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# Protocol to evaluate methods designed for the construction of representative driving cycles

## Protocolo para evaluar métodos diseñados para la construcción de ciclos de conducción representativos

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**ABSTRACT:** Multiple methods have been developed to construct driving cycles. However, a procedure to verify the ability of those methods to construct driving cycles that accurately represent local driving patterns has yet to be established. In this manuscript, we propose a protocol that addresses this need. We first define driving pattern representativeness and then propose a procedure and metrics to evaluate it. We argue that driving cycles should also reproduce vehicles' energy consumption and tailpipe emissions. i.e., driving cycles should be constructed in the way that fuel consumption and tailpipe emissions of a given vehicle technology following the driving cycle in a chassis dynamometer are similar to the values observed in the regular use of that vehicle technology in the region for which the driving cycle was obtained. Based on this statement, we include a procedure and metrics to evaluate the ability of the method under evaluation to fulfill these requirements.

**RESUMEN:** Se han desarrollado múltiples métodos para construir ciclos de conducción. Sin embargo, aún no se ha establecido un procedimiento para verificar la capacidad de esos métodos de construir ciclos de conducción que representen con precisión los patrones de conducción locales. En este manuscrito, proponemos un protocolo que aborda esta necesidad. Primero establecemos una definición de representatividad del patrón de conducción y luego proponemos un procedimiento y métricas para evaluarlo. Argumentamos que los ciclos de conducción también deberían reproducir el consumo de energía y las emisiones de escape de los vehículos. Es decir, los ciclos de conducción deben construirse de manera que el consumo de combustible y las emisiones del tubo de escape de una determinada tecnología de vehículo siguiendo el ciclo de conducción en un dinamómetro de chasis sean similares a los valores observados en el uso normal de esa tecnología de vehículo en la región para la cual se obtuvo el ciclo de conducción. Con base en esta declaración, incluimos un procedimiento y métricas para evaluar la capacidad del método bajo evaluación para cumplir con estos requisitos.

## 1. Introduction

A driving pattern describes how vehicles are driven in a given region [1], while a Driving Cycle (DC) is a speed-time series that represents that driving pattern [1–3]. DCs are mainly used to evaluate the energy efficiency (fuel or energy consumption) and the environmental performance (tailpipe emissions) of vehicles. Multiple methods have been developed to construct those representative DCs. However, a procedure to verify the ability of those methods to produce DCs that accurately represent local driving patterns has not yet been established. On the other hand, homologation driving cycles are used to verify or compare the performance of vehicles. These DCs are not representative of the operating conditions of a specific region. Thus, they do not allow the evaluation of the energy or environmental performance of vehicles in a region of interest.

The methods most frequently used to construct a DC are Micro-trips (MT) and Monte Carlo Markov Chains (MCMC). Even though the basic idea of each of these

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methods remains the same, multiple variations exist in their implementation. Another method that has generated great interest is the Fuel-Based method (FBM) [1]. This is a deterministic method (each time the method is executed with the same database, it obtains the same solution) that selects, from the monitored travel database, the trip that has the smallest difference between its specific fuel consumption $(SFC_c)$ and the average SFC of all trips $\left(\mathrm{Min}\left|SFC_c - \overline{SFC}\right|\right)$. A detailed description of all these methods can be found in references [4, 5].

When implementing any of these methods or when proposing a new method to construct DCs, there exists the possibility that the DC constructed does not represent the driving pattern of the region under consideration. Potential errors may be due to i) the inability of the method to produce representative DC and, ii) the incorrect implementation of the method.

The verification of new methods proposed for constructing DCs has been performed by implementing databases with constant accelerations and decelerations micro-trips that only included speed and time data, which can determine if the implemented computational algorithm presents errors since the driving pattern is known [6].

Therefore, there is a need for a procedure to evaluate the implementation of the method and its capacity to produce DCs that accurately represent local driving patterns. Additionally, it is desirable a methodology to verify that the generated DCs allow the reproduction of the energy consumption (fuel or electric energy consumption) and pollutant emissions (for non-electric vehicles) of the vehicles, as the DCs are mainly used for this purpose.

As a first step, a definition of representativeness is needed to evaluate when a DC represents a driving pattern. Some authors used the same set of monitored trips to compare the representativeness of the LA01 cycle and the LA92 cycle [7]. Those two DCs were developed using the MCMC and MT methods, respectively. This study used the parameters of speed (average speed and maximum speed) and the Speed-Acceleration Frequency Distribution matrix (SAFD) as the criteria for selecting the representative DC. Nevertheless, this study did not establish an explicit definition for representativeness or a method to verify it on a DC. None of the extensive references consulted for our study did so either.

Most authors, whose purpose is to develop new methods to construct DCs, have used two or three Characteristic Parameters (CP), also known as Performance Values (PVs), as assessment criteria to select the representative DC. The most frequently used CPs are average speed, average positive acceleration, and positive kinetic energy [4, 5]. The number of CPs used has been growing with time [5]. Based on these observations, other authors stated that a DC represents a driving pattern when each of the characteristic parameters obtained from the proposed DC $(CPs^*)$ are similar or equal to the characteristic parameters that describe the driving pattern (CPs) [1]. The minimum number of CPs to fully describe a driving pattern and time duration of a DC are defined in other studies using the MT method [8, 9].

Based on this definition, this study proposes a protocol to evaluate the capacity of a given method of producing DCs that i) represent a local driving pattern, ii) reproduce the energy or fuel consumption, and iii) reproduce the emissions of pollutants from vehicles that use fuels. Next, we will describe the proposed protocol and in section 3, for illustrative purposes, we will use this protocol to evaluate the FBM, MCMC, and MT methods.

## 2. Methodology: protocol to evaluate methods for constructing DCs

We propose a protocol to evaluate any DC construction methods with two phases. The first phase evaluates the ability of the method under evaluation to identify driving patterns. The second phase quantifies the capacity of the method of reproducing a DC that represents the driving patterns and reproduces energy consumption and pollutant emissions from vehicles.

### 2.1 Evaluating the method´s ability to identify driving patterns

To evaluate the ability of the method under evaluation to identify driving patterns, a data set of trips with the same simple and well-defined driving pattern is used as input to the method under evaluation. The method under evaluation should be able to produce a DC identical to the driving pattern supplied as input.

Three cases of simple driving patterns are proposed. The first is an artificial driving pattern consisting of constant acceleration and deceleration of 0.28 m/s2 along with a constant top speed of 80 km/h, Figure 1a. The second driving pattern, also artificial, consists of 3 segments with different accelerations and decelerations $(0.28, 0.14$, and $0.56 m/s^2)$ along with top speeds (40, 60, and 80 km/h, respectively), as shown in Figure 1b.

The last driving pattern proposed is a real trip, as shown in Figure 1c, chosen randomly by the authors from a set of monitored trips of a fleet of buses [10]. This trip

**Table 1** Characteristic parameters (CPs) used in this study to describe driving patterns.

| Group | CP | Unit |
|---|---|---|
| Speed | Average speed | km/h |
| | Maximum speed | km/h |
| Acceleration | Average acceleration | $m/s^2$ |
| | Average deceleration | $m/s^2$ |
| | Maximum acceleration | $m/s^2$ |
| | Maximum deceleration | $m/s^2$ |
| Operational modes (percentage of time) | Idling | % |
| | Acceleration | % |
| | Deceleration | % |
| | Cruising | % |
| Dynamics | Positive Kinetic Energy | $m/s^2$ |

has an average speed of 12.4 km/h, a top speed of 43.9 km/h, and a top acceleration and deceleration of $1.16$ and $-1.29 m/s^2$, respectively. Annex 1 lists the time series of this proposed driving pattern.

Each of these driving patterns is repeated 20 times and the database obtained in each case is provided as input data for the method under evaluation. In a previous study, we determined that twenty repetitions are enough for existing stochastic methods to produce results close to the average [1].

## 2.2 Evaluating the method's capacity to produce representative DC

This second phase evaluates the method's capacity to produce a DC that i) represents local driving patterns, ii) reproduces vehicle energy consumption, and iii.) tailpipe emissions.

### Evaluation of the method's capacity to produce DC that represents driving patterns

As stated in the introductory section, a DC represents a driving pattern when its $CPs^*$ are similar to the CPs of the driving pattern. The CPs used in this work are the most used CPs to describe driving patterns in state-of-the-art [8], and they are presented in Table 1.

Therefore, to evaluate this representativeness, the relative difference (RDi) of each CP is evaluated through Equation 1, where i corresponds to each of the characteristic parameters listed in Table 1.

$$RD_i = \left| \frac{CP_i^* - CP_i}{CP_i} \right| \tag{1}$$

Equation 1 can be applied directly to deterministic methods to construct a DC, such as in the Fuel-based and the Trip-based methods. However, stochastic methods such as Micro trips and Monte Carlo Markov Chains produce different results each time the method is applied. Therefore, we propose that, for these types of stochastic methods, the $CPi^*$ in Equation 1 should be obtained as an average value after using the method at least 500 times with the same input database [6]. Additionally, the interquartile range (IQRi) for each RDi should be calculated (Equation 2) to evaluate their dispersion. In Equation 2, $Q_{75}$ corresponds to the value of the 75th percentile, and $Q_{25}$ corresponds to the value of the 25th percentile.

$$IQR_i = Q_{75} - Q_{25} \tag{2}$$

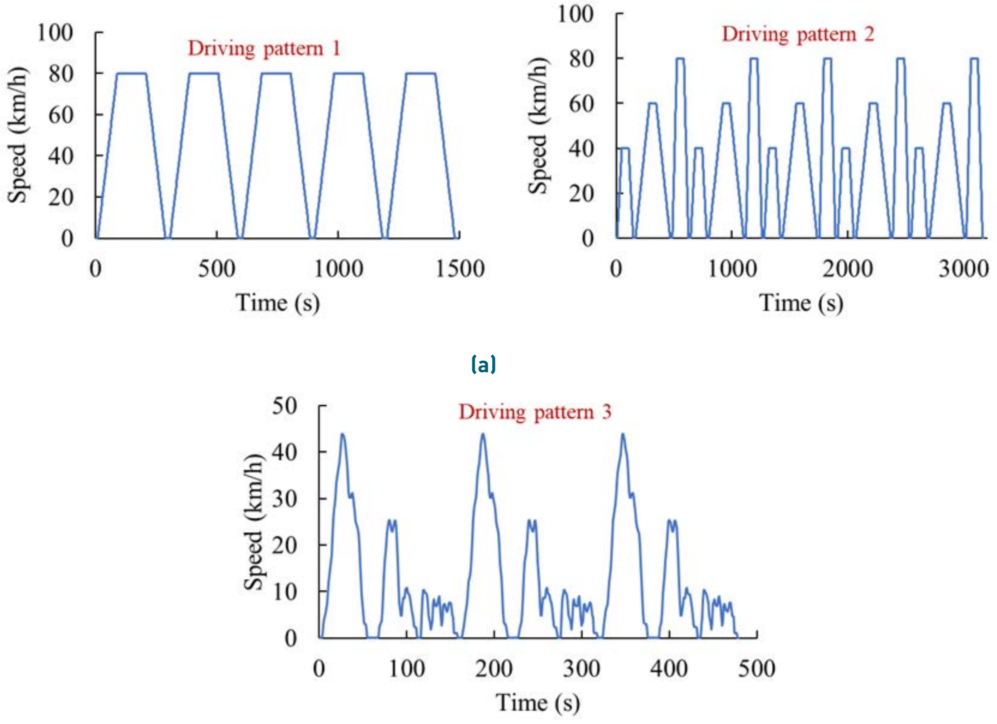
Finally, to obtain a single metric that encompasses the performance of the method, it is proposed to use the average relative difference (ARD) of all $CP^*$ through Equation 3, where n corresponds to the total number of characteristic parameters used.

$$ARD = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{CP_i^* - CP_i}{CP_i} \right| \tag{3}$$

### Evaluation of the method's capacity to produce a DC that reproduces energy consumption

As specified above, the main use of DCs is to evaluate the energy consumption (fuel consumption or electric energy) of vehicles. We propose to evaluate the ability of the method to produce a DC that reproduces the actual energy consumption of the vehicle in the following way: For a representative sample of vehicle technologies, measure the energy consumption of these vehicles following the DC produced by the method under evaluation, on the chassis dynamometer. The energy consumption values per kilometer traveled should be similar to those observed for the same technologies in their normal use in the same region for which the DC was obtained. Finally, the capacity of the DC to reproduce the energy consumption of the vehicles is quantified as the average relative difference of energy consumption, using an equation similar to Equation 3. The major drawback of this proposal for evaluating DC construction methods is that it involves an expensive and time-consuming second experimental phase.

A first approximation to accomplish this evaluation is to add the measurement of instantaneous energy consumption data of the vehicle to speed measuring data of the monitoring campaigns conducted to determine driving patterns. Then, during the evaluation phase of the method, these instant energy consumptions are used to estimate the consumption of the different vehicle technologies following the DC produced by the method under evaluation. Although this alternative is convenient, it involves additional costs in the vehicle fleet monitoring campaign, and it cannot be applied to methods such as MCMC. As a second gross approximation, the Vehicle



(a)

(b)

(c)

**Figure 1** Driving patterns used as input data for the evaluation of DC construction methods. a) Artificial driving pattern consisting of a single constant acceleration, b) Artificial driving pattern consisting of 3 accelerations and top speeds, and c) Real driving pattern selected arbitrarily from measurements from the normal operation of a fleet of buses

Specific Power (VSP), can be determined (Equation 4) for each vehicle technology when it follows the DC reported by the method under evaluation. For each vehicle technology, this procedure involves the characteristics of the monitored vehicles, such as the mass of the vehicle (M), the aerodynamic coefficient (Cd), the coefficient of rolling resistance (fr), and the frontal area (A). In Equation 4, V is the vehicle's speed, and $\rho$ is the average air density, $\theta$ is the road grade, and $\mathrm{g}$ is gravity

$$VSP = \frac{1}{2M}\rho C_d A V^3 + f_r g V \operatorname{Cos}\theta + aV + gV \operatorname{Sin}\theta \qquad (4)$$

The value obtained from converting VSP to units of energy consumption per distance traveled is then compared with that observed in the same vehicle technologies in normal use.

## Evaluation of the method's capacity to produce a DC that reproduces pollutant emissions

In the case of engine-powered vehicles, in addition to fuel consumption, the evaluation of the tailpipe emissions is fundamental. Therefore, it is highly desirable that the DC generated by the method to construct DC under evaluation allows the reproduction of tailpipe emissions of the vehicles when they are measured on the chassis dynamometer.

In the same way, as in the previous section, this capacity of the method is evaluated as the difference between the pollutant emissions measured when the vehicle follows the DC generated by the methodology under evaluation in a chassis dynamometer and the emissions observed for the same technology's vehicles during its normal operation in the region for which the DC was developed.

As in the previous case, the first approximation consists of adding instantaneous measurements of tailpipe emissions during the monitoring campaign developed to grasp the driving pattern in the region of interest. This involves using specialized equipment such as PEMS (Portable Emissions Measurement System) for the measurement of pollutants. Subsequently, in the evaluation phase of the method in its capacity to reproduce tailpipe emissions, these measurements are used to quantify vehicle emissions following the DC generated by the methodology under evaluation. It is recommended that a comparison in terms of emission indexes (mass amount of pollutant emitted per unit of distance traveled) of $CO$, $CO_2$, $NOx$, and PM be made.

The second potential approximation is the use of vehicle-emission models. There have been multiple efforts to develop models to estimate tailpipe emissions [6, 11–13]. However, the authors do not know of any well-accepted model to predict accurately the instantaneous emission of $CO$, $NOx$, and PM starting from the instantaneous velocity and fuel consumption data.

### Evaluation of Driving cycle's duration

In addition to the evaluations already proposed, a test to evaluate the appropriate duration of the DC is highly recommended. The aim is to minimize the duration of the DC without losing representativeness in the DC regarding the driving pattern, or accuracy in the reproducibility of energy consumption and emissions of pollutants. The determination of the protocol to evaluate the appropriate duration of a DC is the subject of subsequent work.

## 3. Results and discussion

In order to illustrate the application of the proposed validation protocol, we will apply that protocol to the MT, MCMC, and FBM methods. Initially, three databases were built, as shown in Figures 1a, 1c. Each of them consisted of 20 trips and was used as the input data in the MT, MCMC, and FBM methods. The details of the implementation of the MT, MCMC, and FBM methods used in this work can be found in other studies [1, 6, 14, 15].

### 3.1 Methods' ability to identify driving patterns

The FBM selects, as the representative DC, the trip with fuel consumption equal to the average consumption of all monitored trips. Since all trips are the same, this method, by definition, reproduces the input driving patterns described in Figure 1 and Appendix 5. The MT method divides each trip into segments of speed versus time: the initial and final speed of the vehicle is 0 km/h. A candidate-DC is constructed by splicing quasi-randomly selected micro-segments [16]. Typically, average speed, average positive acceleration, and idling percentage are used to evaluate the representativeness of the candidate-DCs. An RDi of less than a pre-established threshold, usually 5%, is the criterion used for selecting the candidate-DC as representative DC.

Given the stochastic nature of this method, the generated DC changes each time that the method is repeated. To consider this aspect, the entire process was repeated 500 times, and therefore, 500 representative DCs were obtained for each pattern. For illustrative purposes, Figure 2 shows the result obtained for a randomly selected case. As expected, this method usually reproduces the driving pattern but is presented in different sequences of input patterns (Figure 2b and 2c). For the most frequent uses of DCs, this variation in the sequence of micro-trips is not a problem. However, there are cases where the DC generated by the MT method does not reproduce the driving pattern. Figure 2b illustrates this situation, in which the number of micro-segments with a top speed of 40 and 80 km/h varied. We found that the MT method reproduced the driving pattern in 97.2% of the 500 iterations performed.

In the MCMC method, the speed and acceleration data are classified into bins called states. Based on these states, a transition matrix is constructed by calculating the transition frequency from state Xi to state Xi+1. Then, the Monte Carlo technique is used to select quasi-randomly states from the transition matrix. Finally, these states are re-encoded in speed data to obtain a candidate DC. The candidate-DC is selected as representative DC when its SAFD is similar to the one obtained for the driving pattern. We found that the MCMC method was not able to construct any DCs following the protocol described in Section 2.

### 3.2 Methods' ability to generate DC that represents driving patterns

Using Equation 1, we determined the relative differences between the $CPs^*$ of the DC generated by each method and the CPs that describe the driving pattern illustrated in Figure 1a. The CPs listed in Table 1 were considered. Based on these results, the average relative differences (ARD) were obtained using Equation 3. The process was repeated for the driving patterns illustrated in Figures 1b and 1c. Since the FBM is a deterministic method, by definition, it produces an ARD of 0% for each of the driving patterns considered due to one of the repeated trips in the input database for the method being selected, and this selected trip has the same $CPs^*$ as the CPs. The MT method is stochastic, and therefore, the average values must be considered after having repeated the method 500 times. Table 2 shows that this method presents ARD values of 0%, 2.8%, and 0.7% for the case of driving patterns 1, 2, and 3, respectively. The CP that presents the highest RD was the percentage of time in deceleration. These values are below 5%, which is the acceptable threshold for the RDi [4, 17], and thus, it can be considered that this method has the ability to produce DCs that reproduce driving patterns. Table 2 also shows the IQR obtained using this method. It shows that the IQRs were 0%, 6.6%, and 2% for the driving patterns 1, 2, and 3, respectively.

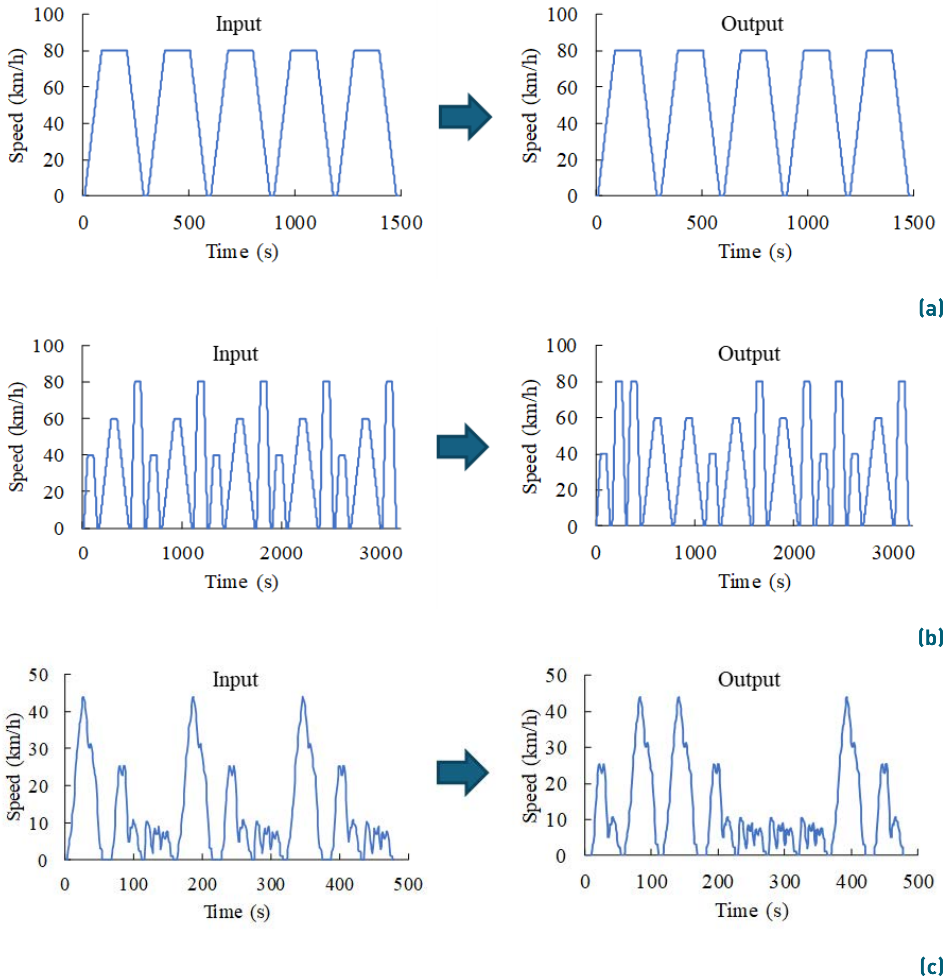


**Figure 2** Obtained DCs using the MT method for driving pattern a.) 1, b.) 2 and c.) 3

**Table 2** RDi, IQRi, and ARD results obtained evaluating the capacity of the MT method of generating DCs that represents the driving patterns 1, 2, and 3 (DP1, DP2, DP3, respectively)

| | DP 1 | | DP 2 | | DP 3 | |
|---|---|---|---|---|---|---|
| | RD | IQR | RD | IQR | RD | IQR |
| Max speed | 0 | 0 | 0 | 0 | 0 | 0 |
| Ave speed | 0 | 0 | 2.4 | 3.2 | 1.7 | 4.9 |
| Max accel | 0 | 0 | 0 | 0 | 0 | 0 |
| Max decel | 0 | 0 | 0 | 0 | 0 | 0 |
| Ave accel | 0 | 0 | 4.3 | 6.7 | 0.4 | 1.1 |
| Ave decel | 0 | 0 | 4.3 | 6.6 | 0.7 | 2.1 |
| % idling | 0 | 0 | 1.9 | 2.7 | 1.4 | 4.2 |
| % accel | 0 | 0 | 5.8 | 20.3 | 0.9 | 2.7 |
| % decel | 0 | 0 | 5.9 | 19.8 | 0.2 | 0.7 |
| % cruising | 0 | 0 | 2.5 | 8.1 | 1.75 | 5.2 |
| PKE | 0 | 0 | 4.3 | 4.9 | 0.4 | 1.1 |
| ARD | 0.0 | 0.0 | 2.8 | 6.6 | 0.7 | 2.0 |

### 3.3 Methods' ability to generate a DC that reproduces energy consumption and pollutant emissions

As specified in the evaluation protocol, the capacity of the methods to generate a DC that reproduce the energy consumption is quantified through the relative difference of energy consumption that vehicles show when they follow the generated DC by the method under evaluation against the real energy consumption of the vehicles under real-world conditions.

Using the driving pattern number 3 specified in Appendix 5, together with the simultaneous measurements of fuel consumption and pollutant emissions, also described in Appendix 5, the DCs generated by the MT and FBM methods were evaluated. Following this protocol, the FBM method generated, by definition, DCs that reproduced the energy consumption and tailpipe emissions due to the variables of the selected trip are equal to the average of the trips in the database. Hence, the differences would be equal to zero. When following this evaluation protocol, the MT method generated DC, leading to average relative differences in fuel consumption of 1.2% after 500 iterations and an IQR of 3.5%. In the case of pollutant emissions, this method generated average relative differences of 0.2%, 1.1%, and 2% for $CO$, $CO_2$, and $NOx$, respectively. As stated before, the MCMC did not produce any DC following this protocol because the method cannot consider additional variables, such as those presented in Appendix 5, for the different operating states considered by the method to construct the driving cycle.

According to several studies [5, 8, 18], the MT method is the most commonly used for developing driving cycles, which showed variations of less than 5% (established as the limit) when following the protocol and can improve its performance in reproducing emissions and fuel consumption with variations in the method such as the Energy Based Micro Trip method (EBMT) described in [18]. In the case of MCMC, options should be identified to include other variables of interest in the state matrix, such as emissions and fuel consumption as additional variables of interest alongside speed and time. Finally, the FBM presents the best results in this validation protocol, given its differences equal to zero, and in the implementation case presented in [1], it outperformed the other methods for generating driving cycles.

## 4. Conclusions

We propose the following protocol to evaluate driving cycle construction methods: Using a well-known driving pattern as input to the method under evaluation and observe its ability to construct driving cycles (DC) that i) represents the input driving pattern and ii) reproduces the vehicles´ energy consumption and tailpipe emissions. Three simple driving patterns were selected arbitrarily for this purpose. Two of them consist of ramps of constant acceleration and deceleration along with constant top speeds. The third pattern consists of 2.6 minutes of real simultaneous measurements of instant speed, fuel consumption, and emission rates of $CO$, $CO_2$, $NO$, and $NO_2$ obtained by monitoring a fleet of buses.

A DC represents a driving pattern when the characteristic parameters that describe the DC are similar to those that describe the driving pattern. Based on this definition, we evaluated the driving pattern representativeness through the average relative differences between characteristic parameters (ARD). A threshold of 5% was established as an acceptable value for the ARD.

A DC reproduces energy consumption and tailpipe emissions, when for a given vehicle, these two variables measured following the driving cycle on a chassis dynamometer are similar to the observed in the normal use of that vehicle technology in the region for which the driving cycle was obtained. Therefore, the reproducibility of energy consumption and tailpipe emissions is quantified through the relative differences between the measured and observed values (RD).

Aiming to illustrate the application of this protocol, we applied it to the Micro-trip, the Markov chain- Monte Carlo, and the Fuel-Based methods. We observed that the Fuel-Based method produced DCs representing the input driving pattern and reproduced fuel consumption and tailpipe emissions. The MT method generated DCs with ARD<2.8%, leading to average relative differences in fuel consumption of 1.2% after 500 iterations. The Markov chain-Monte Carlo method did not produce DCs following this protocol.

Finally, implementing the three proposed driving patterns in this study and running the DC construction methods (500 iterations for stochastic methods) allows for evaluating the proper implementation of the computational algorithm and its capability to reproduce driving patterns, energy consumption, and emissions if the method allows it. These representative driving cycles can be used to evaluate new vehicle technologies or design and validate vehicles or vehicle components.

## 5. Appendix 1

### Simultaneous data of speed, fuel consumption, and $CO_2$, $CO$, $NO$, and $NO_2$ tailpipe emissions taken from the normal operation of diesel-fueled buses

| **Tiempo** | **Velocidad** | **Fuel consumption** | $CO_2$ **emissions** | $CO$ **emissions** | $NO$ **emissions** | $NO_2$ **emissions** |
|---|---|---|---|---|---|---|
| (s) | (km/h) | (L/s) | (g/s) | (g/s) | (g/s) | (g/s) |
| 0 | 0.00 | 0.00064 | 1.717 | 0.0105 | 0.0169 | 0.0010 |
| 1 | 0.00 | 0.000643 | 1.717 | 0.0102 | 0.0169 | 0.0011 |
| 2 | 0.00 | 0.000665 | 1.749 | 0.0090 | 0.0169 | 0.0011 |
| 3 | 0.00 | 0.001288 | 1.757 | 0.0093 | 0.0169 | 0.0011 |
| 4 | 0.76 | 0.001862 | 1.753 | 0.0110 | 0.0169 | 0.0011 |
| 5 | 2.74 | 0.001077 | 1.774 | 0.0112 | 0.0171 | 0.0012 |
| 6 | 4.05 | 0.001876 | 1.783 | 0.0105 | 0.0171 | 0.0012 |
| 7 | 5.44 | 0.000693 | 1.788 | 0.0113 | 0.0172 | 0.0012 |
| 8 | 6.31 | 0.00109 | 1.863 | 0.0115 | 0.0173 | 0.0013 |
| 9 | 7.28 | 0.002353 | 2.064 | 0.0116 | 0.0173 | 0.0013 |
| 10 | 9.61 | 0.003678 | 2.269 | 0.0156 | 0.0174 | 0.0015 |
| 11 | 12.20 | 0.000831 | 2.898 | 0.0175 | 0.0184 | 0.0015 |
| 12 | 13.46 | 0.001859 | 3.928 | 0.0132 | 0.0245 | 0.0015 |
| 13 | 15.03 | 0.0061 | 3.611 | 0.0159 | 0.0346 | 0.0016 |
| 14 | 17.85 | 0.008197 | 4.005 | 0.0152 | 0.0379 | 0.0017 |
| 15 | 21.36 | 0.010661 | 4.937 | 0.0182 | 0.0414 | 0.0020 |
| 16 | 25.26 | 0.007769 | 5.385 | 0.0842 | 0.0379 | 0.0026 |
| 17 | 27.59 | 0.001676 | 7.232 | 0.1630 | 0.0379 | 0.0027 |
| 18 | 28.65 | 0.007214 | 9.160 | 0.1019 | 0.0513 | 0.0025 |
| 19 | 30.47 | 0.01144 | 7.888 | 0.4944 | 0.0558 | 0.0030 |
| 20 | 33.28 | 0.009123 | 9.804 | 1.3737 | 0.0430 | 0.0036 |
| 21 | 35.70 | 0.000992 | 16.884 | 1.4150 | 0.0408 | 0.0037 |
| 22 | 36.63 | 0.002821 | 19.955 | 0.9936 | 0.0514 | 0.0034 |
| 23 | 37.60 | 0.009909 | 17.860 | 0.5624 | 0.0626 | 0.0030 |
| 24 | 39.47 | 0.011099 | 14.170 | 0.5139 | 0.0710 | 0.0029 |
| 25 | 41.64 | 0.011117 | 14.283 | 0.6487 | 0.0615 | 0.0032 |
| 26 | 43.68 | 0.005222 | 20.498 | 0.4624 | 0.0468 | 0.0035 |
| 27 | 43.87 | 0 | 17.407 | 0.2271 | 0.0554 | 0.0033 |
| 28 | 43.23 | 0 | 12.055 | 0.3608 | 0.0750 | 0.0028 |
| 29 | 42.41 | 0 | 9.781 | 1.1279 | 0.0736 | 0.0028 |
| 30 | 41.02 | 0 | 15.262 | 1.5185 | 0.0446 | 0.0030 |
| 31 | 39.34 | 0 | 20.919 | 0.9832 | 0.0385 | 0.0031 |
| 32 | 37.47 | 0 | 17.897 | 0.5195 | 0.0498 | 0.0028 |
| 33 | 34.66 | 0 | 11.662 | 0.2372 | 0.0707 | 0.0022 |
| 34 | 31.40 | 0.000233 | 5.844 | 0.1358 | 0.0775 | 0.0020 |
| 35 | 30.25 | 0.002392 | 3.158 | 0.0737 | 0.0489 | 0.0021 |
| 36 | 30.24 | 0.006737 | 1.763 | 0.0438 | 0.0236 | 0.0020 |
| 37 | 30.98 | 0.005192 | 1.003 | 0.0270 | 0.0115 | 0.0018 |
| 38 | 31.18 | 0 | 0.609 | 0.0191 | 0.0049 | 0.0016 |
| 39 | 30.15 | 0 | 0.416 | 0.0162 | 0.0027 | 0.0015 |
| 40 | 28.61 | 0 | 0.346 | 0.0149 | 0.0016 | 0.0014 |
| 41 | 27.14 | 0.000108 | 0.634 | 0.0664 | 0.0008 | 0.0014 |
| 42 | 25.13 | 0.000527 | 2.372 | 0.2682 | 0.0008 | 0.0016 |
| 43 | 23.99 | 0.000922 | 5.497 | 0.4686 | 0.0032 | 0.0016 |
| 44 | 23.35 | 0.001 | 7.156 | 0.3189 | 0.0164 | 0.0011 |
| 45 | 22.43 | 0.000354 | 5.504 | 0.1266 | 0.0363 | 0.0007 |
| 46 | 20.07 | 0.000594 | 2.894 | 0.0870 | 0.0398 | 0.0009 |
| 47 | 16.14 | 0.000583 | 1.542 | 0.0509 | 0.0281 | 0.0011 |
| 48 | 12.88 | 0.000593 | 0.937 | 0.0363 | 0.0152 | 0.0011 |
| 49 | 9.24 | 0.000605 | 0.728 | 0.0276 | 0.0073 | 0.0010 |
| 50 | 5.48 | 0.000565 | 0.998 | 0.0253 | 0.0038 | 0.0010 |
| 51 | 3.44 | 0.00064 | 1.552 | 0.0197 | 0.0048 | 0.0010 |
| 52 | 3.08 | 0.000633 | 1.928 | 0.0141 | 0.0101 | 0.0009 |
| 53 | 3.05 | 0.000609 | 1.832 | 0.0105 | 0.0168 | 0.0008 |
| 54 | 2.45 | 0.000609 | 1.712 | 0.0104 | 0.0189 | 0.0009 |
| 55 | 0.36 | 0.000594 | 1.712 | 0.0103 | 0.0179 | 0.0009 |
| 56 | 0.03 | 0.00056 | 1.709 | 0.0105 | 0.0170 | 0.0009 |

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| **Tiempo** | **Velocidad** | **Fuel consumption** | $CO_2$ **emissions** | $CO$ **emissions** | $NO$ **emissions** | $NO_2$ **emissions** |
|---|---|---|---|---|---|---|
| 57 | 0.00 | 0.000625 | 1.708 | 0.0106 | 0.0167 | 0.0010 |
| 58 | 0.00 | 0.000997 | 2.808 | 0.0103 | 0.0310 | 0.0002 |
| 59 | 0.00 | 0.000984 | 2.864 | 0.0087 | 0.0305 | 0.0002 |
| 60 | 0.00 | 0.000987 | 2.818 | 0.0092 | 0.0301 | 0.0003 |
| 61 | 0.00 | 0.000999 | 2.802 | 0.0076 | 0.0301 | 0.0003 |
| 62 | 0.00 | 0.000999 | 2.780 | 0.0087 | 0.0301 | 0.0003 |
| 63 | 0.00 | 0.000999 | 2.785 | 0.0081 | 0.0303 | 0.0003 |
| 64 | 0.00 | 0.000999 | 2.835 | 0.0080 | 0.0304 | 0.0003 |
| 65 | 0.00 | 0.000999 | 2.849 | 0.0075 | 0.0299 | 0.0003 |
| 66 | 0.00 | 0.001005 | 2.832 | 0.0067 | 0.0297 | 0.0003 |
| 67 | 0.00 | 0.001024 | 2.783 | 0.0074 | 0.0298 | 0.0003 |
| 68 | 0.37 | 0.000995 | 2.819 | 0.0071 | 0.0297 | 0.0003 |
| 69 | 2.31 | 0.000977 | 2.787 | 0.0089 | 0.0300 | 0.0003 |
| 70 | 2.86 | 0.001221 | 2.804 | 0.0080 | 0.0302 | 0.0003 |
| 71 | 3.76 | 0.002307 | 2.847 | 0.0076 | 0.0299 | 0.0003 |
| 72 | 6.00 | 0.002569 | 2.816 | 0.0077 | 0.0296 | 0.0003 |
| 73 | 9.62 | 0.0052 | 2.802 | 0.0078 | 0.0295 | 0.0003 |
| 74 | 13.42 | 0.007084 | 2.784 | 0.0081 | 0.0287 | 0.0003 |
| 75 | 16.45 | 0.000176 | 2.717 | 0.0087 | 0.0335 | 0.0004 |
| 76 | 18.30 | 0.002251 | 3.152 | 0.0110 | 0.0404 | 0.0004 |
| 77 | 20.10 | 0.009144 | 3.625 | 0.0175 | 0.0616 | 0.0006 |
| 78 | 22.80 | 0.008836 | 4.965 | 0.0523 | 0.0727 | 0.0006 |
| 79 | 25.06 | 0 | 6.489 | 0.3281 | 0.0688 | 0.0006 |
| 80 | 25.43 | 0 | 8.388 | 0.8162 | 0.0670 | 0.0008 |
| 81 | 24.97 | 0 | 12.143 | 0.5000 | 0.0571 | 0.0009 |
| 82 | 23.86 | 0 | 12.500 | 0.2568 | 0.0545 | 0.0007 |
| 83 | 23.12 | 0.000401 | 9.213 | 0.5540 | 0.0495 | 0.0004 |
| 84 | 22.85 | 0.003522 | 10.148 | 0.6943 | 0.0398 | 0.0004 |
| 85 | 23.79 | 0.007227 | 10.622 | 0.2404 | 0.0241 | 0.0005 |
| 86 | 25.29 | 0.001717 | 7.507 | 0.1642 | 0.0131 | 0.0004 |
| 87 | 25.28 | 0 | 3.852 | 0.1110 | 0.0085 | 0.0004 |
| 88 | 23.73 | 0 | 2.453 | 0.0786 | 0.0057 | 0.0003 |
| 89 | 20.31 | 0.000146 | 1.895 | 0.0446 | 0.0097 | 0.0001 |
| 90 | 16.24 | 0.001103 | 1.497 | 0.0683 | 0.0214 | 0.0000 |
| 91 | 11.60 | 0.00119 | 2.459 | 0.2148 | 0.0330 | 0.0000 |
| 92 | 7.45 | 0.000894 | 5.606 | 0.2822 | 0.0270 | 0.0000 |
| 93 | 4.95 | 0.001149 | 6.416 | 0.0687 | 0.0163 | 0.0002 |
| 94 | 4.95 | 0.002428 | 3.642 | 0.0698 | 0.0092 | 0.0002 |
| 95 | 7.19 | 0.004662 | 2.072 | 0.0332 | 0.0079 | 0.0001 |
| 96 | 8.74 | 0.00092 | 1.461 | 0.0245 | 0.0130 | 0.0001 |
| 97 | 8.55 | 0.001564 | 1.192 | 0.0325 | 0.0208 | 0.0000 |
| 98 | 8.91 | 0.004368 | 1.817 | 0.0305 | 0.0288 | 0.0001 |
| 99 | 10.50 | 0.002641 | 2.992 | 0.0196 | 0.0370 | 0.0001 |
| 100 | 10.80 | 0.000124 | 3.271 | 0.1082 | 0.0399 | 0.0001 |
| 101 | 9.79 | 0.001013 | 3.680 | 0.5398 | 0.0512 | 0.0001 |
| 102 | 9.46 | 0.001897 | 6.115 | 0.6583 | 0.0481 | 0.0003 |
| 103 | 9.41 | 0.0002 | 7.803 | 0.1804 | 0.0428 | 0.0003 |
| 104 | 8.56 | 0.000073 | 5.318 | 0.2025 | 0.0457 | 0.0003 |
| 105 | 7.29 | 0.000765 | 5.528 | 0.1056 | 0.0414 | 0.0004 |
| 106 | 6.13 | 0.001262 | 6.928 | 0.0556 | 0.0290 | 0.0005 |
| 107 | 4.45 | 0.001084 | 5.095 | 0.0260 | 0.0218 | 0.0004 |
| 108 | 2.67 | 0.00095 | 2.847 | 0.0255 | 0.0226 | 0.0003 |
| 109 | 2.38 | 0.000872 | 2.521 | 0.0242 | 0.0209 | 0.0003 |
| 110 | 2.36 | 0.00086 | 2.874 | 0.0122 | 0.0155 | 0.0004 |
| 111 | 2.18 | 0.000987 | 2.284 | 0.0032 | 0.0151 | 0.0003 |
| 112 | 0.36 | 0.001002 | 1.492 | 0.0086 | 0.0213 | 0.0002 |
| 113 | 0.02 | 0.000874 | 1.748 | 0.0134 | 0.0262 | 0.0002 |
| 114 | 0.00 | 0.000883 | 2.438 | 0.0123 | 0.0280 | 0.0002 |

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| **Tiempo** | **Velocidad** | **Fuel consumption** | $CO_2$ **emissions** | $CO$ **emissions** | $NO$ **emissions** | $NO_2$ **emissions** |
|---|---|---|---|---|---|---|
| 115 | 0.00 | 0.001271 | 2.598 | 0.0102 | 0.0281 | 0.0002 |
| 116 | 0.35 | 0.00464 | 2.704 | 0.0096 | 0.0277 | 0.0002 |
| 117 | 4.54 | 0.005764 | 2.636 | 0.0087 | 0.0282 | 0.0003 |
| 118 | 8.15 | 0.004007 | 2.654 | 0.0088 | 0.0276 | 0.0003 |
| 119 | 10.39 | 0.000049 | 2.612 | 0.0110 | 0.0267 | 0.0003 |
| 120 | 10.39 | 0.000668 | 2.547 | 0.0125 | 0.0308 | 0.0004 |
| 121 | 9.85 | 0.001045 | 2.890 | 0.0136 | 0.0461 | 0.0005 |
| 122 | 9.61 | 0.001436 | 3.963 | 0.0555 | 0.0540 | 0.0005 |
| 123 | 9.23 | 0.001673 | 4.837 | 0.3276 | 0.0489 | 0.0004 |
| 124 | 7.72 | 0.001331 | 6.593 | 0.6081 | 0.0414 | 0.0004 |
| 125 | 5.03 | 0.000911 | 6.704 | 0.2036 | 0.0290 | 0.0005 |
| 126 | 3.99 | 0.001063 | 5.141 | 0.1700 | 0.0226 | 0.0005 |
| 127 | 3.21 | 0.001271 | 3.374 | 0.0832 | 0.0231 | 0.0004 |
| 128 | 1.83 | 0.003018 | 2.769 | 0.0643 | 0.0271 | 0.0003 |
| 129 | 3.74 | 0.004079 | 2.773 | 0.0399 | 0.0317 | 0.0003 |
| 130 | 7.28 | 0.002495 | 3.073 | 0.0326 | 0.0332 | 0.0003 |
| 131 | 8.41 | 0.000034 | 3.368 | 0.0218 | 0.0331 | 0.0004 |
| 132 | 7.51 | 0.000602 | 3.460 | 0.0171 | 0.0345 | 0.0005 |
| 133 | 6.98 | 0.000948 | 3.290 | 0.0164 | 0.0452 | 0.0005 |
| 134 | 6.88 | 0.001281 | 3.995 | 0.0223 | 0.0516 | 0.0005 |
| 135 | 7.05 | 0.002149 | 4.493 | 0.0510 | 0.0547 | 0.0004 |
| 136 | 8.58 | 0.003668 | 5.859 | 0.0631 | 0.0466 | 0.0006 |
| 137 | 8.96 | 0.000121 | 6.159 | 0.0210 | 0.0286 | 0.0007 |
| 138 | 6.86 | 0.002438 | 4.403 | 0.0164 | 0.0227 | 0.0007 |
| 139 | 4.52 | 0.000543 | 2.949 | 0.0142 | 0.0310 | 0.0007 |
| 140 | 2.79 | 0.001352 | 3.303 | 0.0155 | 0.0346 | 0.0005 |
| 141 | 3.78 | 0.005123 | 3.160 | 0.0167 | 0.0403 | 0.0004 |
| 142 | 7.07 | 0.001643 | 3.613 | 0.0191 | 0.0421 | 0.0006 |
| 143 | 7.40 | 0.000624 | 4.940 | 0.0129 | 0.0303 | 0.0006 |
| 144 | 6.63 | 0.001018 | 4.305 | 0.0042 | 0.0291 | 0.0005 |
| 145 | 6.00 | 0.001115 | 2.733 | 0.0246 | 0.0390 | 0.0006 |
| 146 | 5.66 | 0.001222 | 4.233 | 0.0284 | 0.0383 | 0.0006 |
| 147 | 6.08 | 0.002557 | 4.063 | 0.2065 | 0.0392 | 0.0005 |
| 148 | 7.26 | 0.001107 | 4.198 | 0.5013 | 0.0350 | 0.0005 |
| 149 | 7.67 | 0.000878 | 5.271 | 0.1977 | 0.0269 | 0.0004 |
| 150 | 7.43 | 0.001013 | 4.031 | 0.1622 | 0.0245 | 0.0004 |
| 151 | 6.39 | 0.000934 | 2.848 | 0.0912 | 0.0313 | 0.0005 |
| 152 | 4.84 | 0.001083 | 3.235 | 0.0568 | 0.0349 | 0.0004 |
| 153 | 4.54 | 0.001084 | 3.148 | 0.0382 | 0.0411 | 0.0004 |
| 154 | 1.23 | 0.001206 | 3.505 | 0.0304 | 0.0396 | 0.0005 |
| 155 | 1.02 | 0.001096 | 4.183 | 0.0194 | 0.0327 | 0.0006 |
| 156 | 1.00 | 0.000901 | 3.663 | 0.0100 | 0.0297 | 0.0006 |
| 157 | 0.99 | 0.00089 | 2.940 | 0.0108 | 0.0283 | 0.0006 |
| 158 | 0.11 | 0.000901 | 2.752 | 0.0103 | 0.0292 | 0.0006 |
| 159 | 0.00 | 0.001113 | 2.747 | 0.0101 | 0.0295 | 0.0006 |

# Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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# Author contributions

M. D. Giraldo-Galindo, L. F. Quirama-Londoño and J. I. Huertas-Cardozo: Conceived and designed the analysis. M. D. Giraldo-Galindo and L. F. Quirama-Londoño: Collected the data. M. D. Giraldo-Galindo and L. F. Quirama-Londoño: Contributed data or analysis tools. M. D. Giraldo-Galindo and L. F. Quirama-Londoño: Performed the analysis.M. D. Giraldo-Galindo, L. F. Quirama-Londoño and J. I. Huertas-Cardozo: Wrote the paper.

# Data availability statement

The data associated with this study (Appendix 5) were extracted from some projects developed in Toluca and Mexico City, Mexico, in 2014 using a PEMS Semtech EcoStar, OBD II and GPS Garmin 16x. The authors confirm that the data supporting the findings of this study are available within the article.

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