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Research Article

Improving VANETs Connectivity with a Totally Ad Hoc Living Mobile Backbone

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The vehicular ad hoc network (VANET) for intelligent transportation systems is an emerging concept to improve transportation security, reliability, and management. The network behavior can be totally different in topological aspects because of the mobility of vehicular nodes. The topology can be fully connected when the flow of vehicles is high and may have low connectivity or be invalid when the flow of vehicles is low or unbalanced. In big cities, the metropolitan buses that travel on exclusive lanes may be used to set up a metropolitan vehicular data network (backbone), raising the connectivity among the vehicles. Therefore, this paper proposes the implementation of a living mobile backbone, totally ad hoc (MOB-NET), which will provide infrastructure and raise the network connectivity. In order to show the viability of MOB-NET, statistical analyses were made with real data of express buses that travel through exclusive lanes, besides evaluations through simulations and analytic models. The statistic, analytic, and simulation results prove that the buses that travel through exclusive lanes can be used to build a communication network totally ad hoc and provide connectivity in more than 99% of the time, besides raising the delivery rate up to 95%.

1. Introduction

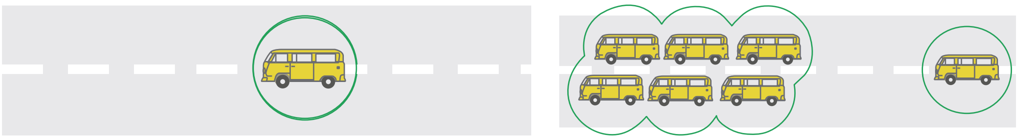
Automobiles are the most used means of transportation by millions of people all around the world. Due to their wide use there is the necessity of establishing communication among them, with the goal of providing safety and entertainment to their occupants. A solution capable of providing this communication is the creation of a vehicular ad hoc network (VANET) [1].

Ad hoc networks are characterized by being built anywhere; nevertheless, the existence of a fixed infrastructure is not needed (normally created through the existence of access points or base stations) [2]. The VANETs can be characterized as a particular case of ad hoc networks, generally differentiated due to the fact that the mobility of the nodes (vehicles) is bigger, the circulation of the nodes in the network is scarce or unbalanced and being limited by the orientation of the freeway or the urban roads [1, 3].

In these networks, the main challenges concerning communication are related to the lack of connectivity among the vehicles, which can be caused by the scarce or unbalanced traffic [4–7]. As shown in Figure 1, the scarce traffic occurs when a vehicle cannot find neighbors to communicate; meanwhile, the unbalanced traffic happens when the vehicles are not evenly distributed in the roads.

To VANETs, the connectivity among the vehicles is vital, significantly affecting the packets forwarding and the applications performance. Some studies [8–10] recommend the installation of access points (APs) on the edges of the roads to supply connectivity to the nearby vehicles. However, the cost of the infrastructure for deploying and maintenance of these networks is very expensive [7]. Besides, the static infrastructure is little adaptable and scalar, requiring a team of people for maintenance and security routines to avoid theft and depredation, mainly in big cities. Other studies explore the temporary connectivity in networks tolerant to delays and disconnections, where the delivery of the data is not guaranteed [11, 12].

The target of this paper is more ambitious. In big cities, the metropolitan buses that travel on exclusive lanes may be used



(a) Scarce traffic (b) Unbalanced traffic

Figure 1: Scarce and unbalanced traffic in VANETs.

to set up a metropolitan vehicular data network (backbone). The proposed communication network has as focus the building of a living mobile backbone, totally ad hoc, based on metropolitan buses (MOB-NET), in order to provide infrastructure and raise the connectivity of the network. The objective of MOB-NET is to provide connectivity in more than 99% of the time, guaranteeing the end-to-end message delivery among the most diverse applications.

In order that MOB-NET can fulfill its goal and endorse the network connectivity, first the connectivity of the buses at the backbone must be verified. Vehicular mobility and connectivity are investigated by statistic analysis applied on real data from mobility registers of the urban transportation in the city of Curitiba, Brazil, plus evaluations through simulations and analytic models. The results prove that the use of the transportation network composed by the express buses can provide connectivity and favor the message exchange among vehicles that are in its neighborhood.

The rest of the paper is organized in the following way: Section 2 presents the living mobile backbone (MOB-NET) characteristics and introduces some important concepts. Section 3 proposes an analytical model for the intervehicular distance. The simulation of MOB-NET by means of a vehicular mobility generator is presented in Section 4. Section 5 evaluates the MOB-NET performance using a network simulator. Concluding remarks and future directions are presented in Section 6. Finally, Appendix A gives experimental studies based on real data from mobility registers of the urban transportation in the city of Curitiba.

2. Living Mobile Backbone Totally Ad Hoc (MOB-NET)

The MOB-NET is a living mobile data communication network, totally ad hoc, formed by the express buses from the urban public transportation network of Curitiba city. The MOB-NET function is to provide connectivity and favor the message exchange among the vehicles in a wide region.

2.1. Urban Public Transportation Network. An urban transportation network is a connected group of routes or lanes where buses transporting passengers move around. In these networks, there may be several kinds of buses and roads. The buses are basically classified by the transport capacity and kind of fuel. The roads can be classified by the maximum speed limit, number of lanes, and direction of movement and by being exclusives or shared [13]. A key concept in public transportation networks is the concept of *bus line*, consisting basically of different buses that cover the same trajectory (each one with its own temporal scheduling).

The present research was carried out using real data from mobility registers of the urban transportation in the city of Curitiba, which is located in Paraná, Brazil, and owns more than two million inhabitants. This transportation network is used by 85% of the population, integrating the whole city and more 14 municipalities of the metropolitan region. Its success was inspirational to many similar public transportation systems introduced around the world, for example, the *Transantiago* in Santiago (Chile) and the *Los Angeles' Orange Line* (USA), among others [13].

Curitiba's public transportation network possesses the most diverse kinds of buses and roads, being the exclusive and express lanes the most prominent. There are 185 express buses and 81 kilometers of exclusive two-way roads, which allow passing, are localized on the central corridor of big avenues and connect the main neighborhoods to downtown [13].

Our starting point is a simple intervehicular distance model that is supported by the statistical analysis of a set of real traces of the public transportation system. These traces include the complete schedule for five consecutive working days, in February 2014, and the corresponding GPS traces with the positions of all the vehicles during the whole circulation period. These traces were supplied by the Company of Urbanization of the City of Curitiba (URBS, in Portuguese language). Appendix A gives useful additional information.

The network connectivity is a fundamental quantity and is determined by factors as quantity of vehicles that are circulating in a certain environment, schedule of circulation, manner as the vehicles are distributed in the lanes, and the range of the radio frequency signals. To evaluate the connectivity of the buses belonging to MOB-NET, experimental, analytical, and simulated studies were performed. The experimental and analytic studies comprehend statistic analysis of the inter-vehicular distance, characterization of the probability distribution, and the analytical model.

Finally, the simulation studies are related to the reproduction of the experimental data with the use of a vehicular mobility generator software and a network simulator.

2.2. Proposed Data Communication Network. The proposed data communication network in this project is formed by the buses that are in constant movement through all the extension of the express lanes, by this way being considered alive and independent of fixed infrastructure. This network, besides allowing the information exchange among the buses,

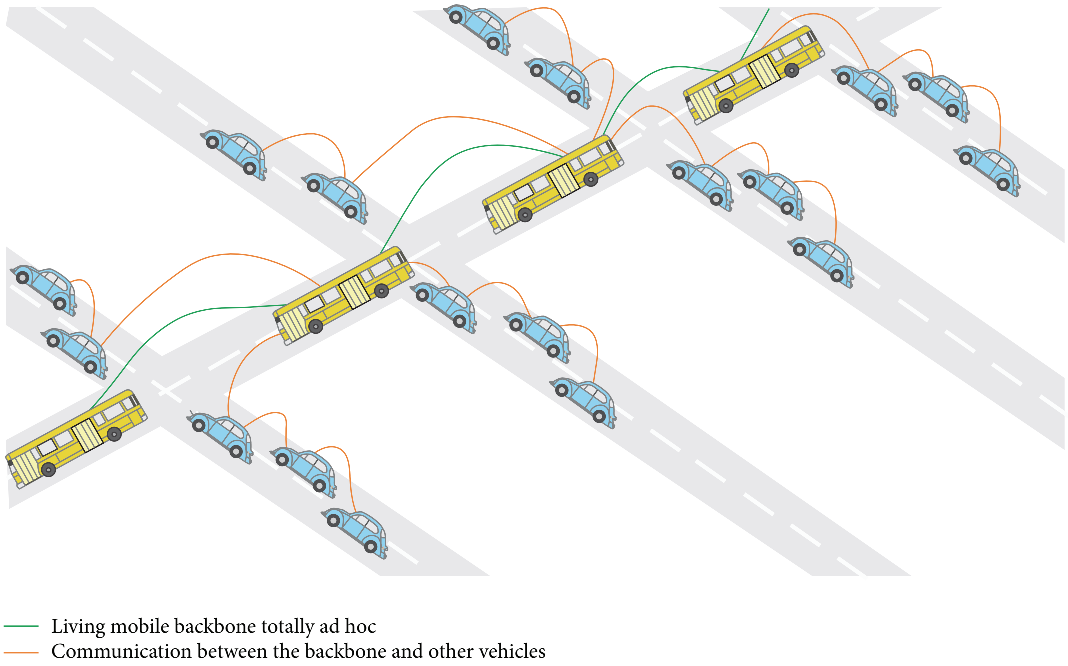


Figure 2: Topology of the proposed data communication network (MOB-NET).

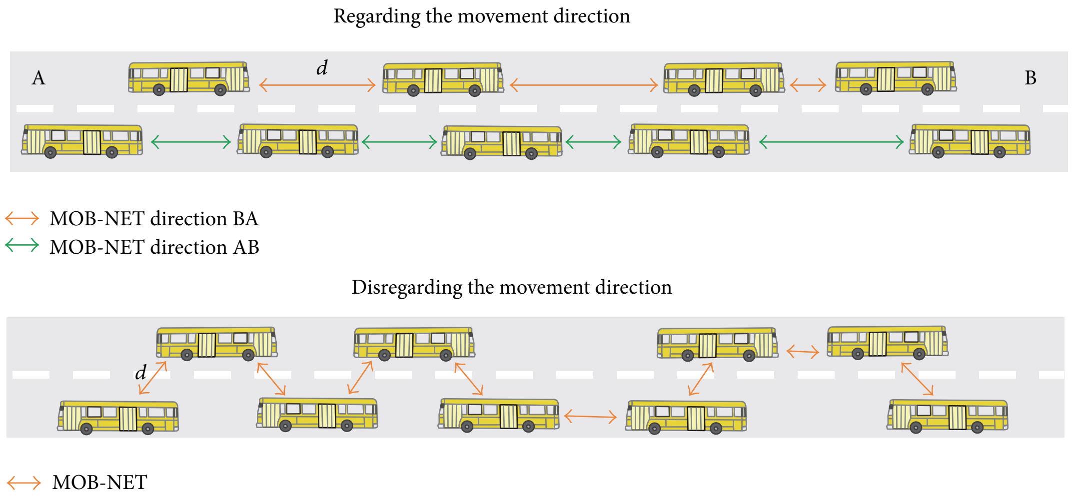


Figure 3: Data communication network regarding and disregarding the direction of movement of the buses.

aims for the information exchange among vehicles separated by many kilometers. Figure 2 illustrates the network topology.

The data communication network can be established considering or not the movement direction of the buses. As illustrated by Figure 3, when the direction is considered, the communication occurs only among the buses that follow the same orientation (only AB direction or only BA direction); however, when the direction is disregarded, the communication occurs independently of the movement direction.

In order that the data communication network can be used to connect distant vehicles, the buses that compose it must remain connected as much time as possible. In VANETs, the vehicles communicate among each other through radio frequency signals. The rules so this communication occurs are defined by the IEEE 802.11p standard [14, 15]. Such standard determines that the maximum transmission distance between the nodes, in absence of obstacles, is of one thousand meters. This way, so that the MOB-NET's buses remain connected, they must follow this standard and keep a distance shorter or equal to 1 km among each other during all the circulation time and in all the extension of the road.

The *intervehicular distance* (d) is defined as the distance, in kilometers, between a certain vehicle (bus) and its closest neighbor. The *connectivity degree* (g_c) of the network is

Table 1: Results from the chi-square test considering four candidate probability distributions.

Distribution	Parameters		P value
Exponential	—	$\lambda = 1.804$	0.003
Lognormal	$\mu = -1.019$	$\sigma = 1.126$	$1.4e-11$
Gamma	$\alpha = 1.634$	$\beta = 0.339$	$1.1e-5$
Weibull	$\alpha = 1.121$	$\beta = 0.601$	0.012

defined as the time percentual where the intervehicular distance assumes a value less than or equal to the transmission radius of the wireless system (r), and it is formally defined by

$$g_c \triangleq P[d \le r], \tag{1}$$

where $P[\cdot]$ denotes the probability of an event.

3. Analytical Model

Based on the GPS traces, histograms for the intervehicular distance were obtained and tested against several probability distributions from the literature as, for example, exponential, gamma, lognormal, Weibull, and so forth. The maximum likelihood estimation (MLE) [16] was used to elect the distribution parameters. To determine the most appropriate distribution, a goodness of fit was made through the Pearson's chi-square test [17]. The obtained results indicate that the Weibull distribution cannot be rejected, being able to characterize analytically the intervehicular distance.

The Weibull distribution has pdf given by

$$f_d(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}\exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right], \quad x \ge 0, \tag{2}$$

where α is the continuous shape parameter ($\alpha > 0$) and β is the continuous scale parameter ($\beta > 0$). The mean and variance associated with this distribution are given by

$$\begin{aligned}\mu_d &= \beta\cdot\Gamma\left(1+\frac{1}{\alpha}\right),\\ \sigma_d^2 &= \beta^2\cdot\left[\Gamma\left(1+\frac{2}{\alpha}\right)-\Gamma^2\left(1+\frac{1}{\alpha}\right)\right],\end{aligned} \tag{3}$$

where $\Gamma(\cdot)$ is the Gamma function.

As an example, Figure 4 shows a representative histogram and the fitted Weibull distribution. This histogram considers a single bus line, traveling in Area 1 (see Appendix A), during the period 04 h 31 min PM to 07 h 30 min PM. Table 1 presents the related results from the chi-square test.

The exponential distribution represents the simplest and commonly considered hypothesis in the literature [18]. This hypothesis fails to predict the behavior the intervehicular distance because it assumes that the distances follow a Poisson process, whereas this is not the case in vehicular traffic.

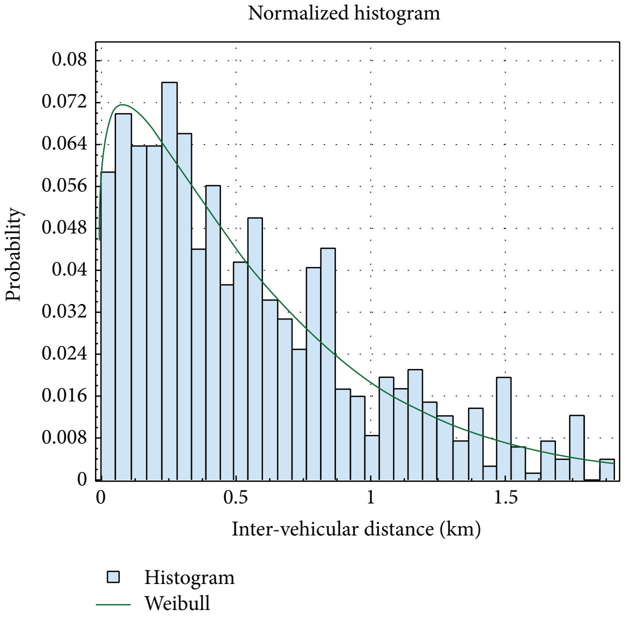


Figure 4: Normalized histogram for the intervehicular distance with one line (04 h 31 min PM to 07 h 30 min PM).

3.1. Line Superposition. In this section, an analytical model is proposed for the intervehicular distance considering the overlapping or superposition of bus lines. The superposition occurs when n bus lines operate over the same lane at the same time. Figure 5 illustrates such superposition.

Let there be a stochastic process which registers the intervehicular distance associated to a determined bus line i, where $i = 1, \ldots, n$. Each intervehicular distance is independently distributed according to a nonnegative probability distribution $F_{X_i}(x)$. We look for the intervehicular distances' distribution of the superposition of the individual processes, that is, when n bus lines operate over the same lane at the same time.

Let Y be a nonnegative random variable that characterizes the intervehicular distance in the superposition process (Figure 5). We propose to consider[1]

$$Y = \min(X_1, X_2, \ldots, X_n); \tag{4}$$

then,

$$\begin{aligned}F_Y(y) &= P[Y \le y] = P[\min(X_1, X_2, \ldots, X_n) \le y]\\ &= P[(X_1 \le y)\cup(X_2 \le y)\cup\cdots\cup(X_n \le y)]\\ &= 1-[1-F_{X_1}(y)]\cdots[1-F_{X_n}(y)].\end{aligned} \tag{5}$$

Considering the Weibull distribution with parameters α_i and β_i, for each individual process, it can be found that

$$\begin{aligned}F_Y&(y)\\ &= 1-\left[\exp\left\{-\left(\frac{y}{\beta_1}\right)^{\alpha_1}\right\}\right]\cdots\left[\exp\left\{-\left(\frac{y}{\beta_n}\right)^{\alpha_n}\right\}\right]\\ &= 1-\exp\left\{-\sum_{i=1}^{n}\left(\frac{y}{\beta_i}\right)^{\alpha_i}\right\}.\end{aligned} \tag{6}$$

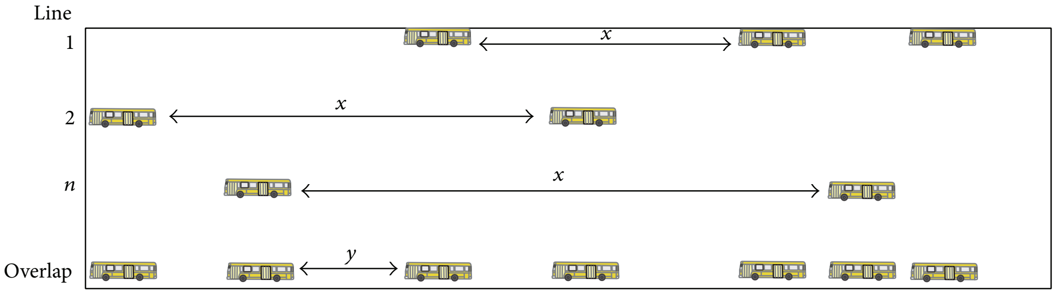


Figure 5: Superposition of bus lines.

In case of all distributions being identical, it is obtained that

$$F_Y(y) = 1 - \exp\left\{-n\left(\frac{y}{\beta}\right)^{\alpha}\right\}. \tag{7}$$

It is also a Weibull distribution where the scale parameter becomes $\beta' = \beta/n^{1/\alpha}$. Furthermore, the mean and variance for the final process are $\mu_Y = \mu_X/n^{1/\alpha}$ and $\sigma_Y^2 = \sigma_X^2/n^{2/\alpha}$, respectively.

Based on this result, it is possible to determine analytically the number of lines which is necessary to obtain a certain connectivity degree according to the transmission radius of the wireless system:

$$\begin{gathered} g_c = F_Y(r) = 1 - \exp\left\{-n\left(\frac{r}{\beta}\right)^{\alpha}\right\}, \\ n \geq -\left(\frac{\beta}{r}\right)^{\alpha} \ln\left(1 - g_c\right). \end{gathered} \tag{8}$$

As an example of the applicability of the equation above, if $\alpha = 1.10$, $\beta = 0.60$, and $g_c = 0.96$, it is found $n \geq 1.83$ for $r = 1$ km. Figure 6 shows the number of lines necessary to obtain a connectivity degree equal to 70%, 90%, 96%, and 99%, with the wireless transmission radius ranging from 0.1 km to 1 km.

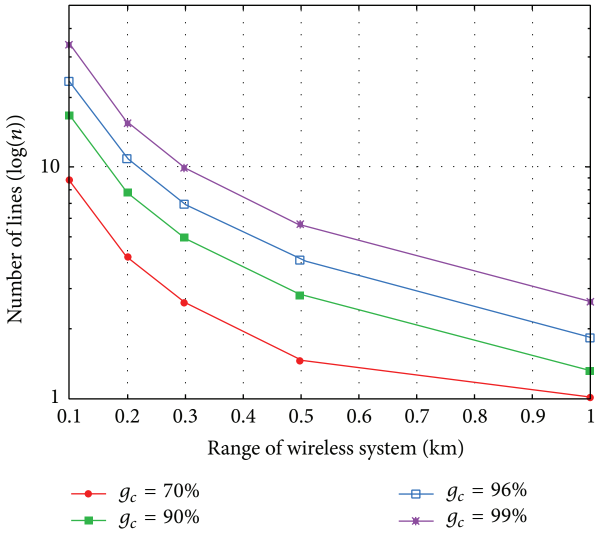


Figure 6: Number of lines necessary to obtain a certain connectivity degree according to the transmission radius of the wireless system.

It can be perceived in Figure 6 that as the number of lines grow, the transmission radius can be reduced. With the connectivity degree in 70%, it is necessary about three lines for the wireless transmission radius equal to 0.3 km. To obtain a larger connectivity degree it is necessary a bigger number of lines, approximately 10 lines to reach 99% with the same radius of 0.3 km. Raising the radius to 1 km, it is necessary approximately one line to reach a connectivity degree of 70% and three lines for 99%.

4. Simulation Studies

The objective of the simulation studies consists in creating simulations of the buses movements which portrait the reality observed in the experimental studies about the intervehicular distance and the connectivity in MOB-NET. For that, a vehicular mobility generator software is used parameterized with information obtained from real data. The utilized software is the VanetMobiSim [19] version 1.1.

4.1. Simulation Environment. The movements of the buses that travel through exclusive and express lanes follow a certain pattern, which is defined through the lane topology, circulation schedule and number of lines. In the simulations made for this work, environments that aim to reflect the real behavior of the express buses were created. For that reason, four different time intervals were considered. In each time interval the same quantity of buses per kilometer (density) was defined, observed in the real scenario with three lines (see Appendix A) and for each one of those buses it was attributed an exclusive lane in which they can move. Furthermore, the maximum and mean speed, the number of traffic lights and their stopping time were captured from the real data. Table 2 presents a summary of the used parameters on the simulations and Figure 7 illustrates an exclusive lane where the buses move forming the MOB-NET.

On Table 2 it can be observed that, as an example, in the Schedule 1 simulations have been made in a lane with 2 km length and 0.1 km wide, with 3 buses/km. At this time period, the buses can reach a maximum speed of 51 km/h and are subject to 5 traffic lights with a downtime of 20 seconds. It is important to highlight that the downtime at the traffic lights

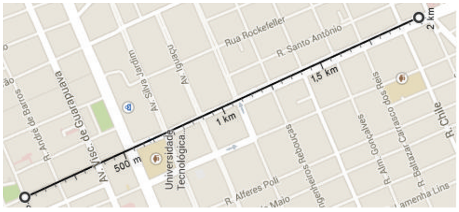


Figure 7: Exclusive lane where the express buses move to form the MOB-NET.

Table 2: Parameters used for the simulation.

Parameters	Values (s)
Schedule	05 h 30 min AM until 08 h 30 min AM (1); 08 h 31 min AM until 04 h 30 min PM (2); 04 h 31 min PM until 07 h 30 min PM (3); 07 h 31 min PM until 11 h 59 min PM (4)
Lane extension (km)	2 × 0.1
Density (bus/km) by schedule	3.0; 2.2; 3.4; 1.8
Maximum speed (km/h) by schedule	51; 53; 50; 54
Number of traffic lights	5
Downtime of the traffic lights (s)	20
Simulation time (s)	600

Table 3: Results of the mean, variance, and connectivity degree disregarding the direction of the movement of the buses.

Schedule	Mean (km)	Variance (km)	Connectivity degree (%)
1	0.308	0.049	100.00
2	0.435	0.083	95.13
3	0.284	0.031	100.00
4	0.362	0.038	99.53

is low, after all, the lines possess a system which synchronizes the opening and the closing to minimize the bus stopping time.

4.2. Simulation Results. The carried simulations were evaluated taking as a base the intervehicular distance. So, it is possible to verify in all the evaluations that the normalized histograms have similar characteristics to the ones presented in the experimental studies (see Appendix A).

Besides that, the intervehicular distances concentrate under one kilometer. In the worst case (Figure 8) less than 5% of the intervehicular distances are bigger than 1 km. Thus, it is evident the possibility to create simulation environments which reproduce the observed characteristics in the experimental studies and that keep a connectivity degree to guarantee the functioning of MOB-NET.

Table 3 presents mean and variance for the intervehicular distances and for the connectivity degree, considering the set of obtained histograms. In addition, Pearson's chi-square test indicates that the Weibull distribution cannot be rejected to all the analyzed cases (schedules).

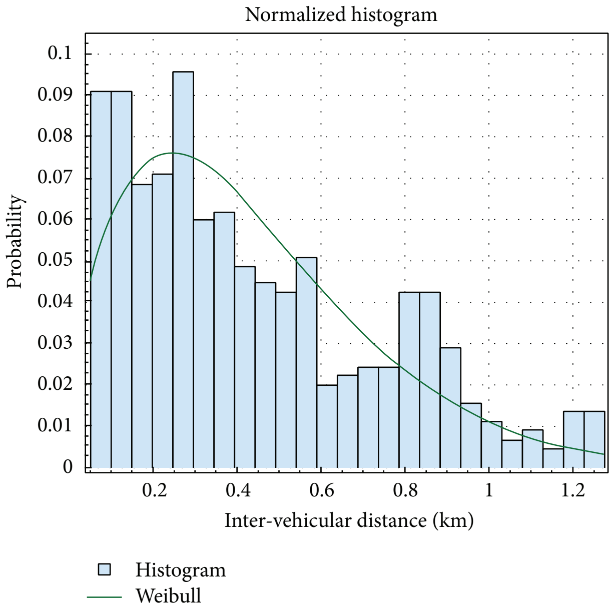


Figure 8: Normalized histogram for the intervehicular distance for Schedule 2.

5. Evaluation of MOB-NET Using a Network Simulator

MOB-NET was evaluated through simulations using the simulator NS-2 (Network Simulator) version 2.35 [20]. To demonstrate its efficiency, performance comparisons were made with scenarios that do not use MOB-NET.

5.1. Simulation Environment. The network simulations focus on examining MOB-NET in 3 scenarios. In Scenario 1, it was attempted to analyze only the performance of the buses in MOB-NET. The used networks in the simulations consider rectangular areas of 2 km × 1 km and 4 km × 1 km, with the same quantity of buses per kilometer (density) observed in the real scenario with three lines. For the Scenario 1 simulations, each bus transmits their radio frequency signals in a radius of 1 km and it was attributed for each of these buses an exclusive lane in which it can move, representing the topology of MOB-NET.

In Scenario 2, the used networks in the simulations consider rectangular areas of 2 km × 1 km and 4 km × 0.5 km with 10, 20, 30, 40, 50, and 60 vehicles distributed through the entire simulation place. In this scenario, each one of the vehicles transmits their radio frequency signals in a 500 m radius.

In Scenario 3, the used networks in the simulations are also rectangular areas of 2 km × 1 km and 4 km × 0.5 km, but with only 10 vehicles distributed through the entire simulation place. In this new scenario, each vehicle transmits their radio frequency signals in 300 m, 500 m, 750 m, and 1 km radius. In Scenarios 2 and 3, simulations were made with and without MOB-NET, with the same density observed in the real scenario with three lines.

Table 4: Simulation parameters setting.

Parameters	Values
Simulator	NS-2 (2.35)
Routing protocol	AODV
Simulation area	2 km × 1 km and 4 km × 0.5 km
Number of vehicles	10, 20, 30, 40, 50, 60
MOB-NET density	3.4 bus/km
Mobility model	*VanetMobiSim*
Range radius of the vehicles	300 m, 500 m, 750 m, 1000 m
Maximum speed of the vehicles	40 km/h
Maximum speed on the MOB-NET	54 km/h
Traffic pattern	UDP/CBR with 2 messages per second
Number of simultaneous connections	5 connections
Simulation time	600 s
Radio propagation model	*twoRay ground*
MAC layer specifications	IEEE 802.11p

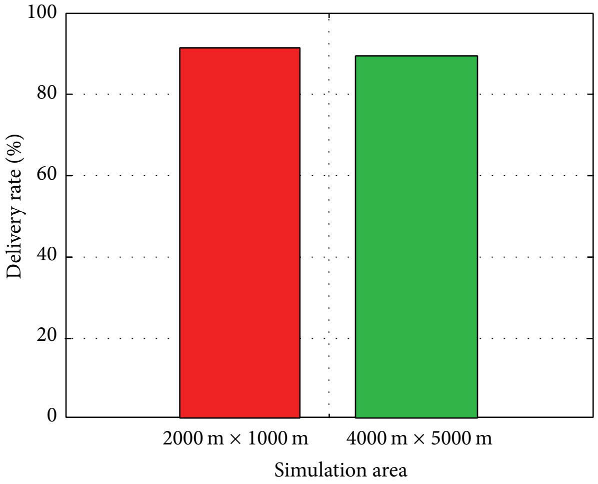


Figure 9: Delivery rate for MOB-NET buses in a 2 km × 1 km and 4 km × 0.5 km network—Scenario 1.

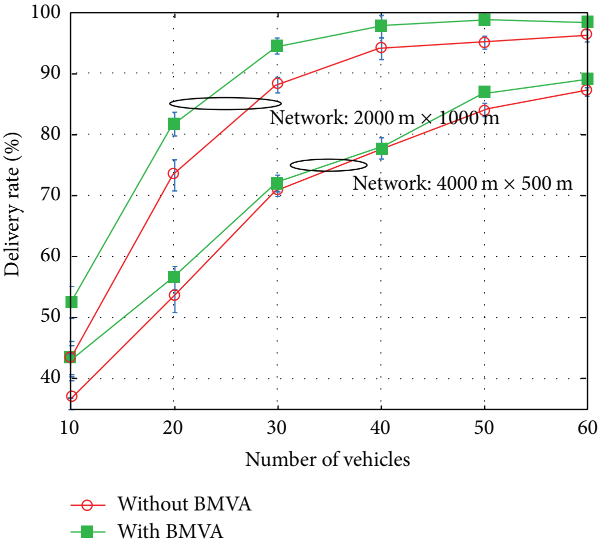


Figure 10: Delivery rate versus the variation of vehicles in a 2 km × 1 km and 4 km × 0.5 km network—Scenario 2.

Besides, in all scenarios, the vehicles dislocate following the movement model established by the VanetMobSim, with speeds until 54 km/h.

The *Two-Ray Ground* propagation loss model is considered [21], while the MAC layer follows the IEEE 802.11p standard [14, 22]. The traffic pattern consists of connections (UDP) with a constant bit rate (CBR) among 5 pairs of nodes chosen randomly. The simulations are made by 600 seconds and all the presented results are averages considering 35 simulations with the same traffic model, but with different mobility patterns. For these simulations the established confidence interval is 95%. The simulation parameters are summarized on Table 4.

5.2. Metrics. The MOB-NET was evaluated using as a base the following metrics:

(i) *Packets Delivery Rate*: it is the proportion of data packets delivered to the destination in relation to the quantity of data packets sent by the origin.

(ii) *Throughput*: it represents the quantity of data transferred between two nodes during the time interval on which they remain connected.

5.3. Simulation Results. Figure 9 shows the results obtained for the delivery rate of the buses that constitute the MOB-NET for the Scenario 1. In this scenario, the MOB-NET buses communicate only with each other. There is no communication with other types of vehicles. It can be observed that in both cases the packets delivery rate was bigger than 89%.

Figures 10 and 11 present the obtained results for the packets delivery rate and throughput versus the number of vehicles in the network for Scenario 2. Such results compare the delivery rate and the throughput of a network that uses MOB-NET and of a network that does not use it. In this scenario, it is possible to observe networks of different dimensions, whose purpose is to obtain routes with different sizes. In a longer network, as it is the case of the 4 km × 0.5 km, it is possible to find routes with more hops between the origin and the destination in relation to that with 2 km × 1 km.

It is possible to notice, in Figure 10, that the delivery rate rises with the adding of vehicles in the network with MOB-NET and without MOB-NET. However, with MOB-NET it was possible to obtain better results independently of the number of vehicles in the network, with bigger relevance for the cases in which there were until 30 vehicles, the fact which proves its importance in networks with low connectivity.

It is observed in Figure 11 that the throughput also rises with the increasing of the number of vehicles with and without MOB-NET. However, as expected, in cases where

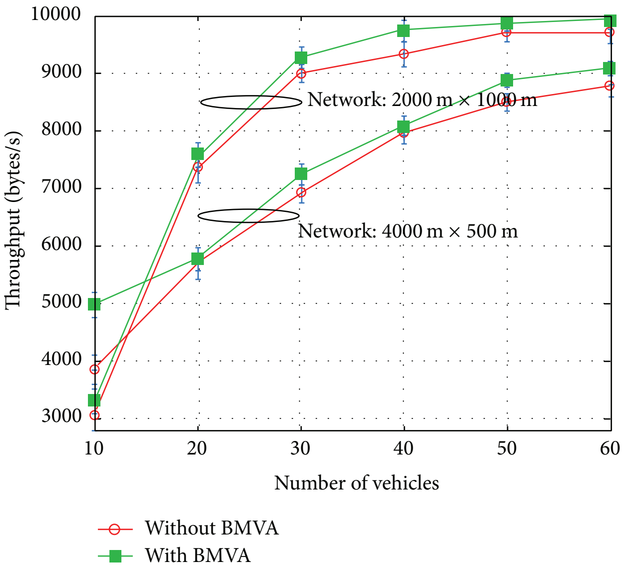


FIGURE 11: Throughput versus the variation of vehicles in a 2 km × 1 km and 4 km × 0.5 km network—Scenario 2.

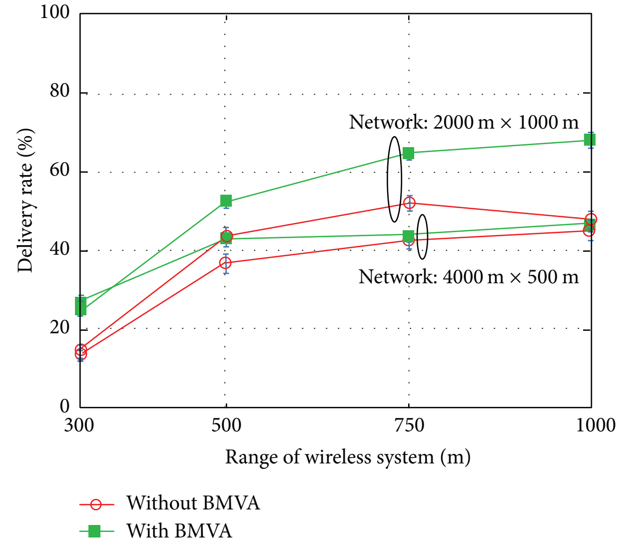


FIGURE 12: Delivery rate versus the variation of the system transmission radius in a 2 km × 1 km and 4 km × 0.5 km network with 10 vehicles—Scenario 3.

MOB-NET was considered, better results were obtained, apart from the number of vehicles in the network.

Figures 12 and 13 present the obtained results for the delivery rate and throughput versus the transmission radius of the wireless system for Scenario 3. It is perceived that the delivery rate rises with the increase on the transmission radius in both cases (with and without MOB-NET). Nevertheless, environments that used MOB-NET presented better results. In Figure 12, a 4 km length network with 10 vehicles with a 300 m radius can be observed, configuring an environment with considerable lack of connectivity. Still, MOB-NET was able to provide infrastructure and raise the delivery rate in more than 95%.

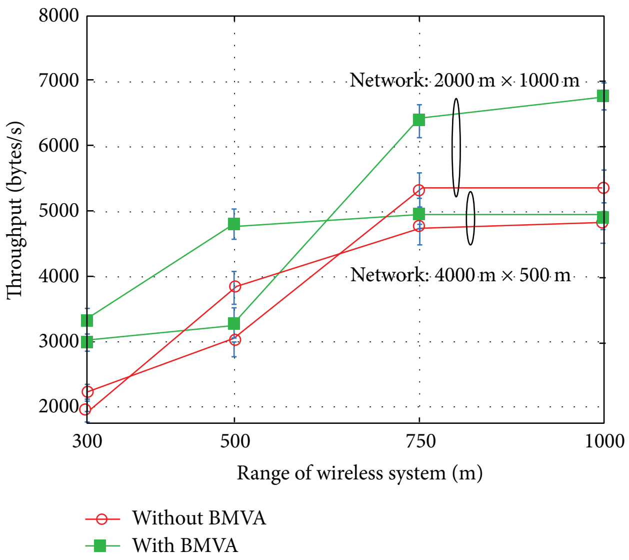


FIGURE 13: Throughput versus the variation of the system transmission radius in a 2 km × 1 km and 4 km × 0.5 km network with 10 vehicles—Scenario 3.

Figure 13 depicts the throughput, which also rises with the increase on the transmission radius with or without MOB-NET. But, in cases where MOB-NET was considered, better results were obtained, independently of the transmission radius of the wireless system.

6. Conclusions

This paper presented MOB-NET, a living mobile data communications network, totally ad hoc, composed by the express buses of Curitiba's urban public transportation system, whose function is to provide connectivity and favor the message exchange among vehicles in a wide region. In order to show the MOB-NET's viability in relation to the connectivity degree, statistic analysis with real data was made, besides evaluations through simulations and analytical models.

The statistical analysis was produced considering or not the displacement direction of the buses. When considering the direction, with three or more lines traveling through the lane, a connectivity degree higher than 95% was achieved. When the direction was disregarded, the connectivity degree was even greater, reaching values bigger than 99%.

Furthermore, the curve fitting was accomplished, whose purpose was to find the probability density function that better represents the intervehicular distance. The obtained results demonstrated that the Weibull distribution cannot be rejected, being able to characterize analytically the intervehicular distance.

The creation of an analytical model for the intervehicular distance considering the bus lines superposition was also a study subject. With this model, it was possible to analytically determine the necessary number of lines to obtain certain connectivity degree according to the transmission radius of the wireless system. The mentioned model implied, for example, that three lines are necessary to obtain a 99% connectivity degree when the transmission radius is about 1 km.

The simulation results show the possibility to create simulation environments that reproduce the characteristics observed in the experimental and analytic studies, keeping a needed connectivity degree for the proper functioning of the system. At the same time, the network simulations showed that MOB-NET can provide infrastructure and raise the delivery rate in up to 95%.

Finally, this paper confirmed through statistic analysis with real data and evaluations through simulations and analytical models that it is possible to create a living mobile backbone, totally ad hoc, in order to provide infrastructure and rising the connectivity in the network. Thus, the express buses driving through exclusive lanes, in the city of Curitiba, can be used to interconnect vehicles separated up to dozens of kilometers. Furthermore, the presented results through the distribution fitting and the analytical model can be applied in other scenarios that involve buses and express lanes.

Future works include the development of a routing protocol targeting the maximization of the connectivity that will act together with MOB-NET.

Appendix

A. Analysis of Real Data Traces

The Company of Urbanization of the City of Curitiba (URBS) has supplied information about the geographic coordinates of all the buses, updated independently and periodically with a period of two minutes. According to Curitiba's urban transportation model, the buses were grouped in lines, which always operate in a preestablished lane. To obtain the real data in order to make the characterization of the intervehicular distance, two representative areas from an express lane with two kilometers of extension (Marechal Floriano Peixoto Avenue) were selected. The first area (Area 1) corresponds to a central region, and the second area (Area 2) corresponds to a peripheral region (district).

The observations were made for five consecutive working days in February 2014. Such information was picked during the whole circulation period, which extends from 05 h 30 min AM until 11 h 59 min PM. The data collecting schedule was divided in four classes: from 05 h 30 min AM until 08 h 30 min AM, from 08 h 31 min AM until 04 h 30 min PM, from 04 h 31 min PM until 07 h 30 min PM, and from 07 h 31 min PM until 11 h 59 min PM; after all, according to the class, there is a specific number of buses that act in lines that travel on the selected lane. It is noticed that the characterization of the intervehicular distance can be evaluated according to the direction of the displacements, the number of lines, and the circulation schedule.

A.1. Experimental Studies. The characterization of the intervehicular distance is reached by a space-time analysis of the real movements of the buses. The temporal analysis is made in relation to a given time instant, t_j, in which the spatial displacement of the evaluated bus can occur or not. The space displacement is related with the positions occupied by the buses, based on a geographic coordinates system (latitude, longitude, and altitude), in time instant t_j.

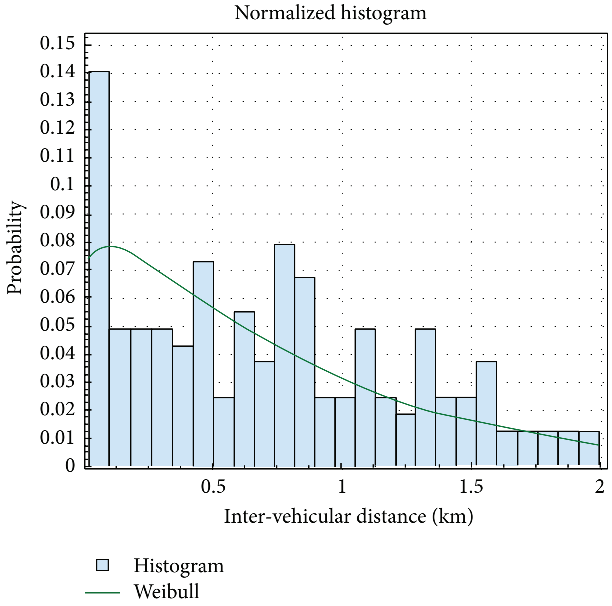


Figure 14: Normalized histogram for the intervehicular distance with one line, regarding the direction of the movement.

With the geographic coordinates of the buses observed during the time interval Δt, the distance between them can be calculated for several preestablished instants of time. So, obtaining the geographic coordinates of two buses $P1 = (\theta_1, \lambda_1)$ and $P2 = (\theta_2, \lambda_2)$ in latitude θ and longitude λ, over the globe of R radius, during the time interval $\Delta t = (t_n - t_0)$, it is possible to calculate the distance d_Δ between them for the time instants $t_0, \ldots, t_n$, through the following formula [23]:

$$d_\Delta = R \cdot \cos^{-1}\left[\sin(\theta_1)\sin(\theta_2) + \cos(\theta_1)\cos(\theta_2)\cos(\lambda_1 - \lambda_2)\right]. \tag{A.1}$$

The information about the geographic coordinates, observed during the time interval Δt, is updated in an independent way for each bus; thus, a miscalculation of the distance d_Δ may happen. Therefore, if the geographic coordinates of a bus L are sent in the time instant t_j and those for its neighbor M in the time instant t_{j+k}, a displacement L can occur during the time interval $t_{j+k} - t_j$, which must be predicted in the intervehicular distance calculation. In the following, a set of results will be presented and analyzed.

A.2. Analysis regarding the Direction of the Movement of the Buses. Figures 14, 15, 16, and 17 present the intervehicular distance as normalized histograms for Area 2. The data is presented considering one, three, five, and seven bus lines traveling in the same direction of the lane, between 04 h 31 min PM and 07 h 30 min PM.

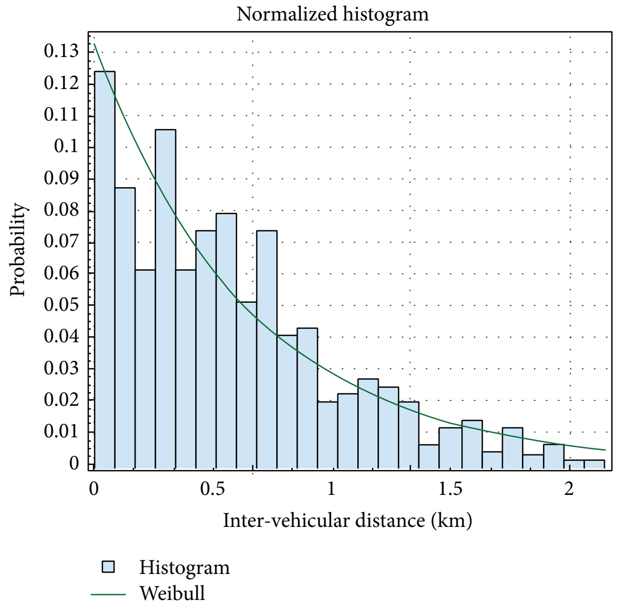


FIGURE 15: Normalized histogram for the intervehicular distance with three lines, regarding the direction of the movement.

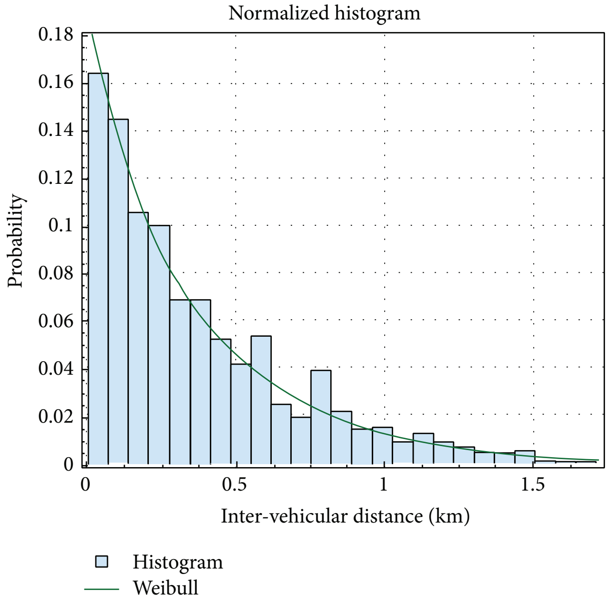


FIGURE 16: Normalized histogram for the intervehicular distance with five lines, regarding the direction of the movement.

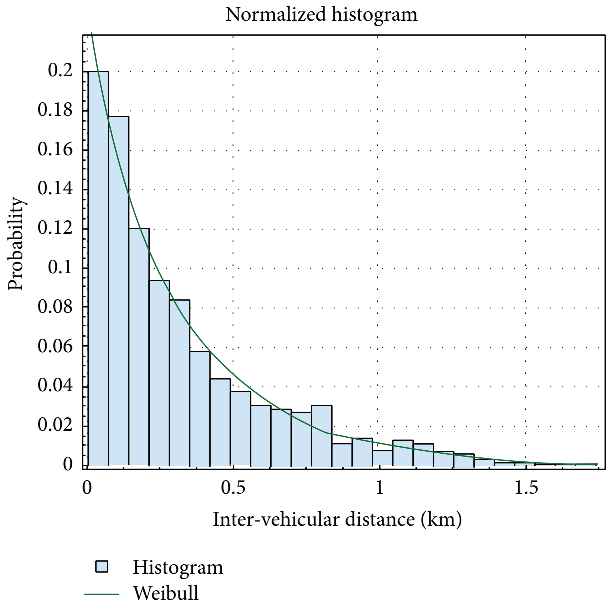


FIGURE 17: Normalized histogram for the intervehicular distance with seven lines, regarding the direction of the movement.

TABLE 5: Result of the mean, variance, and connectivity degree regarding the direction of the movements of the buses.

Numbers of lines	Mean (km)	Variance (km)	Connectivity degree (%)
One	0.77	0.49	71.50
Three	0.47	0.22	91.75
Five	0.38	0.16	93.75
Seven	0.32	0.11	94.86

It can be noticed that in the normalized histograms, as the number of lines traveling grows, the intervehicular distance lowers. With one single line (Figure 14), a significant percentage of buses with distances longer than one kilometer (approximately 28%) can be seen. In the histograms with three, five, and seven lines (Figures 15, 16, and 17), a fall of distances longer than one kilometer can be gradually noticed, getting to approximately 5% with seven lines. In all cases, the curve of the theoretical probability density that best characterizes the behavior of the intervehicular distance is also presented.

The mean and variance for the intervehicular distances and for the connectivity degree are presented in Table 5. It is possible to verify that from three lines traveling on the lane, the mean distance is not more than 500 meters and the connectivity degree surpasses 91%. As the number of lines that travel on the lane grows, the mean distance shortens, and the connectivity degree among the buses of MOB-NET rises, as expected.

A.3. Analysis Disregarding the Direction of the Movement of the Buses. Figures 18, 19, 20, and 21 present the intervehicular distance as normalized histograms for Area 2. The data is presented with one, three, five, and seven lines traveling in both directions of the lane, in the time interval of 04 h 31 min PM to 07 h 30 min PM.

It is noticeable that in the normalized histograms, as the number of lines traveling grows, the intervehicular distance reduces. With one single line (Figure 18), it can be noticed that around 17% of the distances are bigger than one kilometer. In the histograms with three, five, and seven lines (Figures 19, 20, and 21); a gradable reducing in the distances longer

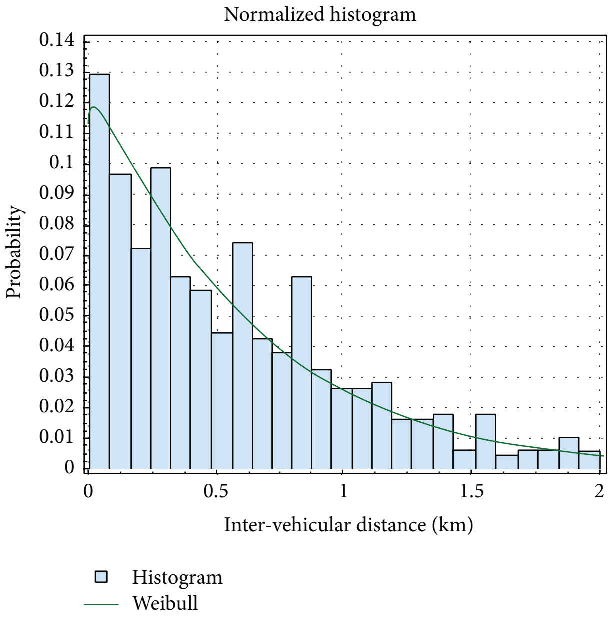


Figure 18: Normalized histogram for the intervehicular distance with one line, disregarding the direction of the movement.

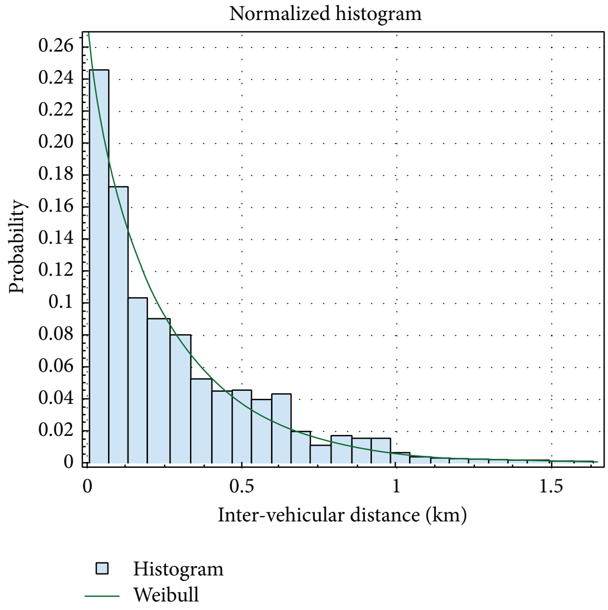


Figure 19: Normalized histogram for the intervehicular distance with three line, disregarding the direction of the movement.

than one kilometer can be noticed, getting to approximately 1% with seven lines.

The mean and variance for the intervehicular distances and for the connectivity degree are presented in Table 6. In this case, the metrics are even better, with three or more lines, the mean distance among the buses is not more than 300 meters and the connectivity degree surpass the 98%, getting to 99.33% with seven lines.

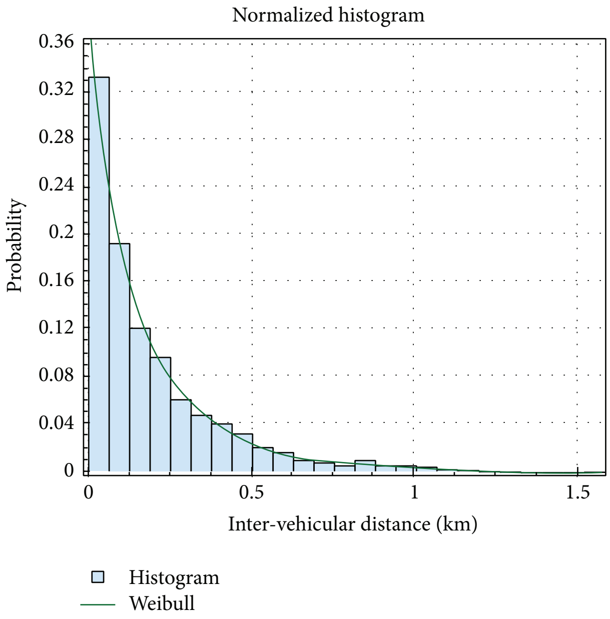


Figure 20: Normalized histogram for the intervehicular distance with five lines, disregarding the direction of the movement.

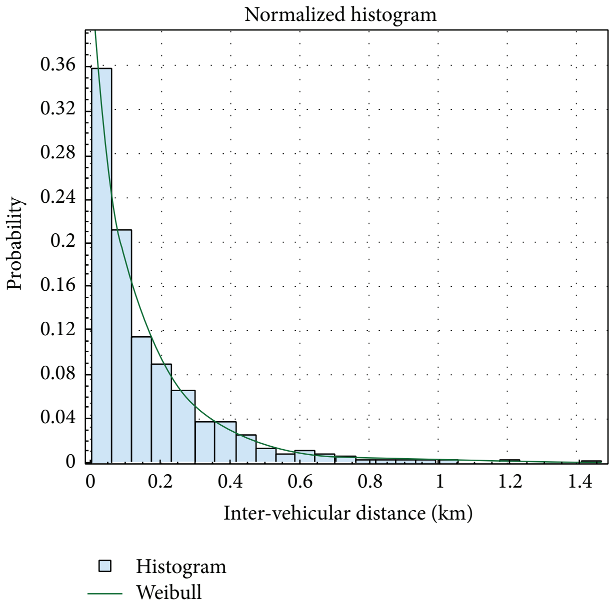


Figure 21: Normalized histogram for the intervehicular distance with seven lines, disregarding the direction of the movement.

Above all, it is still noticed that the mean intervehicular distance reduces when the direction of movement is disregarded, as expected.

A.4. Distribution Fitting. In order to find the probability density function that best characterizes the intervehicular distance, a distribution fitting was made, in relation to the real captured data. The maximum likelihood estimation (MLE) [16] was used to elect the most correct parameters.

Table 6: Result of the mean, variance, and connectivity degree disregarding the direction of the movements of the buses.

Numbers of lines	Mean (km)	Variance (km)	Connectivity degree (%)
One	0.56	0.31	83.50
Three	0.27	0.07	98.74
Five	0.18	0.04	99.01
Seven	0.15	0.02	99.33

Table 7: Values of α and β and P value regarding the movement direction of the buses.

Number of lines	α	β	P value
One	1.15	0.81	0.140
Three	1.00	0.47	0.021
Five	0.95	0.37	0.058
Seven	0.97	0.31	0.140

Table 8: Values of α, β, and P value disregarding the movement direction of the buses.

Number of lines	α	β	P value
One	1.10	0.60	0.253
Three	0.96	0.26	0.011
Five	0.91	0.18	0.013
Seven	0.91	0.14	0.012

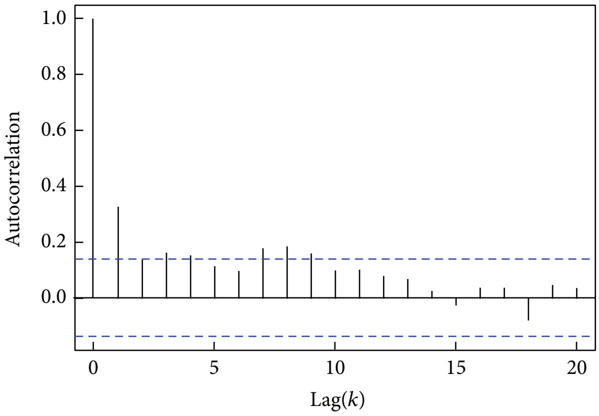


Figure 22: Autocorrelation of the intervehicular distance for a certain bus line.

In possession of the collected data for the inter-vehicular distance, a hypothesis evaluation was made through the Pearson's chi-square test [17]. For that reason, the normalized histograms for the intervehicular distance were tested against several probability distributions from the literature as, for example, exponential, gamma, lognormal, Weibull, and so forth. The obtained results indicate that the Weibull distribution cannot be rejected (at the 1% significance level) by all the analyzed cases, being able to characterize analytically the intervehicular distance. Tables 7 and 8 show the values of α, β and P value for the set of normalized histograms considering the Weibull distribution.

A.5. Autocorrelation. Figure 22 presents the autocorrelation of the intervehicular distance measured from one single line (line 550 by the Company of Urbanization of the City of Curitiba) during the schedule of 04 h 31 min PM to 07 h 30 min PM. With the analysis of the referred figure, it is possible to verify absence of temporal dependences, since the autocorrelation does not present meaningful values in relation to the temporal displacement.

A.6. QQ-Plot Analysis. In this section, an analysis is made from QQ-Plot charts aiming to validate the proposed analytical model for the distribution of intervehicular distance (Section 3.1). A QQ-Plot (chart) is a chart of the sampling quantile versus the expected quantile under the hypothesis of a given distribution probability [24].

We simulate the superposition of $n = 3$ bus lines considering that each individual process follows a Weibull distribution with $\alpha = 1.10$ and $\beta = 0.60$ (Figures 23(a) and 23(b)) and $n = 7$ bus lines with $\alpha = 0.80$ and $\beta = 0.50$ (Figures 23(c) and 23(d)). Equation (7) corresponds to the expected distribution. We notice that our approach presents good agreement.

Conflict of Interests

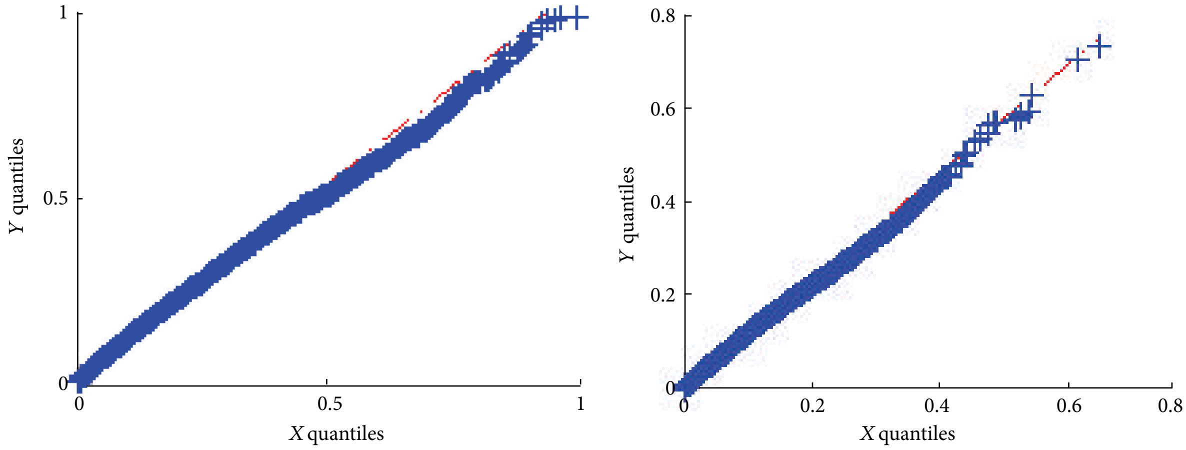
The authors declare that there is no conflict of interests regarding the publication of this paper.

Endnotes

1. According to Cox [25] the exact density of a superposition of n independent and identically distributed renewal processes in equilibrium is

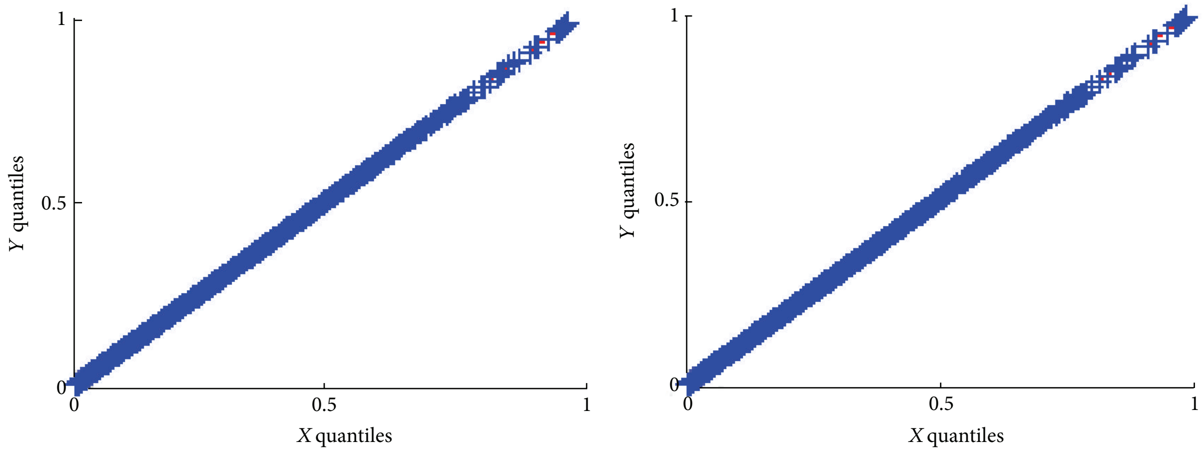
$$f_Y(y) = -\frac{d}{dy}\left[S_X(y)\left\{\int_y^{\infty}\frac{S_X(u)}{\mu_X}du\right\}^{n-1}\right],$$

where $S_X(x) = 1 - F_X(x)$ is the survivor function of each component process. Unfortunately, when each individual process follows a Weibull distribution, the integral



(a) 3 lines

(b) 7 lines



(c) 3 lines

(d) 7 lines

Figure 23: QQ-Plot analysis.

results in an incomplete gamma function, making it difficult to obtain tractable algebraic expressions. However, we show in the appendix, by computer simulation, that our approach presents good agreement.

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