmitted

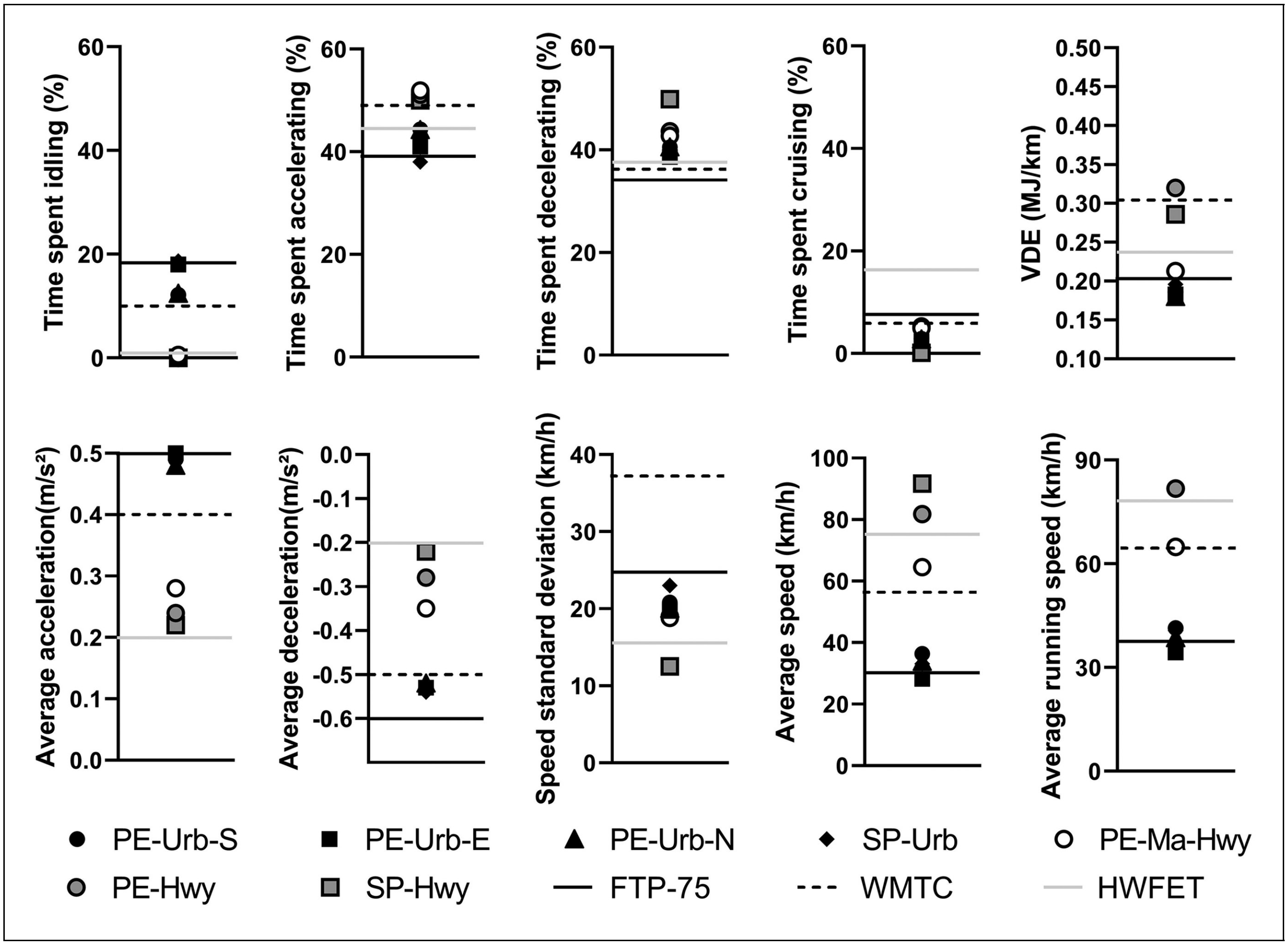

Figure 7. Kinematics characteristics parameters (*CPi*) and vehicular demanded energy (VDE) collected with motorcycles.
Note: FTP = Federal Test Procedure; HWFET = Highway Fuel Economy Driving Cycle; WLTC = Worldwide Harmonized Light Vehicles Test Cycle.

through the tire could be accumulated in the vehicle's battery during deceleration phases. In urban routes with regenerative braking, this analysis indicated a decrease of 44% in VDE for cars and a lesser decrease of 16% in VDE for motorcycles (because of their lower inertia). In highway routes with regenerative braking, the impact would be smaller on the VDE, because the percentage of time decelerating is lower (cars present a decrease of 15% and motorcycles present a decrease of 4%).

Local Driving Cycles (LDCs) Developed: Kinematic and Energy Analysis

In this subsection, LDCs are developed for each grouping of routes presented in the previous section. A total of eight LDCs were developed, consisting of four for cars and four for motorcycles, to represent the urban and highway traffic of the two cities. Subsequently, the cycles are analyzed using kinematic and energy parameters. In addition, the LDCs were also compared with SDCs (FTP-75, WLTC, HWFET, and WMTC).

Local Driving Cycles (LDCs) for Cars. Four LDCs were developed for cars in this study (see Figure 8): LDC PE/SP-Urb; LDC PE-Ma-Hwy; LDC PE-Hwy, and LDC SP-Hwy. Different behaviors were observed for each of the conditions represented, displaying the differences that exist in Brazilian roads. Table 5 displays the kinematics characteristics parameters (CP_i) of the four developed driving cycles and the three commonly used SDCs (FTP-75, WLTC, and HWFET). This table also lists, in parentheses, the coefficient of variation of each cycle and the FTP-75 (for urban cycles), and for each cycle and the HWFET (for highway cycles).

Comparing the LDC PE/SP-Urb with the FTP-75 SDC, it was verified that both present a high percentage of time idling (24.2% and 17.9%, respectively), as is expected in the traffic of the big cities. In addition, Table

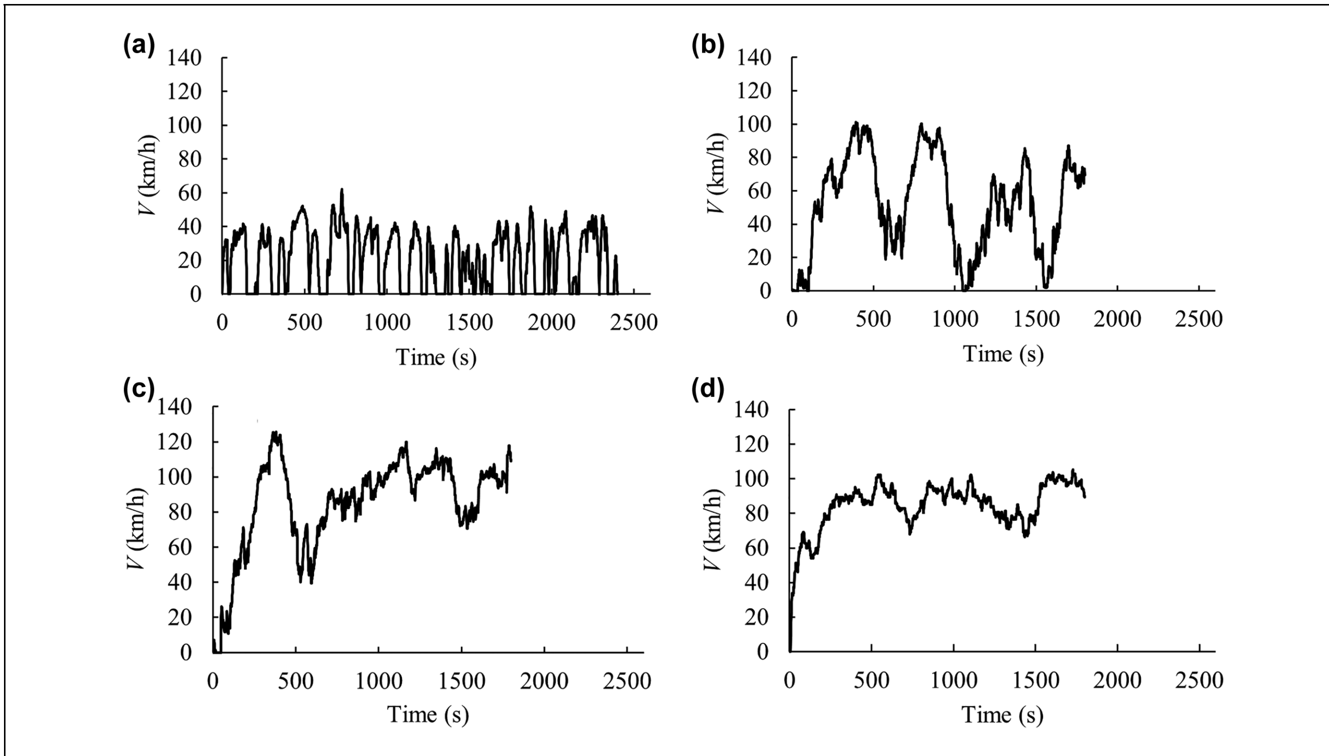

Figure 8. Cars' local driving cycles (LDCs): (*a*) LDC PE/SP-Urb, (*b*) LDC PE-Ma-Hwy, (*c*) LDC PE-Hwy, and (*d*) LDC SP-Hwy.

Table 5. Kinematics Characteristics Parameters (CP_i) and Vehicular Demanded Energy (VDE) of Cars' Driving Cycles

	Urban		Highway				
Kinematics characteristics parameter	PE/SP-Urb*	FTP75	PE-Ma-Hwy**	PE-Hwy**	SP-Hwy**	HWFET	WLTC
Time spent idling (%)	24.2 (21%)	17.9	2.5 (93%)	2.0 (83%)	0.3 (42%)	0.5	12.5
Time spent accelerating (%)	35.9 (7%)	39.4	42.9 (2%)	41.4 (5%)	19.9 (54%)	44.2	43.9
Time spent decelerating (%)	36.6 (3%)	35.0	34.3 (9%)	34.3 (9%)	17.3 (54%)	38.8	40.0
Time spent cruising (%)	3.2 (58%)	7.7	20.3 (15%)	22.3 (21%)	62.5 (82%)	16.5	3.7
Average acceleration (m/s^2)	0.5 (7%)	0.5	0.4 (52%)	0.3 (40%)	0.4 (44%)	0.2	0.41
Average deceleration (m/s^2)	–0.5 (-17%)	–0.6	–0.5 (-53%)	–0.4 (–34%)	–0.3 (–30%)	–0.2	–0.44
Speed standard deviation (km/h)	16.8 (30%)	25.7	28.9 (39%)	27.2 (35%)	14.3 (10%)	16.5	36.1
Average speed (km/h)	21.8 (31%)	34.1	52.5 (27%)	84.9 (6%)	84.5 (6%)	77.7	46.6
Average running speed (km/h)	28.8 (26%)	41.6	53.9 (26%)	86.6 (7%)	84.7 (6%)	78.1	53.2
VDE (MJ/km)	0.315 (17%)	0.400	0.420 (5%)	0.518 (19%)	0.428 (6%)	0.393	0.475

Note: HWFET = Highway Fuel Economy Driving Cycle; WLTC = Worldwide Harmonized Light Vehicles Test Cycle.
*The coefficient of variation (CV_i) of the developed driving cycle and FTP-75 is displayed in parentheses.
**The coefficient of variation (CV_i) of the developed driving cycle and HWFET is displayed in parentheses.

5 lists low values of time spent idling for the highway LDCs PE-Ma-Hwy, PE-Hwy, and SP-Hwy (2.5%, 2.0%, and 0.3%, respectively), and for the HWFET SDC (0.5%). It was also observed that the cycles developed for urban areas have an average speed less than 35 km/h, average running speed less than 42 km/h, and an acceleration equal to 0.5 m/s^2. On the other hand, highway driving cycles presented higher values for average speed and average running speed (greater than 50 km/h) and lower values for acceleration (up to 0.4 m/s^2). These results indicate how the urban driving cycles (LDC PE/SP-Urb and FTP-75) and highway driving cycles (LDCs PE-Ma-Hwy, PE-Hwy, SP-Hwy, and HWFET) have different characteristics.

Additionally, it was verified that the SDC used in Europe—WLTC—presents kinematics characteristics

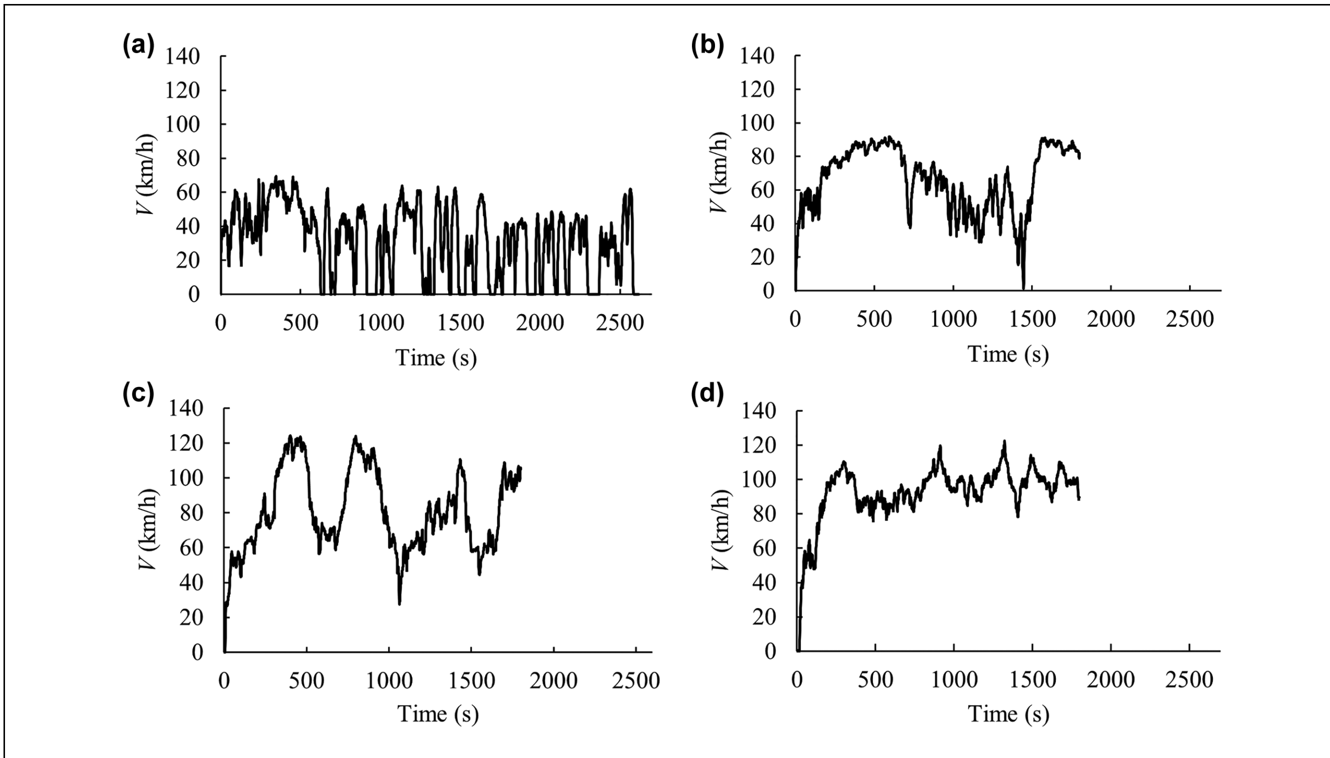

Figure 9. Motorcycles' local driving cycles (LDCs): (*a*) LDC PE/SP-Urb, (*b*) LDC PE-Ma-Hwy, (*c*) LDC PE Hwy, and (*d*) LDC SP-Hwy.

parameters between the values of the local urban driving cycles and local highway driving cycles developed in the present study. The percentage of time idling in the WLTC is always less than the local urban driving cycles, but greater than any local highway driving cycles developed in this study. Moreover, an opposite pattern was observed for the average speed (i.e., higher values in comparison to urban driving cycles and lower values in comparison to highways cycles). These differences were expected, as the WLTC cycle was developed to represent both cities and highways.

The analysis of the similarities between the developed LDCs and the SDCs indicates that FTP-75 is more adequate to represent PE/SP-Urb than WLTC. This is observed numerically through $\overline{CV}_{kin}$ (22% for FTP-75 and 24% for WLTC) and CV_{energy} (14% for FTP-75 and 27% for WLTC). For highways, the comparison between the developed LDC and an SDC (HWFET and WLTC) shows that the $\overline{CV}_{kin}$ is 41% for WLTC and 32% for HWFET, and CV_{energy} is 10% for WLTC and 12% for HWFET.

From the energy point of view (see Table 5), the lowest VDE occurred in the LDC PE/SP-Urb and FTP75 urban cycles (0.315 and 0.400 MJ/km). These lower values can be attributed to their lower average speeds. The WLTC and PE-Ma-Hwy driving cycles, which have mixed characteristics between urban and highway traffic, presented values of 0.475 and 0.420 MJ/km, respectively. Finally, the highway cycles, HWFET, SP-Hwy, and PE-Hwy, presented VDE values of 0.393, 0.428, and 0.518 MJ/km, respectively. HWFET presented the lowest VDE of all the highway driving cycles, which can be related to the lower average acceleration. Besides, PE-Hwy is the LDC with the highest VDE. This driving cycle has the highest average speed and a high coefficient of variation of the speed, indicating a greater occurrence of accelerations and decelerations.

Local Driving Cycles (LDCs) for Motorcycles. Figure 9 displays the four LDCs developed for motorcycles. Visually, different behaviors are noted for each of the represented traffic conditions. In addition, Table 6 presents the CP_i and VDE of the LDCs and SDCs (FTP-75, HWFET, and WMTC).

Comparison between LDCs and SDCs for motorcycles leads to results similar to those observed in the analysis for the cars (presented in the Local Driving Cycles for Cars subsection). Urban cycles exhibited a high percentage of idling time than highway cycles (see Table 6). In addition, urban driving cycles present lower average speeds and higher average accelerations when compared with highway driving cycles. Similar to the WLTC cycle for cars, the WMTC cycle has intermediate characteristics between urban driving cycles and highway

Table 6. Kinematics Characteristics Parameters (CP_i) and Vehicular Demanded Energy (VDE) of Motorcycles' Driving Cycles

	Urban		Highway				
Kinematics characteristics parameters	PE/SP-Urb*	FTP75	PE-Ma-Hwy**	PE-Hwy**	SP-Hwy**	HWFET	WMTC
Time spent idling (%)	15.6 (10%)	17.9	0.1 (92%)	0.1 (114%)	0.5 (3%)	0.5	8.8
Time spent accelerating (%)	41.0 (3%)	39.4	42.7 (2%)	42.2 (3%)	37.8 (11%)	44.2	47.8
Time spent decelerating (%)	40.7 (11%)	35.0	30.4 (17%)	31.0 (16%)	36.5 (1%)	38.8	37.7
Time spent cruising (%)	2.8 (66%)	7.7	26.9 (34%)	26.7 (34%)	25.2 (30%)	16.5	5.7
Average acceleration (m/s^2)	0.5 (3%)	0.5	0.3 (36%)	0.3 (36%)	0.3 (29%)	0.2	0.4
Average deceleration (m/s^2)	–0.5 (–5%)	–0.6	–0.4 (–44%)	–0.4 (–38%)	–0.3 (–12%)	–0.2	–0.5
Speed standard deviation (km/h)	20.5 (16%)	25.7	19.1 (10%)	23.2 (24%)	16.7 (1%)	16.5	37.9
Average speed (km/h)	31.9 (5%)	34.1	66.6 (11%)	80.6 (3%)	92.6 (12%)	77.7	57.8
Average running speed (km/h)	37.8 (7%)	41.6	66.6 (11%)	80.6 (2%)	93.0 (12%)	78.1	63.4
VDE (MJ/km)	0.189 (5%)	0.203	0.225 (5%)	0.296 (14%)	0.315 (19%)	0.242	0.305

Note: HWFET = Highway Fuel Economy Driving Cycle; WLTC = Worldwide Harmonized Light Vehicles Test Cycle.
*The coefficient of variation (CV_i) of the developed driving cycle and FTP-75 is displayed in parentheses.
**The coefficient of variation (CV_i) of the developed driving cycle and HWFET is displayed in parentheses.

driving cycles for motorcycles. The LDC PE/SP-Urb driving cycle developed for motorcycles and WMTC SDC present $\overline{CV}_{kin}$ of 26% and CV_{energy} of 33%. These results are higher than the values found when comparing the same urban cycle with the FTP-75 ($\overline{CV}_{kin}$ of 13% and CV_{energy} of 5%).

Lower VDE is observed for the LDC PE/SP-Urb driving cycle and FTP-75 urban driving cycle (0.189 and 0.203 MJ/km), which can be attributed to the lower values of average speeds. HWFET, LDC SP-Hwy, and LDC PE-Hwy highway driving cycles have higher average speeds, which leads to higher VDE compared with urban cycles (0.242, 0.315, and 0.296 MJ/km, respectively).

Finally, the cycles developed for cars and motorcycles were compared to verify if there is any scenario in which a single driving cycle would be appropriate to represent the local traffic for both types of vehicle. This comparison was performed separately with each one of the following double cycles (cars and motorcycle): LDC PE-Hwy (kinematic coefficient of variation, $\overline{CV}_{kin} = 19\%$), LDC PE-Ma-Hwy ($\overline{CV}_{kin} = 25\%$), LDC SP-Hwy ($\overline{CV}_{kin} = 24\%$), and LDC PE/SP-Urb ($\overline{CV}_{kin} = 13\%$). Specifically, cars spent 8% more time idling, and motorcycles have an average speed 10 km/h higher than cars. These results indicate that one driving cycle for each type of vehicle is required to represent each dataset.

Comparison with Other Local Driving Cycles. Comparing the LDC developed by de Andrade et al. (for Recife at off-peak hours in the route PE-Urb-S) with the urban LDC developed in this study (for Recife and São Paulo City, at peak and off-peak hours, encompassing routes PE-Urb-S, PE-Urb-N, PE-Urb-E, and SP-Urb), a $\overline{CV}_{kin}$ of 5% for cars and 4% for motorcycles was found (*12*). Thus, the more general LDC developed in the present study was able to also represent a more specific situation.

In another comparative study, the urban driving cycles developed in this study were compared with driving cycles developed for cities in Brazil and around the world, as shown by de Andrade et al. (*8*). Comparing the LDC PE/SP-Urb (for cars) with LDC Fortaleza/Brazil (pop. 2.6 million), a $\overline{CV}_{kin}$ of 14% was found, and comparing the LDC PE/SP-Urb (for cars) with LDC Santa Maria/Brazil (pop. 285,000) yielded a $\overline{CV}_{kin}$ of 42%, showing that the developed urban driving cycle of this study (using Recife, pop. 1.6 million and São Paulo, pop. 12.4) is more suitable for larger cities, as expected. Comparing the LDC PE/SP-Urb (for cars) with other larger cities around the world (Athens, pop. 3.1 million; Bangalore, pop. 13.6 million; Beijing, pop. 21.5 million; Sidney, pop. 5.3 million; and Shanghai, pop. 26.3 million) resulted in a $\overline{CV}_{kin}$ of 26%, pointing to the differences of traffic between countries. In addition, when the LDC PE/SP-Urb (for motorcycles) was compared with other driving cycles for motorcycles around the world (Hanoi, pop. 5.2 million; Shanghai, pop. 26.3 million; and Taipei, pop. 2.6 million), it resulted in a $\overline{CV}_{kin}$ of 22%.

Conclusion

In this study, it was investigated whether it is possible to find a single driving cycle capable of reproducing the traffic behavior of different vehicle types, road types, and different cities. This study was carried out in two major Brazilian cities—Recife City and São Paulo City—where speed data were collected with smartphone GPS receivers of 1 Hz in four urban routes (three in Pernambuco State: PE-Urb-S, PE-Urb-N, and PE-Urb-

E; and one in São Paulo State: SP-Urb) and three highway routes (two in Pernambuco State: PE-Ma-Hwy and PE-Hwy; and one in São Paulo State: SP-Hwy) using both cars and motorcycles.

In this study, a group of routes, or driving cycles, are considered statistically similar if their average coefficient of variation in relation to the kinematic characteristic parameters ($\overline{CV}_{kin}$) and the coefficient of variation in relation to the vehicular demand energy (CV_{energy}) are both below 10%. The comparison of the speed dataset collected with cars on all the seven defined routes resulted in $\overline{CV}_{kin}$ of 42% and CV_{energy} of 13%. For motorcycles, $\overline{CV}_{kin}$ of 42% and CV_{energy} of 25% were observed. These results indicated that a single driving cycle is unable to represent the traffic of the seven routes analyzed for each type of vehicle.

When evaluating both states (i.e., Pernambuco and São Paulo) but considering only their highway routes, $\overline{CV}_{kin}$ of 38% and CV_{energy} of 10% for cars, and $\overline{CV}_{kin}$ of 34% and CV_{energy} of 20% for motorcycles were found. The difference between the three highway routes can be mainly observed by the speed standard deviation (13.4–25.7 km/h for cars, and 12.5–19.0 km/h for motorcycles) and average speed (51.2–87.6 km/h for cars, and 64.5–91.7 km/h for motorcycles). The results also indicate that, for urban traffic in the two Brazilian major cities, the average vehicle behavior is similar. For example, in the four urban routes, cars presented an average speed between 22.1 and 25.6 km/h, and VDE between 0.298 and 0.361 MJ/km; motorcycles presented an average speed between 28.2 and 36.4 km/h, and VDE between 0.180 and 0.196 MJ/km.

Afterwards, it was observed that a single driving cycle was capable of correctly representing simultaneously the urban traffic in both cities (São Paulo and Recife) for the same type of vehicle ($\overline{CV}_{kin}$ of 10% and CV_{energy} of 8% for cars, and $\overline{CV}_{kin}$ of 9% and CV_{energy} of 9% for motorcycles). In addition, it was possible to extend this conclusion for only the three urban routes of Recife City, where the analyses of the speed dataset displays that different regions within the Recife City presented similar driving behavior ($\overline{CV}_{kin}$ of 8% and CV_{energy} of 6% for cars, and $\overline{CV}_{kin}$ for 7% and CV_{energy} of 2% for motorcycles).

It was found that cars and motorcycles demanded distinct driving cycles, since the comparison between their cycles presented $\overline{CV}_{kin}$ of 19% for LDC PE-Hwy, $\overline{CV}_{kin}$ of 25% for LDC PE-Ma-Hwy, $\overline{CV}_{kin}$ of 24% for LDC SP-Hwy, and $\overline{CV}_{kin}$ of 13% LDC PE/SP-Urb. Thus, eight driving cycles were developed: four for motorcycles and four for cars, two for urban traffic and six for highway traffic.

The analysis of the developed driving cycles also indicated that the SDC adopted by the Brazilian legislation (FTP-75) is not adequate to represent the urban routes analyzed in Recife City and São Paulo City, as it presents $\overline{CV}_{kin}$ (between FTP-75 and PE/SP-Urb) of 22% for cars and 13% for motorcycles. The comparison between the highway cycle used in Brazil for cars—HWFET—and the highway driving cycles developed in this study leads to the same conclusion, since they resulted in $\overline{CV}_{kin}$ of 32%. In addition, it was also observed that: 1) the FTP-75 ($\overline{CV}_{kin}$ = 22%) represents the local urban traffic of cars better than the WLTC ($\overline{CV}_{kin}$ = 24%); 2) the HWFET ($\overline{CV}_{kin}$ = 32%) is a better fit to represent the highway traffic of cars than the WLTC ($\overline{CV}_{kin}$ = 41%); and 3) the FTP-75 ($\overline{CV}_{kin}$ = 13%) captures the local urban traffic behavior of motorcycles better than WMTC ($\overline{CV}_{kin}$ = 26%).

In summary, based on the studies of Recife and São Paulo, each vehicle (car and motorcycle) demands its own driving cycle; SDCs are not appropriate to represent local traffic conditions; driving cycles developed for larger cities should not be applied to smaller cities; driving cycles developed for a country should not be applied to other countries; the same driving cycle can represent the urban traffic of distinct cities; and each highway demands its own driving cycle. With the characterization of the traffic, those developed driving cycles can be used to test existing vehicles for consumption and pollution, as well to design new vehicles (e.g., electrical, hybrid, autonomous) suited for the local traffic.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: G. Andrade, F. Magnani; data collection: G. Andrade, F. Magnani; analysis and interpretation of results: G. Andrade, F. Magnani, M. Santos, F. Araújo; draft manuscript preparation: M. Santos, G. Andrade, F. Araújo, F. Magnani. All authors reviewed the results and approved the final version of the manuscript.

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