On the Impact of Virtual Traffic Lights on Carbon Emissions Mitigation

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***Abstract*—Considering that the transport sector is responsible for an increasingly important share of current environmental problems, we look at intelligent transportation systems (ITS) as a feasible means of helping in solving this issue. In particular, we evaluate the impact in terms of carbon dioxide (CO_2) emissions of virtual traffic light (VTL), which is a recently proposed infrastructureless traffic control system solely based on vehicle-to-vehicle (V2V) communication. Our evaluation uses a real-city scenario in a complex simulation framework, involving microscopic traffic, wireless communication, and emission models. Compared with an approximation of the physical traffic light system deployed in the city, our results show a significant reduction on CO_2 emissions when using VTLs, reaching nearly 20% under high-density traffic.**

***Index Terms*—Carbon dioxide (CO_2) emissions, fuel consumption, vehicular ad hoc networks (VANETs), virtual traffic lights (VTLs).**

I. Introduction

GLOBAL warming and climate change have impacted the policy scene for the implementation of measures toward low-carbon resource-efficient economies. Decarbonization of the transport sector is particularly important, because in the European Union (EU), this sector accounts for around 25% of total carbon dioxide (CO_2) emissions, according to a study of the European Environment Agency (EEA) [1]. This same study also reports that car journeys comprised 72% of all passenger kilometers in EU-27 (excluding Cyprus and Malta) and have clearly represented the dominant mode of transport over the past few decades. One aggravating factor is the ever-increasing traffic levels that have neutralized the average emissions reduction per vehicle obtained due to the design of more efficient vehicles.

In parallel with the effort to develop more efficient and environmentally friendly vehicles, the design of mechanisms that improve the efficiency of road utilization, i.e., real-time traffic information systems and collaborative routing systems [2], [3], highway platooning [4], or adaptive traffic signal control [5], [6], can produce substantial additional benefits toward the reduction of the carbon footprint of road transportation. In the critical fraction of CO_2 g/km, we argue that more emphasis should be put on the *mechanics* of how each kilometer is traveled, including the route choice and the traffic control signage that is in place. In-vehicle intelligent transportation system (ITS) technologies will play a key role in this more efficient utilization of the road as we witness the inclusion of routing engines and traffic signs as in-vehicle systems.

Aside from improving safety and road network efficiency, we argue that ITS measures lead to significant improvements in terms of environmental impact. Thus, evaluating and quantifying the impact of such technologies in terms of CO_2 emissions is very important and can eventually lead to its integration in the assignment of the emissions value of new cars, which is relevantly reflected in the final price/yearly taxes and can contribute to a more rapid dissemination of such technologies.

In this paper, we focus on the evaluation and quantification of the impact in terms of CO_2 emissions of the recently proposed concept of virtual traffic lights (VTLs) [6], where the traditional road-based physical traffic signals are replaced by in-vehicle representations, supported only by vehicle-to-vehicle (V2V) communication. Our main goal is to provide evidence of the significant reductions in average network emissions that can be obtained through a novel ITS technology enabled by vehicular ad hoc networks (VANETs). Furthermore, we aim at providing a methodology and an associated simulation platform to study the environmental impact of any ITS measure.

The remainder of this paper is organized as follows. In the next section, we briefly present the relevant related work in traffic signal control and the environmental impact of ITS measures. Then, Section III introduces the VTL concept and the system main characteristics. Section IV provides an overview on the main system models, i.e., emissions and fuel consumption (see Section IV-A) and the microscopic traffic model (see Section IV-B). Section V presents a methodology for evaluating carbon emissions and the impact that the VTL system has on their mitigation. Section VI details the simulation scenario and evaluation metrics and provides the main results (individual and aggregated). Section VII closes this paper with the main conclusions.

II. Related Work

A. *Traffic Signal Control*

Traffic signal control has attracted much attention from the research community over the past few decades. Classical

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control concepts assume a cyclic operation of traffic signals, where the flows of different directions are periodically served [7]. The main control strategies can broadly be categorized into static and adaptive control.

Static control strategies, also commonly called pretimed, run precomputed and fixed signal plans. Signal plans are determined by using historical data to infer the best parameters (e.g., green split) for each intersection. However, pretimed control cannot respond to real-time traffic variations and often results in inefficient utilization of intersection capacity [8].

On the other hand, adaptive control strategies change signal plan in adaptation to the varying traffic conditions. Intelligent systems use basic sensors and optimization algorithms to increase traffic flow, whereas other systems use more complex technology to gather more information for the traffic signal to make a decision [9]. Systems such as the Split Cycle Offset Optimization Technique (SCOOT) [10] or the Sydney Coordinated Adaptive Traffic System (SCATS) [11] make use of detectors placed in the vicinity of intersections to adapt to variations in the traffic demand.

The advent of VANETs made possible a variety of new strategies that leverage on V2V and vehicle-to-infrastructure (V2I) communications. Additional and more precise information (e.g., vehicle speed and position) on each vehicle can be exchanged among vehicles or with a centralized control unit. On the most simple setting, the traffic signal periodically broadcasts its scheduling information over the wireless medium to vehicles in its vicinity [12]. In [5], the authors describe an adaptive traffic signal control system based on wireless communication between vehicles and a controller node placed at the intersection; control delay and queue length metrics are exchanged using a VANET data-dissemination platform. Cai *et al.* propose a dynamic programming algorithm, using vehicle speed, position, and waiting time as state variables [13]. In [14], a distributed multi-agent-based approach is adopted to develop a traffic-responsive signal control system. The adaptive behavior of this type of systems uses the information of vehicles (e.g., speed and position) that can thus overcome the shortcomings of traffic signal control systems based on detectors placed at fixed locations. The stop-or-go message is conveyed to drivers through the traditional road-based lamp.

B. Environmental Impact of ITS Measures

Past research work on ITS had improving safety and road network efficiency as the main objectives. However, the evaluation of the environmental impact and the inclusion as a metric in algorithms are currently aspects of major importance. For instance, in [15], the environmental benefits of car sharing have been studied in North America. The authors have concluded that car sharing reduces the overall annual pollutant emissions and the average distance traveled significantly declined, although more individuals have access to automobiles.

Bell qualitatively and quantitatively demonstrated in [16] how vehicle technologies and ITS have a role to play in reducing the impact of traffic on the environmental and health. The paper specifies a set of measures, i.e., traffic signal control, demand management, road pricing, speed limits, traffic calming, and vehicle control systems, to achieve this goal. In [17] and [18], the authors acknowledged the importance of the driver behavior on fuel consumption and associated pollutants emissions and proposed eco-driving schemes or incentive systems that decreased fuel costs and pollutant emissions. Recently, in [19], Tsugawa and Kato have presented and discussed various ITS approaches for significant energy savings and emission mitigation demonstrated by field or experimental data. The authors have concluded that vehicular communications play an essential role not only in safety but in energy savings as well [19]. However, in these papers, the most recent work on traffic signal control strategies, as well as the related environmental performance, is not considered.

In [5], the authors describe an adaptive traffic signal control system based on V2I communications. The authors demonstrated that their strategy based on the optimization of green phases outperformed the classical method (pretimed); delay is decreased by 28%, and pollutant emissions are decreased by up to 8.9% (6.5% for CO_2 emissions). However, the strategy was evaluated only to a single intersection.

Tielert *et al.* assessed in [12] the environmental gains of the traffic-light-to-vehicle communication (TLVC) application. For this specific application, key influencing factors on pollution emissions are gear choice and the information distance to obtain an efficient speed adaptation. Although single-vehicle analysis presented large improvements in terms of pollutant emissions, road-network-wide simulation yields a reduction in fuel consumption of only up to 8% [12]. Furthermore, to evaluate the environmental impact of TLVC, modeling the communication aspect as a fixed information distance was considered sufficient [12].

In [20], Sommer *et al.* analyze the environmental impact of the proposed dynamic rerouting algorithm and the traditional metric *travel time*. The authors demonstrate that the optimization of these metrics can be conflicting in some situations. If only the travel time will be used in the optimization process of ITS, emission metrics are often suboptimal [20].

III. Virtual Traffic Light

The road network has become ubiquitous such that, in the conterminous U.S., for example, we can get no farther from a road than 35 km [21]. It is geometrically unavoidable that these millions of kilometers of roads meet at some points, forming road junctions of different topologies. Based on the 2009 Tiger/Line data [22], it was computed that the number of intersections in the U.S. amounts to approximately 50 million [6]. In terms of traffic flow, these junctions constitute critical points, which are the subject of a vast amount of research toward its optimization. This optimization can either be based on a topological/geometrical approach (through grade separation or roundabout design, e.g., [23]) or on a signalization approach, particularly through intelligent traffic signals (e.g., [24]).

In this paper, we focus on the role of VANETs for the optimization of road intersections based on intelligent traffic signals. One common aspect to all the strategies presented in Section II-A is the utilization of fixed infrastructure to support the operation of intelligent traffic control strategies.

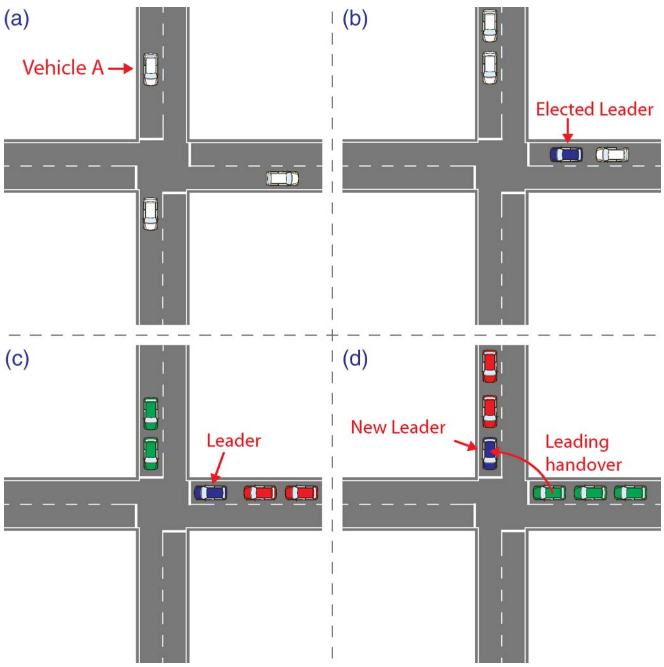

Fig. 1. (a) Conflict-free intersection. Vehicle A uses periodic beaconing to advertise its position and heading as it approaches the intersection. No conflicts are detected, and it is not necessary to create a VTL. (b) Periodic beaconing of concurrent vehicles results in the detection of a crossing conflict and in the need to create a VTL. One of the conflicting vehicles is elected as the intersection leader and will create and control the VTL. This leader stops at the intersection and replaces a road-based traffic signal in a temporary control of the intersection. (c) Leader is stopped at the intersection and optimizes the functioning of the VTL based on the number of vehicles in each approach and periodically broadcasts VTL messages with the color of each approach/lane. (d) When the cycle ends and the green light is assigned to the leader approach/lane, the current leader selects a new leader from the vehicles stopped under red lights. This new leader continues the cycle. If there are no stopped vehicles under red lights, then the VTL ceases to exist.

Furthermore, many of these strategies assume the existence of a centralized control unit[1] and cyclic operation. In this paper, we propose a new paradigm, called VTL, in which control is decentralized and self organized, operation is acyclic, and traffic signal information is individually and directly presented in each vehicle. In our system, vehicles behave as sensors in the road transportation network.

In [6], we presented the VTL concept, advocating for a paradigm shift from traffic signals as road-based infrastructures to traffic signals as in-vehicle virtual signs supported only by V2V communication. The implementation of the VTL system results in improved traffic flow due to the optimized management of individual intersections, which is enabled not only by the neighborhood awareness of VANET protocols but due to the scalability of the solution as well, which renders signalized control of intersections truly ubiquitous. This ubiquity allows us to maximize the throughput of the complete road network rather than the reduced number of road junctions that are currently managed by physical traffic signals.

The principle of operation of VTLs is relatively simple and is illustrated in Fig. 1. Each vehicle has a dedicated application unit (AU), which maintains an internal database with information about intersections where a VTL can be created. When approaching such intersections, the AU checks whether there is a VTL running that must be obeyed or a VTL needs to be created as a result of perceiving crossing conflicts between approaching vehicles [see Fig. 1(a) and (b)].

Beaconing and location tables, which are features of VANET geographical routing protocols (for example, see [25]), are used to determine whether a VTL needs to be created. Each node maintains a location table that contains information about every node in its vicinity, which is constantly updated through the reception of new beacons. The periodicity of these beacons can be increased as vehicles approach an intersection.

If a VTL needs to be created, then all vehicles that approach the intersection must agree on the election of one of the vehicles as the *leader*, which will be responsible for creating the VTL and broadcasting the traffic signal messages [see Fig. 1(c)]. This vehicle works as a *temporary virtual infrastructure* for the intersection and takes the responsibility of controlling the VTL. Once this leader has been elected, a VTL cycle for the intersection control is initiated with a red light for the leader approach/lane. This condition ensures that the leader will remain in the intersection for the duration of a complete cycle. Based on the number of vehicles in each approach, the leader can set the traffic signal parameters, such as the phase layout and the green splits assigned to each approach, in an optimized manner. During the existence of a VTL *leader*, the other vehicles act as passive nodes in the protocol, listening to traffic signal messages and presenting these messages to the driver through the in-vehicle displays.

During a complete VTL cycle, the leader commutes the traffic light (TL) phase among the conflicting approaches/lanes. When the green light is in the leader's lane, the control of the VTL system must be handed over to a new leader in a different approach/lane. If there are vehicles that stopped under the red light at the intersection, the current leader selects one of these vehicles to become the new leader, which will maintain the intersection control in a consistent sequence [see Fig. 1(d)]. If there are no stopped vehicles under the red light, then a new leader will be elected through the previously explained process whenever necessary. Fig. 2 depicts the principle of the operation of the VTL system in terms of stages.

In a primal paper, where the VTL concept was presented, the dynamic performance of the system has also been studied. The selected mobility metric was the average increase in flow rate of the VTL protocol versus the real physical traffic signals as a function of vehicle density. Large-scale simulations that emulate a real dense urban scenario provided compelling evidence on the viability and significant benefits of the proposed scheme in terms of the mobility metric (up to 60% increase at high densities). This new self-organizing traffic paradigm thus holds the potential for revolutionizing traffic control, particularly in urban areas [6].

The interaction between vehicles and pedestrians also needs to be considered. The most direct and traditional approach that could be foreseen is the communication of the traffic signal information to pedestrians through smart phones or simple road infrastructure. The virtual indication of traffic signals by the leading vehicle is also proposed.

[1]A decentralized signal control strategy has recently been proposed by Laemmer and Helbing in [7].

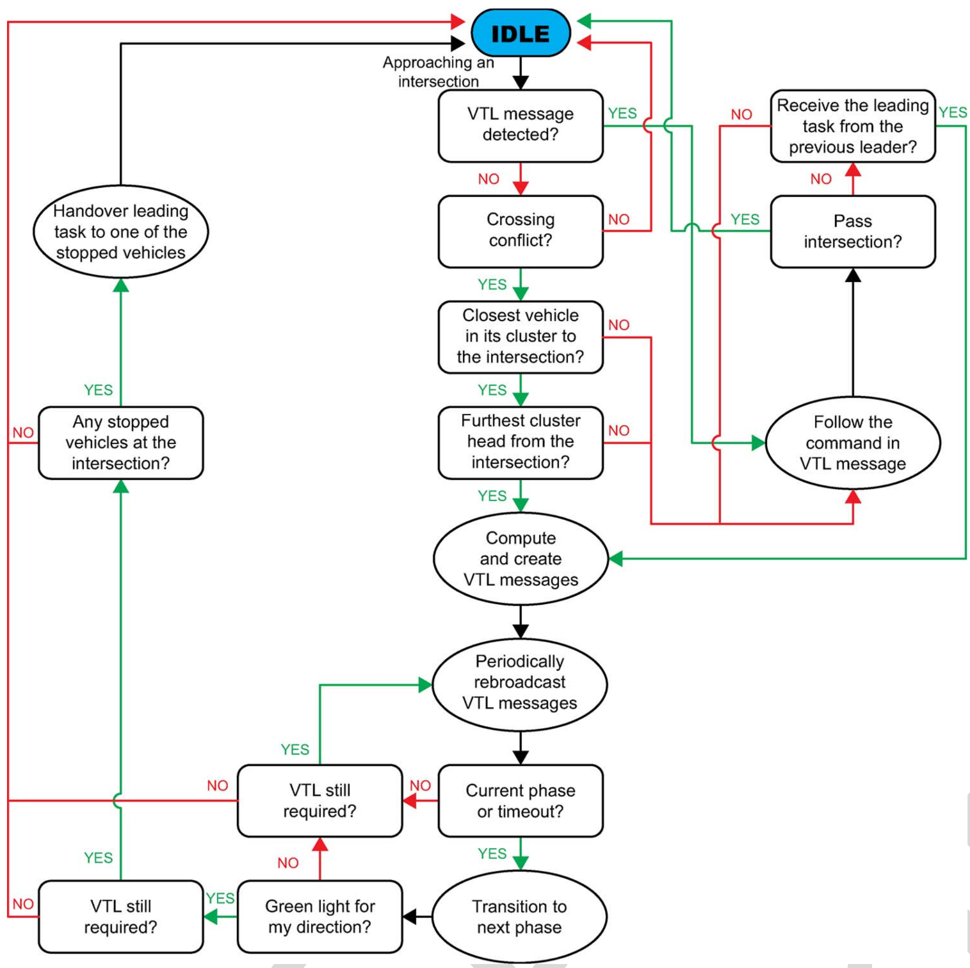

Fig. 2. VTL phase diagram.

An immediate effect of the shift of paradigm of traffic signals as road-based infrastructures to in-vehicle virtual signs is the elimination of physical traffic signals from roads. According to [26], in 1998, 3.25 million traffic lamps were approximately permanently lighted in the road infrastructure of the U.S. based on an estimated number of 260 000 signalized road junctions. We estimate that the electric power consumption of TLs in the U.S. can total an amount around 2 million MW · h/year, which is equivalent to 1.2 million metric tons of CO_2 per year according to [27]. Although this value is significant, it is almost irrelevant when considering the total emissions of personal vehicles in the U.S., which emit around 300 million metric tons of CO_2 per year [28]. VTLs, on the other hand, enable the universal deployment of semaphore-based control on the intersections of the road network, with virtually no impact on energy consumption or carbon emissions.[2]

IV. System Models

A. Emissions and Fuel Consumption Model

Emission models can broadly be categorized into macroscopic, mesoscopic, and microscopic models. Macroscopic models estimate pollutant emissions and fuel consumption mainly based on the average travel speed of the traffic flow. These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions [29], which leads to reduced accuracy in calculations. Moreover, these models cannot capture individual speed fluctuations and cannot take into account individual operation conditions, which are of crucial interest when analyzing a proposal that considers network and vehicle dynamics. Mesoscopic models (e.g., [30]) use more disaggregate trip variables, such as the average speed, the number of stops, and stopped delay, to estimate a vehicle's emission rates on a link-by-link basis. Some regression models that were developed were found to predict fuel consumption and emission rates of hydrocarbons (HC), carbon monoxide (CO), and NO_x to within 88%–90% of instantaneous microscopic emission estimates [31].

Microscopic emission models overcome some of the limitations of large-scale macroscopic models mainly by considering individual vehicles dynamics and their interactions. Emissions and fuel consumption are estimated based on instantaneous individual vehicle variables that can frequently be obtained (e.g., second by second) from a microscopic traffic simulator or another alternative source [e.g., the Global Positioning System (GPS) data logger]. Commonly, these parameters are divided into the following two categories: 1) vehicle parameters and

[2]The low-power consumption of in-vehicle semaphores and associated V2V communications could resort to energy recovery mechanisms from the kinetic energy of vehicles to power the electrical systems.

2) traffic/road parameters. Vehicle parameters include, among others, vehicle mass, fuel type, engine displacement, and vehicle class. On the other hand, network parameters (traffic and road conditions) account for instantaneous vehicle kinematics (e.g., speed or acceleration), aggregated variables (e.g., the time spent in the acceleration mode), or road characteristics (e.g., road grade). Because microscopic emission and fuel consumption models have higher temporal precision and better capture the effects of vehicle dynamics/interactions, they are better suited to evaluate the environmental gains derived from an ITS measure, such as the VTL system.

Several microscopic models have been proposed by the scientific community. These models can be classified into emission maps (speed/acceleration lookup tables), purely statistical models, and load-based models [32]. Major contributions in this field were given by Akcelik *et al.* [33], Barth *et al.* [34] with the comprehensive modal emission model (CMEM), Ahn *et al.* [35], and Cappiello *et al.* [32] with the emissions from traffic (EMIT) model. The latter model has been selected due to computational performance and accuracy reasons. EMIT is a simple dynamic emission model that was derived from statistical and load-based emission models.

This model first estimates the instantaneous tractive power (P_{tr}) using (1), which has the vehicle velocity v (in meters per second) and acceleration a (in square meters per second) as the main parameters

$$P_{tr} = A \cdot v + B \cdot v^2 + C \cdot v^3 + M \cdot a \cdot v + M \cdot g \cdot \sin \vartheta \cdot v \quad (1)$$

where the variables are defined as follows:

- A rolling resistance (in kilowatts per meter per second);
- B speed correction (in kilowatts per square meter per second);
- C air drag resistance (in kilowatts per cubic meter per second);
- M vehicle mass (in kilograms);
- g gravitational constant (in square meters per second);
- ϑ road grade (in degrees).

Depending on the value of P_{tr}, the fuel rate (FR) can be expressed as

$$FR = \begin{cases} \alpha_i + \beta_i v + \gamma_i v^2 + \delta_i v^3 + \zeta_i a v, & \text{if } P_{tr} > 0 \\ \alpha_i', & \text{if } P_{tr} = 0 \end{cases} \quad (2)$$

where α_i, β_i, γ_i, δ_i, and ζ_i are constants that are associated with individual vehicles that were obtained using ordinary least square linear regressions.

The EMIT model allows us to simultaneously calculate several pollutant emissions subproducts, i.e., CO, CO_2, HC, and nitrogen oxide (NO). This calculation is divided into the following two main phases: 1) engine-out (EO) and 2) tailpipe (TP). The following formula for calculating EO pollutant emissions has the same structure as (2) due to the linear relationship with FR:

$$EO_i = \alpha + \mu \cdot FR \quad (3)$$

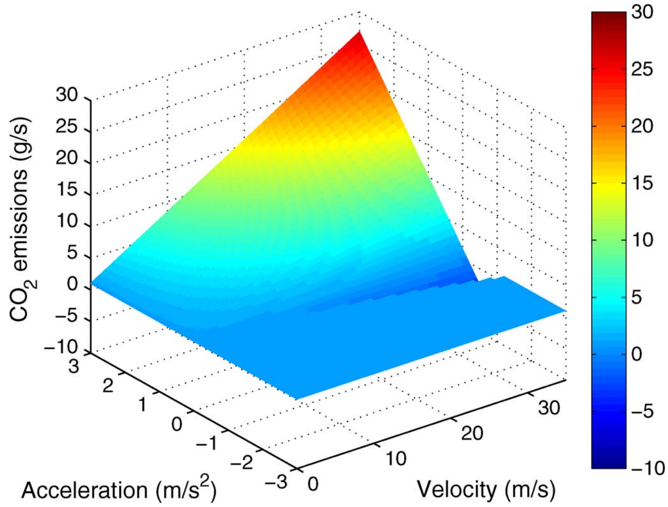

Fig. 3. CO_2 emissions surface as a function of the vehicle acceleration and velocity; increasing values for this metric lead to increased CO_2 emissions. The EMIT model can produce negative values.

CO_2 is the main by-product of the combustion of fossil fuels,[3] and consequently, it is proportional to the FR. The values of CO_2 EO emissions are directly estimated from fuel consumption estimates. Due to this linear relationship, the terms FR or CO_2 can interchangeably be used when analyzing the environmental impact of an ITS technology. Fig. 3 depicts the CO_2 emissions surface for a given input parameter set (acceleration and velocity) with a resolution of 0.1 (m/s^2 and m/s, respectively). Note that negative values for CO_2 can be obtained with the EMIT model. This problem was addressed by considering a minimum value for the emissions that is equal to the constant α_i' when P_{tract} is equal to zero.

After estimating the EO emission for the subproducts of combustion, the EMIT model calculates the TP emission rates. This emission rate is a fraction of the EO emission rate that leaves the catalytic converter, i.e.,

$$TP_i = EO_i \cdot CPF_i \quad (4)$$

where CPF_i denotes the catalyst pass fraction for species i.

The calibration of the parameters of (1) and (2) resorted to light-duty vehicle data that were gathered for CMEM. Because our goal is to evaluate the relative benefit of the VTL technology, we consider the same coefficients for all vehicles that are used in this paper. These parameters are shown in Table I and are based on the values available from the EMIT model [32] (vehicle category 9).[4]

B. Microscopic Traffic Model

To test the feasibility and performance of VANET-based applications, a simulation platform is required to simulate vehicular ad hoc environments. The simulation-based evaluation

[3] Although, in this paper, we mainly assess CO_2 emissions, which is the main by-product of fossil fuels combustion, other subproducts could be evaluated due to their relative importance, particularly at intersections due to the stop-and-go phenomenon.

[4] The definition of each vehicle/technology category of the modal emissions model can be found in [36]. Vehicle category 9 represents a normal emitting car (Tier 1 emission standard), with accumulated mileage greater than 50 000 miles and high power/weight ratio.

TABLE I
EMIT MODEL PARAMETERS

Factor	Value	Unit
A	0.1326	$kW/m/s$
B	2.7384e-3	$kW/(m/s)^2$
C	1.0843e-3	$kW/(m/s)^3$
M	1.3250e-3	kg
g	9.81	m/s^2
ϑ	0	$degrees$
α_i	1.1	g/s
β_i	0.0134	g/m
γ_i	-	$g\ s^2/m^2$
δ_i	1.98e-6	$g\ s^2/m^3$
ζ_i	0.2410	$g\ s^2/m^2$
$\alpha_i^{'}$	0.973	g/s

of VANET protocols requires a network simulator (NS-3) and a road traffic microscopic simulator [Development of Intervehicular Reliable Telematics (DIVERT)]. DIVERT [37], [38] is a sophisticated microscopic simulator based on the intelligent driver model (IDM) [39] with a validated mobility model [40]. The lane-changing model is based on the MOBIL model proposed by Treiber *et al.* in [41]. The mobility patterns are individually influenced by random initialization, within typical values, of attributes such as acceleration, braking, aggressiveness, and risk tolerance [37]. The current mobility model does not account for vehicle speed adaptation based on the received information (e.g., driver reaction to traffic signal controller timing information) as done in [42]. The implementation includes all the common features of a road transportation network (e.g., traffic signals). It allows the simulation of thousands of vehicles with a high degree of realism [38] and with a wide range of configurations (e.g., aggressiveness). NS-3 is a discrete-event network simulator for Internet systems, primarily targeting research and educational use [43]. Several radio access technologies (e.g., IEEE 802.11p), as well as multiple interfaces/channels features and various protocol modules, can be used. In [44], the authors conclude that NS-3 delivers the best overall performance.

The need for a bidirectional coupling of these two components (network and traffic) is fundamental and has been discussed in [45]. Clearly, the mobility of vehicles affects the network connectivity and behavior. Conversely, the results of the network simulation component can also affect the mobility of vehicles. In the case of VTL, this bidirectional coupling is particularly microscopic in both directions. Detailed mobility information (e.g., the position, speed, and heading of each vehicle) needs to be fed to NS-3, which has been coupled with DIVERT [38] to simulate the beaconing, leader election, and virtual light messages in the context of the VTL protocol. Traffic signal information, which results from the exchange of messages of the VTL protocol emulated by NS-3, is provided to the DIVERT simulator; the individual mobility of each vehicle is affected by the regulatory messages conveyed by the VTL (e.g., stop at a given intersection).

V. METHODOLOGY

Our goal is to quantify the impact of the VTL technology on CO_2 emissions mitigation. We should thus analyze CO_2 emissions of vehicles that interact with physical traffic signals and compare the results with the CO_2 emissions of vehicles that use VTLs. To isolate the benefit of the VTL approach, each of the alternatives for intersection control should have identical settings in all possible *static* variables, including the characteristics of vehicles and drivers, the road scenario, and the routes. The differences in the two analyses result from a different mobility behavior of each vehicle that is affected by *dynamic* aspects, which correspond to different traffic conditions due to alternative schemes of intersection control.

To perform these two analyses, the aforementioned EMIT emissions model was integrated into a microscopic traffic simulator. The microscopic traffic simulator outputs the mobility behavior of each vehicle in the form of a virtual GPS trace. By processing this GPS trace, a set of variables can be derived, such as acceleration and speed, which then feed the microscopic emissions model. The emissions of each vehicle are then aggregated to quantify the overall positive impact of the VTL system. Fig. 4 illustrates this architecture and its main components. The main component of the simulation-based evaluation of the decarbonization impact of VTLs is the DIVERT microscopic traffic simulator [37].

The implementation of physical TLs and VTLs in DIVERT is relatively simple and leverages on the car-following equations included in the IDM [39] that affect the acceleration and deceleration patterns of each vehicle. In terms of mobility simulation, physical and virtual traffic signals are identically implemented in DIVERT. For each lane of an approach to an intersection, the traffic simulator creates a temporary dimensionless vehicle on the stop line associated with the lane. This dimensionless vehicle is created under a red light and disappears under a green or yellow light. Variable aggressiveness parameters of each driver result in different behaviors under yellow lights as a function of the distance to the stop line. The intermittent creation of this dimensionless vehicle is thus mandated by the traffic signal control system or the VTL protocol (see Fig. 4) and transparently affects the mobility of vehicles based on the car-following model that governs the acceleration and deceleration variables.

The differences in the two instances of DIVERT illustrated in Fig. 4 refer to the geographic location of physical TLs and VTLs and to the method used to derive the TL color shown to each vehicle. With regard to the geographic location of physical traffic signals, we have replicated the existing deployment in the city of Porto, Portugal. The implemented physical-TL approach is also a loyal representation of the existing scenario. In the current version of DIVERT, the traffic signal control system is very simple and uses fixed green splits for each of the approaches of an intersection. Such simplistic functioning is, however, a good approximation of the current functioning of most of the deployed traffic signals. A recent study has reported that 70%–90% of the deployed traffic signals work under fixed parameterization of cycle duration and green splits [46].

The geographic location of VTL is not fixed and is determined by traffic conditions in confluent approaches of an intersection. Depending on the traffic density, such virtual traffic signals can be present at all intersections or can be almost nonexistent. Instead of the data from fixed traffic

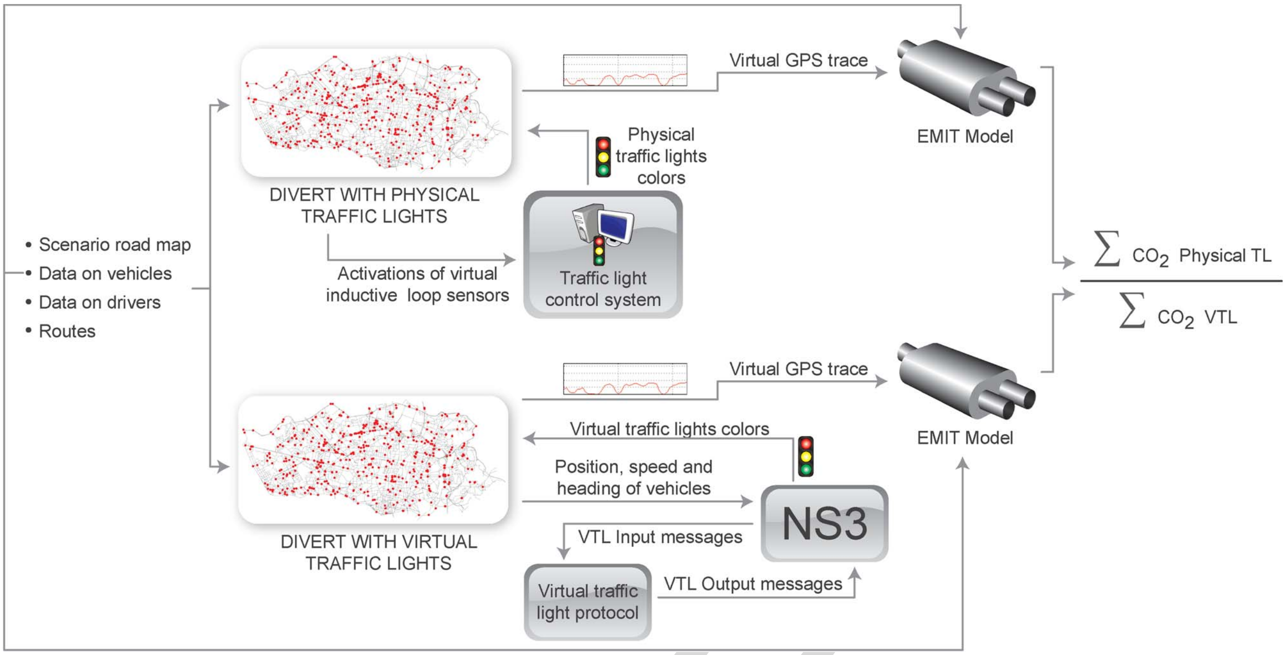

Fig. 4. Evaluation architecture. The main component is the DIVERT microscopic traffic simulator, whose two instances are used to produce virtual GPS traces. The scenario road map, data on vehicles and drivers, and the route of each vehicle are fed to an instance of DIVERT with physical traffic signals and to another instance where the VTL protocol is simulated. The simulation of the network layer of the VTL protocol is done by NS-3. The virtual GPS traces are then fed to two instances of the EMIT model to compute and compare the aggregated values of CO_2 emissions.

counters, the optimization of cycle duration and green splits of a VTL resorts to more complete information, which includes the position, speed, and heading of all vehicles that approach the intersection. This information is provided by DIVERT, and the simulation of its beaconing by each vehicle is done by NS-3. Leader election and the virtual light messages that are broadcast by the leader are also simulated in NS-3 and provide the traffic signal colors that are shown to each vehicle in DIVERT.[5]

VI. Results and Discussion

The results and analysis presented here are based on the system models given in Section IV and follow the methodology provided in Section V (see also the framework depicted in Fig. 4). The two strategies (physical TL and VTL) are compared with making use of the simulation platform in a large-scale scenario (see Section VI-A) and a number of performance metrics (see Section VI-B). First, individual vehicle dynamics are studied (see Section VI-C). To determine the overall benefit that arises from the implementation of the VTL system, individual outputs are consolidated (see Section VI-D).

A. *Simulation Scenario*

To give scale to the analysis of the benefits of VTLs, we evaluate the carbon emissions of vehicles in the road scenario of an entire city. The city of Porto, Portugal, which is the second largest in the country, spans an area of 41.3 km^2 and has a road network that comprises 965 km. Due to a recent stereoscopic aerial survey over the city, where the location of all moving vehicles was pinpointed and their traveling speeds were derived, together with the inference of a 5-s route [40], realistic traffic data are available for Porto. In the aerial survey, a total of 10 566 vehicles were pinpointed. The observed distribution of vehicles per road segment was used to (decrease) increase density to (non)rush-hour values to evaluate the impact of VTL under different conditions. In this paper, the following four different densities of vehicles that move in the city of Porto are then considered:

1) 24 veh/km^2 (low);
2) 120 veh/km^2 (medium-low);
3) 251 veh/km^2 (medium-high);
4) 333 veh/km^2 (high).

With regard to the route of each vehicle, random origin/destination pairs that are based on the observed distribution of vehicles from the aerial survey are generated. We evaluate mobility propagation using wireless transmission ranges of 150–250 m, as defined in [40]. In this paper, stereoscopic aerial photography was used to model urban mobility to compute connectivity and path availability. Communication is mostly direct (one-hop communication) between the leader and vehicles in the vicinity of an intersection.

The road network of the city of Porto has a total of 1991 intersections. Physical TLs control 328 of these 1991 intersections (16%). Fig. 5 depicts the road network, the location of signalized intersections, and one example route followed by a vehicle.[6] Each scenario was evaluated for a period of 30 min.

[5]Videos that show the principle of operation of the VTL system are available at http://www.dcc.fc.up.pt/hc/vtl_porto.avi} and http://www.dcc.fc.up.pt/hc/vtl_complex.avi.

[6]A zoomable webmap that shows the road network, the location of signalized intersections, and the position of vehicles from the aerial survey is available at http://drive-in.cmuportugal.org/porto/.

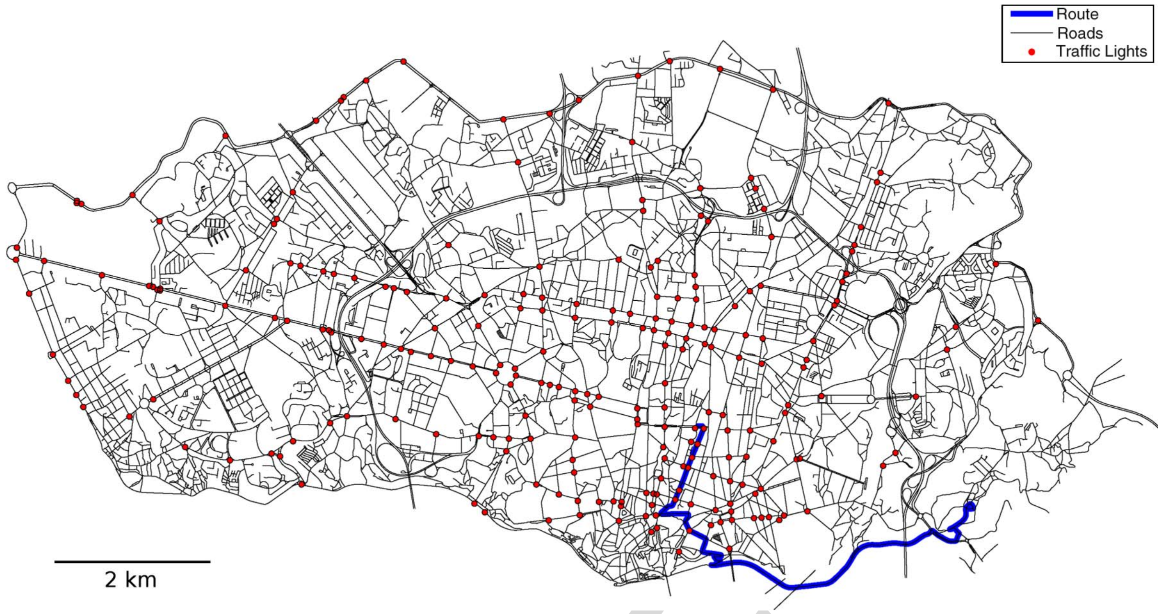

Fig. 5. Road network of the city of Porto comprises 965 km of extension. The red dots display the location of the 328 intersections that are managed by physical traffic signals. The blue line represents an example of a route traversed by a vehicle in this paper.

B. Performance Metrics

To demonstrate the benefits of the VTL system, a number of variables need to be analyzed. In [6], the impact on the traffic flow of VTL was evaluated for the same scenario of the city of Porto. Results have shown an increase of up to 60% in flow rate for high-density scenarios. Here, we want to analyze the environmental impact of VTL, comparing the individual and aggregated CO_2 emissions of vehicles that travel the exact same number of kilometers on the exact same roads, with and without the VTL system.

For this analysis, the definition of each variable, application domain, whether for individual vehicle analysis or aggregated investigations, and unit is given as follows:

- *Instantaneous* CO_2 *emissions* $E^i_{CO_2}$ (individual; in grams per second): Calculated for vehicle i using (2) after knowing the outcome of (1) with appropriate coefficients (see Table I);
- *Route* CO_2 *emissions* (individual; in grams): cumulative sum of an individual vehicle CO_2 emissions for its complete route;
- *Average* CO_2 *emissions per vehicle* (aggregated; in grams): defined as

$$\frac{\sum_{t=0}^{end} \sum_{i}^{n_{cars}} E^i_{CO_2}}{n_{cars}} \tag{5}$$

where t iterates over the seconds of the simulation, and i iterates over all the individual cars.

C. Individual Vehicle Results

Before analyzing the aggregated results of CO_2 emissions for all vehicles in the city of Porto scenario, we analyze the relevant variables for an individual vehicle, highlighting important differences between a route traversed with the VTL system and with the deployed physical-TL system. This preliminary analysis using a single vehicle gives some intuition about the understanding of the aggregated results.

The vehicle that was selected for the current analysis traversed the city following a route (see Fig. 5) that combines a major arterial road and a dense urban area with permanent intersection conflicts, which clearly have distinct characteristics and can lead to different performance. In this paper, medium traffic density is considered (190 vehicles/km^2). Although this overall density is the same with TL and VTL, the distribution of vehicles can be very different as a result from the distinct traffic control schemes.

Fig. 6 depicts the main variables (velocity, acceleration, instantaneous CO_2 emissions, and route CO_2 emissions) for TL (in blue continuous lines) and VTL (in red dashed lines). The variables velocity and acceleration were obtained from the virtual GPS logger. Observing these variables, it is evident that, without the VTL system, the car remained stopped for longer periods mainly due to the semaphored intersections and increased congestion. This fact is particularly evident when the vehicle enters the city center area, which contains a higher density of physical traffic signals and of vehicles. The ubiquity of the VTL solution also led to faster intersection conflict resolution and contributed to congestion dissipation. Another interesting fact is that, with the TL system, the car takes approximately more than 25% of the time to travel the same route for this traffic density. Stated otherwise, the average velocity of the vehicle with the VTL system is considerably increased compared with the physical-TL system.

Observing the graphic of the instantaneous CO_2 emissions depicted in Fig. 6, the correlation between this output and the velocity/acceleration metrics is evident. Increasing acceleration/velocity values leads to increasing instantaneous pollutant emissions. On the other hand, a stopped vehicle has a constant emission rate. The instantaneous emissions cannot directly be

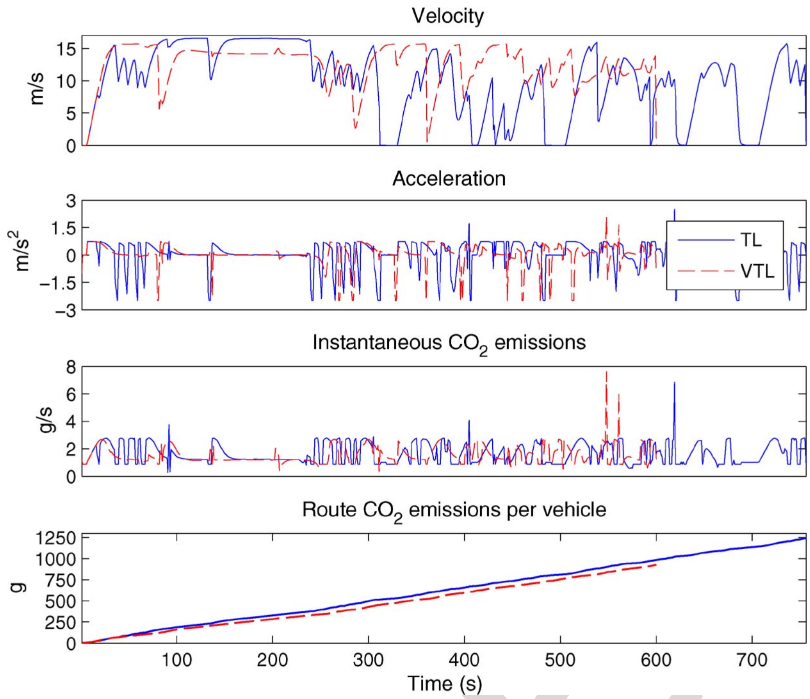

Fig. 6. Individual vehicle metrics comparison [velocity, acceleration, instantaneous CO_2 emissions, and cumulative CO_2 emissions for the traversed route (medium vehicle density)]. The same vehicle traverses the exact same route with and without the VTL system. Differences in all metrics are evident. In addition, note that this particular vehicle takes less than half the time to complete its route with the VTL system.

compared between physical TLs and VTLs, because they happen at different locations of the route. The relevant comparison is the cumulative route CO_2 emissions, which highlights the impact of the implementation of the VTL. Observing this metric, it is clear that the overall number of stops during the route, as illustrated by the vehicle's acceleration and deceleration levels, has a significant impact on vehicle emission rates [47]. For the example route, the cumulative fuel consumption is reduced by approximately 25%, mainly due to the increased traffic flow and consequent less transportation congestion, as well as the ubiquity of the VTL solution, which can detect the existence or not of intersection conflicts.

D. Aggregated Results

Apart from investigating the benefits for individual vehicles, the performance of the VTL system was evaluated by considering all the vehicular interactions that take place in the complete transportation network. To perform this study, the individual pollutant emissions values are aggregated for each simulation to determine the metric average CO_2 emissions per vehicle. This metric is widely used to determine the environmental impact of ITS. Furthermore, it is a referenced measure, which allows direction comparison of results in scenarios with different traffic flows.

To make statistical inference, a number of observations of the system (eight simulation runs for each traffic density) were performed, followed by a statistical analysis to obtain an estimate of the selected performance metric. The mean of the metric *average* CO_2 *emissions per vehicle* is the estimated parameter, and 95% confidence intervals for the estimator are considered in this paper.

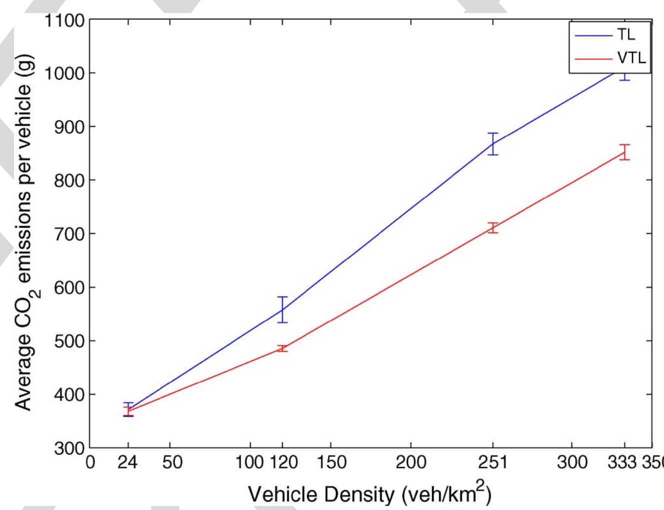

Fig. 7. Aggregated vehicle metric for TL and VTL comparison, given different vehicle densities. This graphic highlights the increased impact of VTL as traffic density becomes higher. Confidence intervals are depicted for each vehicle density and traffic control strategy (TL or VTL).

Fig. 7 represents the selected metric in the TL and VTL scenarios and considers vehicles densities that range from low density to high density. In both scenarios, with the increase of the vehicle density, the average CO_2 emissions per vehicle increase. As the density increases, intersection conflicts become more frequent, which causes increased congestion. Increased congestion leads to the stop-and-go phenomenon, which is associated with constant accelerations and decelerations that are one of the main causes of pollutant emissions. For all vehicle densities, the average CO_2 emissions per vehicle are lower for the VTL case.

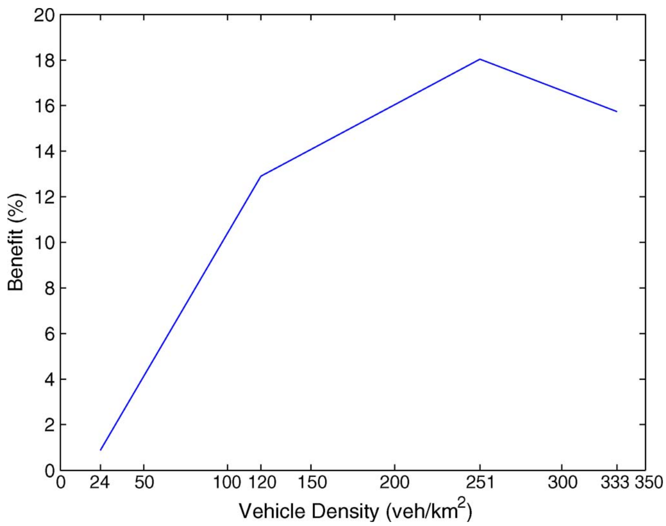

Fig. 8. Improvement in terms of CO_2 emissions due to the implementation of the VTL system in function of the vehicle density.

Fig. 8 depicts the percentage of improvement in terms of CO_2 emissions as a function of the vehicle density. The implementation of the VTL system is beneficial in terms of CO_2 emissions for all the traffic densities that were studied. In addition, as the car density increases, the mitigation in terms of CO_2 becomes more evident. For the selected vehicle densities, the benefit varies between 1% and 18%. Eventually, if we increase the densities to higher values (which are unrealistic for the capacity of the current traffic control system of the city), the benefit would start declining, as the theoretical capacity of the road network, independent of the intersection control scheme that is used, starts to be reached.

Note that there is also a significant increase on the average vehicle velocity between 26% (low density) and 41% (high density). In urban scenarios, however, this case does not lead to increased emissions, because the optimal cruising speed is never reached. The mitigation of carbon emissions occurs due to self-organized ubiquitous traffic control enabled by VTL. At high vehicle densities, the absence of traffic signals at intersections exacerbates the congestion problem, which leads to increased emissions in the physical-TL case. The results presented herein are in accordance with the results published in [6], where the vehicle traffic flow was studied.

VII. Conclusion

The advent of wireless intervehicle communication, which should be available in the near future, opens a variety of opportunities to increase the safety and efficiency of road utilization. With regard to efficiency, an important aspect of its optimization will involve the mitigation of pollutants emission to fight global warming and climate change. In this paper, we have addressed the evaluation of the environmental impact of a challenging application of intervehicle communication, called VTL. Such a system will have to overcome complex problems that are intrinsic to the critical control of the right of way of vehicles in an intersection through a distributed system based on wireless communications. In particular, VTLs face the hurdle of requiring 100% deployment in motorized vehicles to work. However, this penetration problem is a common issue for a variety of other V2V or V2I applications; safety-related applications are a main example that requires high penetration rates for effectiveness and are pushed forward for their evident advantages. Reaching this level of deployment requires governmental commitment to mandate the existing motorized vehicles to install VTLs as an after-market equipment.[7] To tackle this issue, studies must be performed to investigate whether changes can be made to the original VTL system to allow lower penetration rates and the coexistence with the current TL system.

In addition to the significant improvements in traffic flow that have been reported in the work of Ferreira *et al.* and to the increased safety of semaphore-controlled intersections, where accidents can be reduced by more than 30%, this paper has reported a reduction of 18% for the CO_2 emissions of a realistic number of vehicles that travel in a large-scale urban scenario when using the VTL system. Considering only the CO_2 component of the annual circulation tax that is in place in Germany, for example, 2€/g/km, would justify the cost of an after-market VTL system for any car owner.

This paper has been performed for internal combustion-engine vehicles. As further work, we plan to investigate the energy savings that arise from the implementations of ITS measures for hybrid or electric vehicles, which currently have limited autonomy. Furthermore, the simulator should be extended to include alternative emissions-modeling approaches and also modified to perform the calculation in real time of the energy/fuel consumption rather than postprocessing the information. This approach would allow testing innovative algorithms where parameters are changed online, depending on the current energy consumption or emissions. Another interesting topic to study in more detail is pedestrian–vehicle interaction and human–computer interaction.

The inclusion of urban traffic control (UTC) systems in simulation can provide additional insights into the intersection control problem. More specifically, the benefit of the VTL approach compared to such centralized control systems will be studied. In the city of Porto, such UTC systems have been deployed to control part of the traffic signals. We are currently integrating in our simulation platform a replication of the functioning of this UTC based on simulated inputs that correspond to activations of virtual inductive-loop sensors. This line of research involves joint work with the company that develops the UTC system to have a virtual replication of the system that mimics the exact behavior of the traffic signals that are in place in the city of Porto.

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[7]Electronic tolling systems and in-vehicle parking meters are examples of systems that have been the subject of legislation in some parts of the world.

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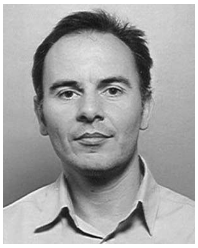

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On the Impact of Virtual Traffic Lights on Carbon Emissions Mitigation

Michel Ferreira and Pedro M. d'Orey

***Abstract*—Considering that the transport sector is responsible for an increasingly important share of current environmental problems, we look at intelligent transportation systems (ITS) as a feasible means of helping in solving this issue. In particular, we evaluate the impact in terms of carbon dioxide (CO_2) emissions of virtual traffic light (VTL), which is a recently proposed infrastructureless traffic control system solely based on vehicle-to-vehicle (V2V) communication. Our evaluation uses a real-city scenario in a complex simulation framework, involving microscopic traffic, wireless communication, and emission models. Compared with an approximation of the physical traffic light system deployed in the city, our results show a significant reduction on CO_2 emissions when using VTLs, reaching nearly 20% under high-density traffic.**

***Index Terms*—Carbon dioxide (CO_2) emissions, fuel consumption, vehicular ad hoc networks (VANETs), virtual traffic lights (VTLs).**

I. Introduction

GLOBAL warming and climate change have impacted the policy scene for the implementation of measures toward low-carbon resource-efficient economies. Decarbonization of the transport sector is particularly important, because in the European Union (EU), this sector accounts for around 25% of total carbon dioxide (CO_2) emissions, according to a study of the European Environment Agency (EEA) [1]. This same study also reports that car journeys comprised 72% of all passenger kilometers in EU-27 (excluding Cyprus and Malta) and have clearly represented the dominant mode of transport over the past few decades. One aggravating factor is the ever-increasing traffic levels that have neutralized the average emissions reduction per vehicle obtained due to the design of more efficient vehicles.

In parallel with the effort to develop more efficient and environmentally friendly vehicles, the design of mechanisms that improve the efficiency of road utilization, i.e., real-time traffic information systems and collaborative routing systems [2], [3], highway platooning [4], or adaptive traffic signal control [5], [6], can produce substantial additional benefits toward the reduction of the carbon footprint of road transportation. In the critical fraction of CO_2 g/km, we argue that more emphasis should be put on the *mechanics* of how each kilometer is traveled, including the route choice and the traffic control signage that is in place. In-vehicle intelligent transportation system (ITS) technologies will play a key role in this more efficient utilization of the road as we witness the inclusion of routing engines and traffic signs as in-vehicle systems.

Aside from improving safety and road network efficiency, we argue that ITS measures lead to significant improvements in terms of environmental impact. Thus, evaluating and quantifying the impact of such technologies in terms of CO_2 emissions is very important and can eventually lead to its integration in the assignment of the emissions value of new cars, which is relevantly reflected in the final price/yearly taxes and can contribute to a more rapid dissemination of such technologies.

In this paper, we focus on the evaluation and quantification of the impact in terms of CO_2 emissions of the recently proposed concept of virtual traffic lights (VTLs) [6], where the traditional road-based physical traffic signals are replaced by in-vehicle representations, supported only by vehicle-to-vehicle (V2V) communication. Our main goal is to provide evidence of the significant reductions in average network emissions that can be obtained through a novel ITS technology enabled by vehicular ad hoc networks (VANETs). Furthermore, we aim at providing a methodology and an associated simulation platform to study the environmental impact of any ITS measure.

The remainder of this paper is organized as follows. In the next section, we briefly present the relevant related work in traffic signal control and the environmental impact of ITS measures. Then, Section III introduces the VTL concept and the system main characteristics. Section IV provides an overview on the main system models, i.e., emissions and fuel consumption (see Section IV-A) and the microscopic traffic model (see Section IV-B). Section V presents a methodology for evaluating carbon emissions and the impact that the VTL system has on their mitigation. Section VI details the simulation scenario and evaluation metrics and provides the main results (individual and aggregated). Section VII closes this paper with the main conclusions.

II. Related Work

A. *Traffic Signal Control*

Traffic signal control has attracted much attention from the research community over the past few decades. Classical

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control concepts assume a cyclic operation of traffic signals, where the flows of different directions are periodically served [7]. The main control strategies can broadly be categorized into static and adaptive control.

Static control strategies, also commonly called pretimed, run precomputed and fixed signal plans. Signal plans are determined by using historical data to infer the best parameters (e.g., green split) for each intersection. However, pretimed control cannot respond to real-time traffic variations and often results in inefficient utilization of intersection capacity [8].

On the other hand, adaptive control strategies change signal plan in adaptation to the varying traffic conditions. Intelligent systems use basic sensors and optimization algorithms to increase traffic flow, whereas other systems use more complex technology to gather more information for the traffic signal to make a decision [9]. Systems such as the Split Cycle Offset Optimization Technique (SCOOT) [10] or the Sydney Coordinated Adaptive Traffic System (SCATS) [11] make use of detectors placed in the vicinity of intersections to adapt to variations in the traffic demand.

The advent of VANETs made possible a variety of new strategies that leverage on V2V and vehicle-to-infrastructure (V2I) communications. Additional and more precise information (e.g., vehicle speed and position) on each vehicle can be exchanged among vehicles or with a centralized control unit. On the most simple setting, the traffic signal periodically broadcasts its scheduling information over the wireless medium to vehicles in its vicinity [12]. In [5], the authors describe an adaptive traffic signal control system based on wireless communication between vehicles and a controller node placed at the intersection; control delay and queue length metrics are exchanged using a VANET data-dissemination platform. Cai *et al.* propose a dynamic programming algorithm, using vehicle speed, position, and waiting time as state variables [13]. In [14], a distributed multi-agent-based approach is adopted to develop a traffic-responsive signal control system. The adaptive behavior of this type of systems uses the information of vehicles (e.g., speed and position) that can thus overcome the shortcomings of traffic signal control systems based on detectors placed at fixed locations. The stop-or-go message is conveyed to drivers through the traditional road-based lamp.

B. Environmental Impact of ITS Measures

Past research work on ITS had improving safety and road network efficiency as the main objectives. However, the evaluation of the environmental impact and the inclusion as a metric in algorithms are currently aspects of major importance. For instance, in [15], the environmental benefits of car sharing have been studied in North America. The authors have concluded that car sharing reduces the overall annual pollutant emissions and the average distance traveled significantly declined, although more individuals have access to automobiles.

Bell qualitatively and quantitatively demonstrated in [16] how vehicle technologies and ITS have a role to play in reducing the impact of traffic on the environmental and health. The paper specifies a set of measures, i.e., traffic signal control, demand management, road pricing, speed limits, traffic calming, and vehicle control systems, to achieve this goal. In [17] and [18], the authors acknowledged the importance of the driver behavior on fuel consumption and associated pollutants emissions and proposed eco-driving schemes or incentive systems that decreased fuel costs and pollutant emissions. Recently, in [19], Tsugawa and Kato have presented and discussed various ITS approaches for significant energy savings and emission mitigation demonstrated by field or experimental data. The authors have concluded that vehicular communications play an essential role not only in safety but in energy savings as well [19]. However, in these papers, the most recent work on traffic signal control strategies, as well as the related environmental performance, is not considered.

In [5], the authors describe an adaptive traffic signal control system based on V2I communications. The authors demonstrated that their strategy based on the optimization of green phases outperformed the classical method (pretimed); delay is decreased by 28%, and pollutant emissions are decreased by up to 8.9% (6.5% for CO_2 emissions). However, the strategy was evaluated only to a single intersection.

Tielert *et al.* assessed in [12] the environmental gains of the traffic-light-to-vehicle communication (TLVC) application. For this specific application, key influencing factors on pollution emissions are gear choice and the information distance to obtain an efficient speed adaptation. Although single-vehicle analysis presented large improvements in terms of pollutant emissions, road-network-wide simulation yields a reduction in fuel consumption of only up to 8% [12]. Furthermore, to evaluate the environmental impact of TLVC, modeling the communication aspect as a fixed information distance was considered sufficient [12].

In [20], Sommer *et al.* analyze the environmental impact of the proposed dynamic rerouting algorithm and the traditional metric *travel time*. The authors demonstrate that the optimization of these metrics can be conflicting in some situations. If only the travel time will be used in the optimization process of ITS, emission metrics are often suboptimal [20].

III. Virtual Traffic Light

The road network has become ubiquitous such that, in the conterminous U.S., for example, we can get no farther from a road than 35 km [21]. It is geometrically unavoidable that these millions of kilometers of roads meet at some points, forming road junctions of different topologies. Based on the 2009 Tiger/Line data [22], it was computed that the number of intersections in the U.S. amounts to approximately 50 million [6]. In terms of traffic flow, these junctions constitute critical points, which are the subject of a vast amount of research toward its optimization. This optimization can either be based on a topological/geometrical approach (through grade separation or roundabout design, e.g., [23]) or on a signalization approach, particularly through intelligent traffic signals (e.g., [24]).

In this paper, we focus on the role of VANETs for the optimization of road intersections based on intelligent traffic signals. One common aspect to all the strategies presented in Section II-A is the utilization of fixed infrastructure to support the operation of intelligent traffic control strategies.

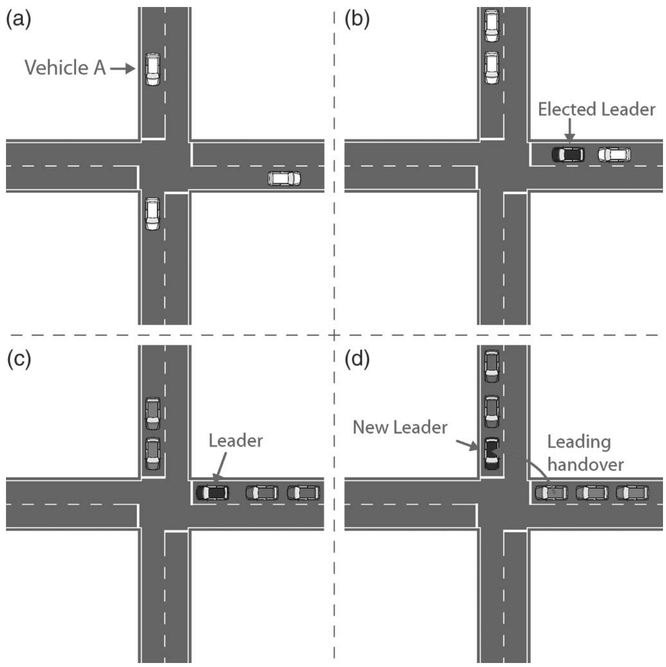

Fig. 1. (a) Conflict-free intersection. Vehicle A uses periodic beaconing to advertise its position and heading as it approaches the intersection. No conflicts are detected, and it is not necessary to create a VTL. (b) Periodic beaconing of concurrent vehicles results in the detection of a crossing conflict and in the need to create a VTL. One of the conflicting vehicles is elected as the intersection leader and will create and control the VTL. This leader stops at the intersection and replaces a road-based traffic signal in a temporary control of the intersection. (c) Leader is stopped at the intersection and optimizes the functioning of the VTL based on the number of vehicles in each approach and periodically broadcasts VTL messages with the color of each approach/lane. (d) When the cycle ends and the green light is assigned to the leader approach/lane, the current leader selects a new leader from the vehicles stopped under red lights. This new leader continues the cycle. If there are no stopped vehicles under red lights, then the VTL ceases to exist.

Furthermore, many of these strategies assume the existence of a centralized control unit[1] and cyclic operation. In this paper, we propose a new paradigm, called VTL, in which control is decentralized and self organized, operation is acyclic, and traffic signal information is individually and directly presented in each vehicle. In our system, vehicles behave as sensors in the road transportation network.

In [6], we presented the VTL concept, advocating for a paradigm shift from traffic signals as road-based infrastructures to traffic signals as in-vehicle virtual signs supported only by V2V communication. The implementation of the VTL system results in improved traffic flow due to the optimized management of individual intersections, which is enabled not only by the neighborhood awareness of VANET protocols but due to the scalability of the solution as well, which renders signalized control of intersections truly ubiquitous. This ubiquity allows us to maximize the throughput of the complete road network rather than the reduced number of road junctions that are currently managed by physical traffic signals.

The principle of operation of VTLs is relatively simple and is illustrated in Fig. 1. Each vehicle has a dedicated application unit (AU), which maintains an internal database with information about intersections where a VTL can be created. When approaching such intersections, the AU checks whether there is a VTL running that must be obeyed or a VTL needs to be created as a result of perceiving crossing conflicts between approaching vehicles [see Fig. 1(a) and (b)].

[1]A decentralized signal control strategy has recently been proposed by Laemmer and Helbing in [7].

Beaconing and location tables, which are features of VANET geographical routing protocols (for example, see [25]), are used to determine whether a VTL needs to be created. Each node maintains a location table that contains information about every node in its vicinity, which is constantly updated through the reception of new beacons. The periodicity of these beacons can be increased as vehicles approach an intersection.

If a VTL needs to be created, then all vehicles that approach the intersection must agree on the election of one of the vehicles as the *leader*, which will be responsible for creating the VTL and broadcasting the traffic signal messages [see Fig. 1(c)]. This vehicle works as a *temporary virtual infrastructure* for the intersection and takes the responsibility of controlling the VTL. Once this leader has been elected, a VTL cycle for the intersection control is initiated with a red light for the leader approach/lane. This condition ensures that the leader will remain in the intersection for the duration of a complete cycle. Based on the number of vehicles in each approach, the leader can set the traffic signal parameters, such as the phase layout and the green splits assigned to each approach, in an optimized manner. During the existence of a VTL *leader*, the other vehicles act as passive nodes in the protocol, listening to traffic signal messages and presenting these messages to the driver through the in-vehicle displays.

During a complete VTL cycle, the leader commutes the traffic light (TL) phase among the conflicting approaches/lanes. When the green light is in the leader's lane, the control of the VTL system must be handed over to a new leader in a different approach/lane. If there are vehicles that stopped under the red light at the intersection, the current leader selects one of these vehicles to become the new leader, which will maintain the intersection control in a consistent sequence [see Fig. 1(d)]. If there are no stopped vehicles under the red light, then a new leader will be elected through the previously explained process whenever necessary. Fig. 2 depicts the principle of the operation of the VTL system in terms of stages.

In a primal paper, where the VTL concept was presented, the dynamic performance of the system has also been studied. The selected mobility metric was the average increase in flow rate of the VTL protocol versus the real physical traffic signals as a function of vehicle density. Large-scale simulations that emulate a real dense urban scenario provided compelling evidence on the viability and significant benefits of the proposed scheme in terms of the mobility metric (up to 60% increase at high densities). This new self-organizing traffic paradigm thus holds the potential for revolutionizing traffic control, particularly in urban areas [6].

The interaction between vehicles and pedestrians also needs to be considered. The most direct and traditional approach that could be foreseen is the communication of the traffic signal information to pedestrians through smart phones or simple road infrastructure. The virtual indication of traffic signals by the leading vehicle is also proposed.

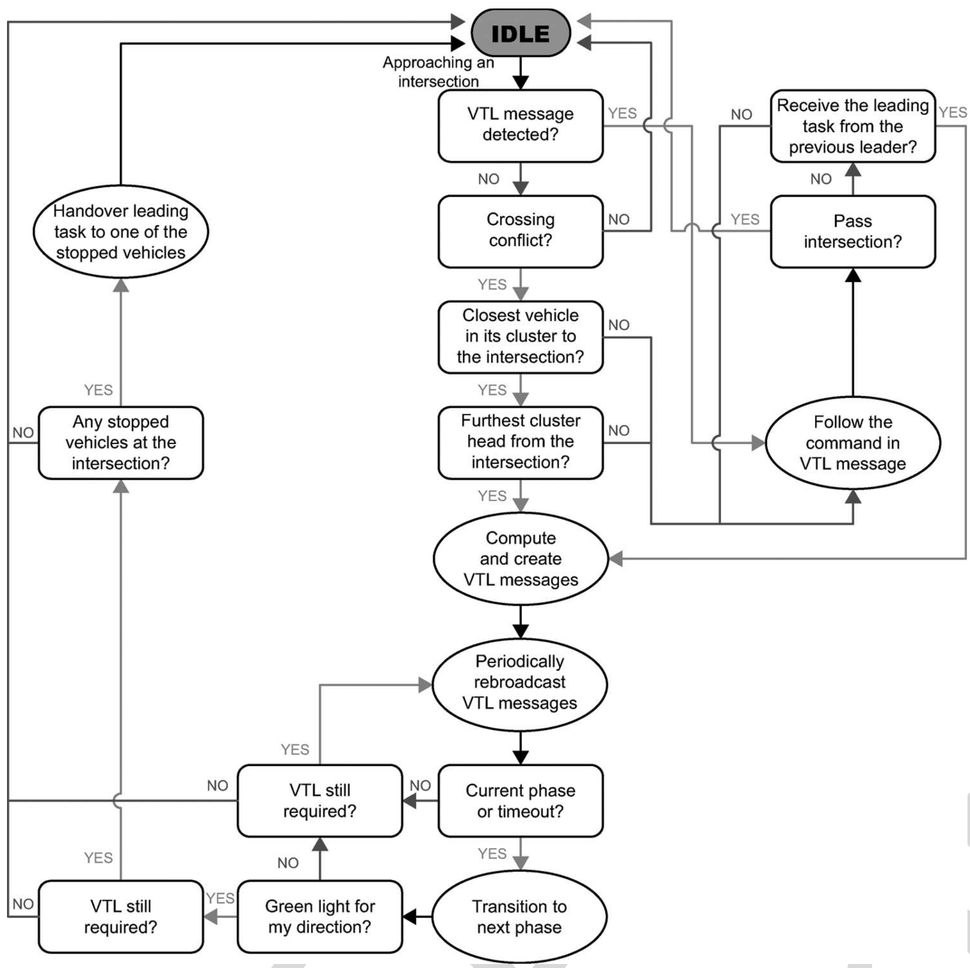

Fig. 2. VTL phase diagram.

An immediate effect of the shift of paradigm of traffic signals as road-based infrastructures to in-vehicle virtual signs is the elimination of physical traffic signals from roads. According to [26], in 1998, 3.25 million traffic lamps were approximately permanently lighted in the road infrastructure of the U.S. based on an estimated number of 260 000 signalized road junctions. We estimate that the electric power consumption of TLs in the U.S. can total an amount around 2 million MW · h/year, which is equivalent to 1.2 million metric tons of CO_2 per year according to [27]. Although this value is significant, it is almost irrelevant when considering the total emissions of personal vehicles in the U.S., which emit around 300 million metric tons of CO_2 per year [28]. VTLs, on the other hand, enable the universal deployment of semaphore-based control on the intersections of the road network, with virtually no impact on energy consumption or carbon emissions.[2]

IV. System Models

A. Emissions and Fuel Consumption Model

Emission models can broadly be categorized into macroscopic, mesoscopic, and microscopic models. Macroscopic models estimate pollutant emissions and fuel consumption mainly based on the average travel speed of the traffic flow. These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions [29], which leads to reduced accuracy in calculations. Moreover, these models cannot capture individual speed fluctuations and cannot take into account individual operation conditions, which are of crucial interest when analyzing a proposal that considers network and vehicle dynamics. Mesoscopic models (e.g., [30]) use more disaggregate trip variables, such as the average speed, the number of stops, and stopped delay, to estimate a vehicle's emission rates on a link-by-link basis. Some regression models that were developed were found to predict fuel consumption and emission rates of hydrocarbons (HC), carbon monoxide (CO), and NO_x to within 88%–90% of instantaneous microscopic emission estimates [31].

Microscopic emission models overcome some of the limitations of large-scale macroscopic models mainly by considering individual vehicles dynamics and their interactions. Emissions and fuel consumption are estimated based on instantaneous individual vehicle variables that can frequently be obtained (e.g., second by second) from a microscopic traffic simulator or another alternative source [e.g., the Global Positioning System (GPS) data logger]. Commonly, these parameters are divided into the following two categories: 1) vehicle parameters and

[2]The low-power consumption of in-vehicle semaphores and associated V2V communications could resort to energy recovery mechanisms from the kinetic energy of vehicles to power the electrical systems.

2) traffic/road parameters. Vehicle parameters include, among others, vehicle mass, fuel type, engine displacement, and vehicle class. On the other hand, network parameters (traffic and road conditions) account for instantaneous vehicle kinematics (e.g., speed or acceleration), aggregated variables (e.g., the time spent in the acceleration mode), or road characteristics (e.g., road grade). Because microscopic emission and fuel consumption models have higher temporal precision and better capture the effects of vehicle dynamics/interactions, they are better suited to evaluate the environmental gains derived from an ITS measure, such as the VTL system.

Several microscopic models have been proposed by the scientific community. These models can be classified into emission maps (speed/acceleration lookup tables), purely statistical models, and load-based models [32]. Major contributions in this field were given by Akcelik *et al.* [33], Barth *et al.* [34] with the comprehensive modal emission model (CMEM), Ahn *et al.* [35], and Cappiello *et al.* [32] with the emissions from traffic (EMIT) model. The latter model has been selected due to computational performance and accuracy reasons. EMIT is a simple dynamic emission model that was derived from statistical and load-based emission models.

This model first estimates the instantaneous tractive power (P_{tr}) using (1), which has the vehicle velocity v (in meters per second) and acceleration a (in square meters per second) as the main parameters

$$P_{tr} = A \cdot v + B \cdot v^2 + C \cdot v^3 + M \cdot a \cdot v + M \cdot g \cdot \sin\vartheta \cdot v \qquad (1)$$

where the variables are defined as follows:

- A rolling resistance (in kilowatts per meter per second);
- B speed correction (in kilowatts per square meter per second);
- C air drag resistance (in kilowatts per cubic meter per second);
- M vehicle mass (in kilograms);
- g gravitational constant (in square meters per second);
- ϑ road grade (in degrees).

Depending on the value of P_{tr}, the fuel rate (FR) can be expressed as

$$FR = \begin{cases} \alpha_i + \beta_i v + \gamma_i v^2 + \delta_i v^3 + \zeta_i a v, & \text{if } P_{tr} > 0 \\ \alpha_i', & \text{if } P_{tr} = 0 \end{cases} \qquad (2)$$

where α_i, β_i, γ_i, δ_i, and ζ_i are constants that are associated with individual vehicles that were obtained using ordinary least square linear regressions.

The EMIT model allows us to simultaneously calculate several pollutant emissions subproducts, i.e., CO, CO_2, HC, and nitrogen oxide (NO). This calculation is divided into the following two main phases: 1) engine-out (EO) and 2) tailpipe (TP). The following formula for calculating EO pollutant emissions has the same structure as (2) due to the linear relationship with FR:

$$EO_i = \alpha + \mu \cdot FR \qquad (3)$$

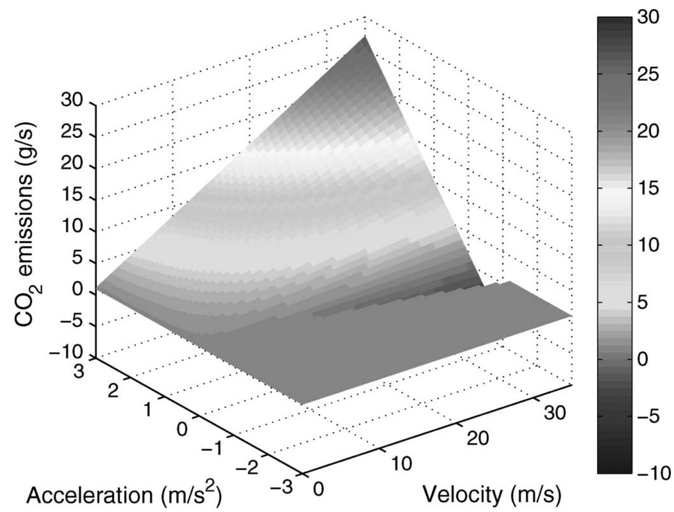

Fig. 3. CO_2 emissions surface as a function of the vehicle acceleration and velocity; increasing values for this metric lead to increased CO_2 emissions. The EMIT model can produce negative values.

CO_2 is the main by-product of the combustion of fossil fuels,[3] and consequently, it is proportional to the FR. The values of CO_2 EO emissions are directly estimated from fuel consumption estimates. Due to this linear relationship, the terms FR or CO_2 can interchangeably be used when analyzing the environmental impact of an ITS technology. Fig. 3 depicts the CO_2 emissions surface for a given input parameter set (acceleration and velocity) with a resolution of 0.1 (m/s^2 and m/s, respectively). Note that negative values for CO_2 can be obtained with the EMIT model. This problem was addressed by considering a minimum value for the emissions that is equal to the constant α_i' when P_{tract} is equal to zero.

After estimating the EO emission for the subproducts of combustion, the EMIT model calculates the TP emission rates. This emission rate is a fraction of the EO emission rate that leaves the catalytic converter, i.e.,

$$TP_i = EO_i \cdot CPF_i \qquad (4)$$

where CPF_i denotes the catalyst pass fraction for species i.

The calibration of the parameters of (1) and (2) resorted to light-duty vehicle data that were gathered for CMEM. Because our goal is to evaluate the relative benefit of the VTL technology, we consider the same coefficients for all vehicles that are used in this paper. These parameters are shown in Table I and are based on the values available from the EMIT model [32] (vehicle category 9).[4]

B. Microscopic Traffic Model

To test the feasibility and performance of VANET-based applications, a simulation platform is required to simulate vehicular ad hoc environments. The simulation-based evaluation

[3] Although, in this paper, we mainly assess CO_2 emissions, which is the main by-product of fossil fuels combustion, other subproducts could be evaluated due to their relative importance, particularly at intersections due to the stop-and-go phenomenon.

[4] The definition of each vehicle/technology category of the modal emissions model can be found in [36]. Vehicle category 9 represents a normal emitting car (Tier 1 emission standard), with accumulated mileage greater than 50 000 miles and high power/weight ratio.

TABLE I
EMIT MODEL PARAMETERS

Factor	Value	Unit
A	0.1326	$kW/m/s$
B	2.7384e-3	$kW/(m/s)^2$
C	1.0843e-3	$kW/(m/s)^3$
M	1.3250e-3	kg
g	9.81	m/s^2
ϑ	0	$degrees$
α_i	1.1	g/s
β_i	0.0134	g/m
γ_i	-	$g\ s^2/m^2$
δ_i	1.98e-6	$g\ s^2/m^3$
ζ_i	0.2410	$g\ s^2/m^2$
$\alpha_i^{'}$	0.973	g/s

of VANET protocols requires a network simulator (NS-3) and a road traffic microscopic simulator [Development of Intervehicular Reliable Telematics (DIVERT)]. DIVERT [37], [38] is a sophisticated microscopic simulator based on the intelligent driver model (IDM) [39] with a validated mobility model [40]. The lane-changing model is based on the MOBIL model proposed by Treiber *et al.* in [41]. The mobility patterns are individually influenced by random initialization, within typical values, of attributes such as acceleration, braking, aggressiveness, and risk tolerance [37]. The current mobility model does not account for vehicle speed adaptation based on the received information (e.g., driver reaction to traffic signal controller timing information) as done in [42]. The implementation includes all the common features of a road transportation network (e.g., traffic signals). It allows the simulation of thousands of vehicles with a high degree of realism [38] and with a wide range of configurations (e.g., aggressiveness). NS-3 is a discrete-event network simulator for Internet systems, primarily targeting research and educational use [43]. Several radio access technologies (e.g., IEEE 802.11p), as well as multiple interfaces/channels features and various protocol modules, can be used. In [44], the authors conclude that NS-3 delivers the best overall performance.

The need for a bidirectional coupling of these two components (network and traffic) is fundamental and has been discussed in [45]. Clearly, the mobility of vehicles affects the network connectivity and behavior. Conversely, the results of the network simulation component can also affect the mobility of vehicles. In the case of VTL, this bidirectional coupling is particularly microscopic in both directions. Detailed mobility information (e.g., the position, speed, and heading of each vehicle) needs to be fed to NS-3, which has been coupled with DIVERT [38] to simulate the beaconing, leader election, and virtual light messages in the context of the VTL protocol. Traffic signal information, which results from the exchange of messages of the VTL protocol emulated by NS-3, is provided to the DIVERT simulator; the individual mobility of each vehicle is affected by the regulatory messages conveyed by the VTL (e.g., stop at a given intersection).

V. METHODOLOGY

Our goal is to quantify the impact of the VTL technology on CO_2 emissions mitigation. We should thus analyze CO_2 emissions of vehicles that interact with physical traffic signals and compare the results with the CO_2 emissions of vehicles that use VTLs. To isolate the benefit of the VTL approach, each of the alternatives for intersection control should have identical settings in all possible *static* variables, including the characteristics of vehicles and drivers, the road scenario, and the routes. The differences in the two analyses result from a different mobility behavior of each vehicle that is affected by *dynamic* aspects, which correspond to different traffic conditions due to alternative schemes of intersection control.

To perform these two analyses, the aforementioned EMIT emissions model was integrated into a microscopic traffic simulator. The microscopic traffic simulator outputs the mobility behavior of each vehicle in the form of a virtual GPS trace. By processing this GPS trace, a set of variables can be derived, such as acceleration and speed, which then feed the microscopic emissions model. The emissions of each vehicle are then aggregated to quantify the overall positive impact of the VTL system. Fig. 4 illustrates this architecture and its main components. The main component of the simulation-based evaluation of the decarbonization impact of VTLs is the DIVERT microscopic traffic simulator [37].

The implementation of physical TLs and VTLs in DIVERT is relatively simple and leverages on the car-following equations included in the IDM [39] that affect the acceleration and deceleration patterns of each vehicle. In terms of mobility simulation, physical and virtual traffic signals are identically implemented in DIVERT. For each lane of an approach to an intersection, the traffic simulator creates a temporary dimensionless vehicle on the stop line associated with the lane. This dimensionless vehicle is created under a red light and disappears under a green or yellow light. Variable aggressiveness parameters of each driver result in different behaviors under yellow lights as a function of the distance to the stop line. The intermittent creation of this dimensionless vehicle is thus mandated by the traffic signal control system or the VTL protocol (see Fig. 4) and transparently affects the mobility of vehicles based on the car-following model that governs the acceleration and deceleration variables.

The differences in the two instances of DIVERT illustrated in Fig. 4 refer to the geographic location of physical TLs and VTLs and to the method used to derive the TL color shown to each vehicle. With regard to the geographic location of physical traffic signals, we have replicated the existing deployment in the city of Porto, Portugal. The implemented physical-TL approach is also a loyal representation of the existing scenario. In the current version of DIVERT, the traffic signal control system is very simple and uses fixed green splits for each of the approaches of an intersection. Such simplistic functioning is, however, a good approximation of the current functioning of most of the deployed traffic signals. A recent study has reported that 70%–90% of the deployed traffic signals work under fixed parameterization of cycle duration and green splits [46].

The geographic location of VTL is not fixed and is determined by traffic conditions in confluent approaches of an intersection. Depending on the traffic density, such virtual traffic signals can be present at all intersections or can be almost nonexistent. Instead of the data from fixed traffic

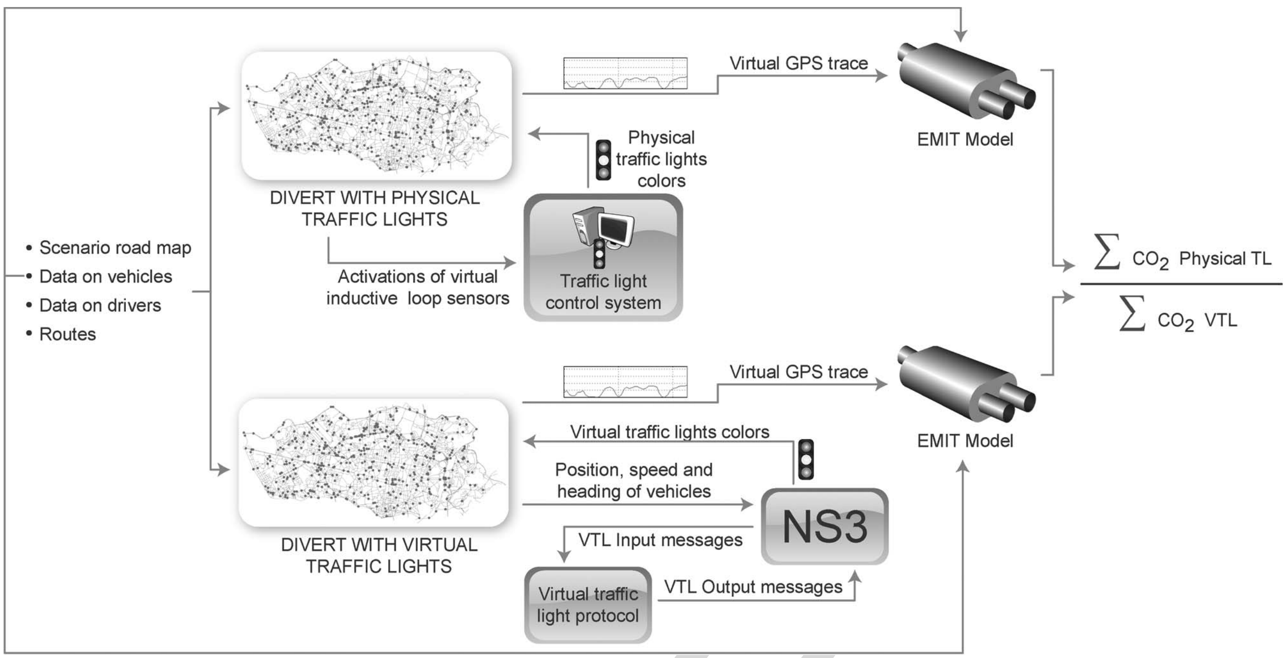

Fig. 4. Evaluation architecture. The main component is the DIVERT microscopic traffic simulator, whose two instances are used to produce virtual GPS traces. The scenario road map, data on vehicles and drivers, and the route of each vehicle are fed to an instance of DIVERT with physical traffic signals and to another instance where the VTL protocol is simulated. The simulation of the network layer of the VTL protocol is done by NS-3. The virtual GPS traces are then fed to two instances of the EMIT model to compute and compare the aggregated values of CO_2 emissions.

counters, the optimization of cycle duration and green splits of a VTL resorts to more complete information, which includes the position, speed, and heading of all vehicles that approach the intersection. This information is provided by DIVERT, and the simulation of its beaconing by each vehicle is done by NS-3. Leader election and the virtual light messages that are broadcast by the leader are also simulated in NS-3 and provide the traffic signal colors that are shown to each vehicle in DIVERT.[5]

VI. Results and Discussion

The results and analysis presented here are based on the system models given in Section IV and follow the methodology provided in Section V (see also the framework depicted in Fig. 4). The two strategies (physical TL and VTL) are compared with making use of the simulation platform in a large-scale scenario (see Section VI-A) and a number of performance metrics (see Section VI-B). First, individual vehicle dynamics are studied (see Section VI-C). To determine the overall benefit that arises from the implementation of the VTL system, individual outputs are consolidated (see Section VI-D).

A. Simulation Scenario

To give scale to the analysis of the benefits of VTLs, we evaluate the carbon emissions of vehicles in the road scenario of an entire city. The city of Porto, Portugal, which is the second largest in the country, spans an area of 41.3 km^2 and has a road network that comprises 965 km. Due to a recent stereoscopic aerial survey over the city, where the location of all moving vehicles was pinpointed and their traveling speeds were derived, together with the inference of a 5-s route [40], realistic traffic data are available for Porto. In the aerial survey, a total of 10 566 vehicles were pinpointed. The observed distribution of vehicles per road segment was used to (decrease) increase density to (non)rush-hour values to evaluate the impact of VTL under different conditions. In this paper, the following four different densities of vehicles that move in the city of Porto are then considered:

1) 24 veh/km^2 (low);
2) 120 veh/km^2 (medium-low);
3) 251 veh/km^2 (medium-high);
4) 333 veh/km^2 (high).

With regard to the route of each vehicle, random origin/destination pairs that are based on the observed distribution of vehicles from the aerial survey are generated. We evaluate mobility propagation using wireless transmission ranges of 150–250 m, as defined in [40]. In this paper, stereoscopic aerial photography was used to model urban mobility to compute connectivity and path availability. Communication is mostly direct (one-hop communication) between the leader and vehicles in the vicinity of an intersection.

The road network of the city of Porto has a total of 1991 intersections. Physical TLs control 328 of these 1991 intersections (16%). Fig. 5 depicts the road network, the location of signalized intersections, and one example route followed by a vehicle.[6] Each scenario was evaluated for a period of 30 min.

[5]Videos that show the principle of operation of the VTL system are available at http://www.dcc.fc.up.pt/hc/vtl_porto.avi} and http://www.dcc.fc.up.pt/hc/vtl_complex.avi.

[6]A zoomable webmap that shows the road network, the location of signalized intersections, and the position of vehicles from the aerial survey is available at http://drive-in.cmuportugal.org/porto/.

Fig. 5. Road network of the city of Porto comprises 965 km of extension. The red dots display the location of the 328 intersections that are managed by physical traffic signals. The blue line represents an example of a route traversed by a vehicle in this paper.

B. Performance Metrics

To demonstrate the benefits of the VTL system, a number of variables need to be analyzed. In [6], the impact on the traffic flow of VTL was evaluated for the same scenario of the city of Porto. Results have shown an increase of up to 60% in flow rate for high-density scenarios. Here, we want to analyze the environmental impact of VTL, comparing the individual and aggregated CO_2 emissions of vehicles that travel the exact same number of kilometers on the exact same roads, with and without the VTL system.

For this analysis, the definition of each variable, application domain, whether for individual vehicle analysis or aggregated investigations, and unit is given as follows:

- *Instantaneous* CO_2 *emissions* $E^i_{CO_2}$ (individual; in grams per second): Calculated for vehicle i using (2) after knowing the outcome of (1) with appropriate coefficients (see Table I);
- *Route* CO_2 *emissions* (individual; in grams): cumulative sum of an individual vehicle CO_2 emissions for its complete route;
- *Average* CO_2 *emissions per vehicle* (aggregated; in grams): defined as

$$\frac{\sum_{t=0}^{end} \sum_{i}^{n_{cars}} E^i_{CO_2}}{n_{cars}} \tag{5}$$

where t iterates over the seconds of the simulation, and i iterates over all the individual cars.

C. Individual Vehicle Results

Before analyzing the aggregated results of CO_2 emissions for all vehicles in the city of Porto scenario, we analyze the relevant variables for an individual vehicle, highlighting important differences between a route traversed with the VTL system and with the deployed physical-TL system. This preliminary analysis using a single vehicle gives some intuition about the understanding of the aggregated results.

The vehicle that was selected for the current analysis traversed the city following a route (see Fig. 5) that combines a major arterial road and a dense urban area with permanent intersection conflicts, which clearly have distinct characteristics and can lead to different performance. In this paper, medium traffic density is considered (190 vehicles/km^2). Although this overall density is the same with TL and VTL, the distribution of vehicles can be very different as a result from the distinct traffic control schemes.

Fig. 6 depicts the main variables (velocity, acceleration, instantaneous CO_2 emissions, and route CO_2 emissions) for TL (in blue continuous lines) and VTL (in red dashed lines). The variables velocity and acceleration were obtained from the virtual GPS logger. Observing these variables, it is evident that, without the VTL system, the car remained stopped for longer periods mainly due to the semaphored intersections and increased congestion. This fact is particularly evident when the vehicle enters the city center area, which contains a higher density of physical traffic signals and of vehicles. The ubiquity of the VTL solution also led to faster intersection conflict resolution and contributed to congestion dissipation. Another interesting fact is that, with the TL system, the car takes approximately more than 25% of the time to travel the same route for this traffic density. Stated otherwise, the average velocity of the vehicle with the VTL system is considerably increased compared with the physical-TL system.

Observing the graphic of the instantaneous CO_2 emissions depicted in Fig. 6, the correlation between this output and the velocity/acceleration metrics is evident. Increasing acceleration/velocity values leads to increasing instantaneous pollutant emissions. On the other hand, a stopped vehicle has a constant emission rate. The instantaneous emissions cannot directly be

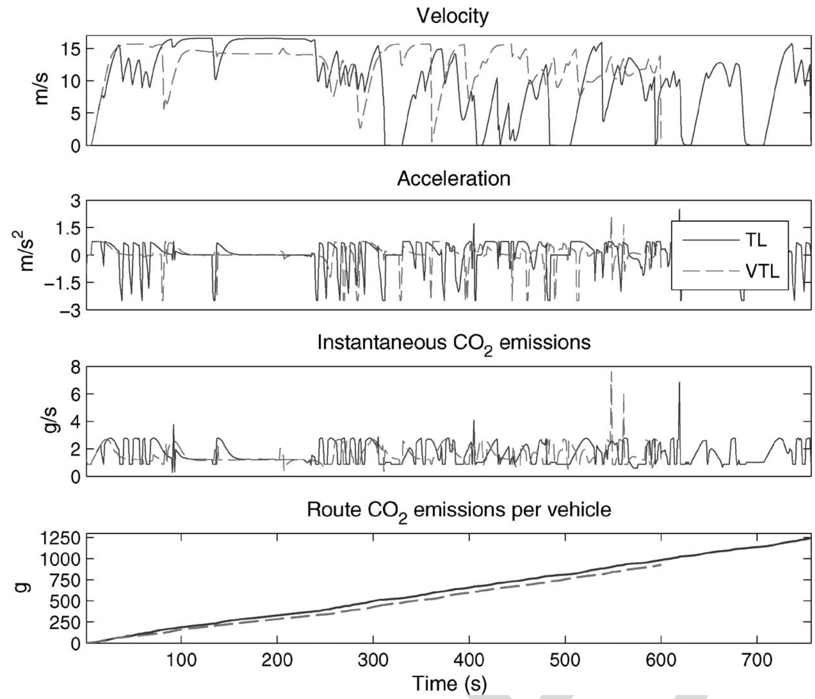

Fig. 6. Individual vehicle metrics comparison [velocity, acceleration, instantaneous CO_2 emissions, and cumulative CO_2 emissions for the traversed route (medium vehicle density)]. The same vehicle traverses the exact same route with and without the VTL system. Differences in all metrics are evident. In addition, note that this particular vehicle takes less than half the time to complete its route with the VTL system.

compared between physical TLs and VTLs, because they happen at different locations of the route. The relevant comparison is the cumulative route CO_2 emissions, which highlights the impact of the implementation of the VTL. Observing this metric, it is clear that the overall number of stops during the route, as illustrated by the vehicle's acceleration and deceleration levels, has a significant impact on vehicle emission rates [47]. For the example route, the cumulative fuel consumption is reduced by approximately 25%, mainly due to the increased traffic flow and consequent less transportation congestion, as well as the ubiquity of the VTL solution, which can detect the existence or not of intersection conflicts.

D. Aggregated Results

Apart from investigating the benefits for individual vehicles, the performance of the VTL system was evaluated by considering all the vehicular interactions that take place in the complete transportation network. To perform this study, the individual pollutant emissions values are aggregated for each simulation to determine the metric average CO_2 emissions per vehicle. This metric is widely used to determine the environmental impact of ITS. Furthermore, it is a referenced measure, which allows direction comparison of results in scenarios with different traffic flows.

To make statistical inference, a number of observations of the system (eight simulation runs for each traffic density) were performed, followed by a statistical analysis to obtain an estimate of the selected performance metric. The mean of the metric *average* CO_2 *emissions per vehicle* is the estimated parameter, and 95% confidence intervals for the estimator are considered in this paper.

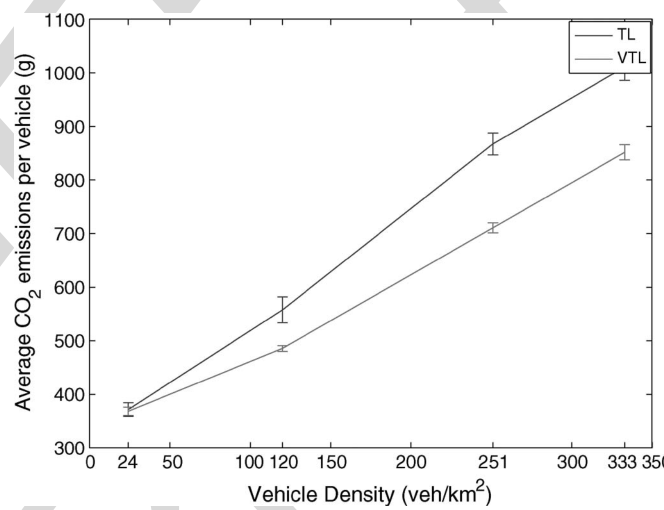

Fig. 7. Aggregated vehicle metric for TL and VTL comparison, given different vehicle densities. This graphic highlights the increased impact of VTL as traffic density becomes higher. Confidence intervals are depicted for each vehicle density and traffic control strategy (TL or VTL).

Fig. 7 represents the selected metric in the TL and VTL scenarios and considers vehicles densities that range from low density to high density. In both scenarios, with the increase of the vehicle density, the average CO_2 emissions per vehicle increase. As the density increases, intersection conflicts become more frequent, which causes increased congestion. Increased congestion leads to the stop-and-go phenomenon, which is associated with constant accelerations and decelerations that are one of the main causes of pollutant emissions. For all vehicle densities, the average CO_2 emissions per vehicle are lower for the VTL case.

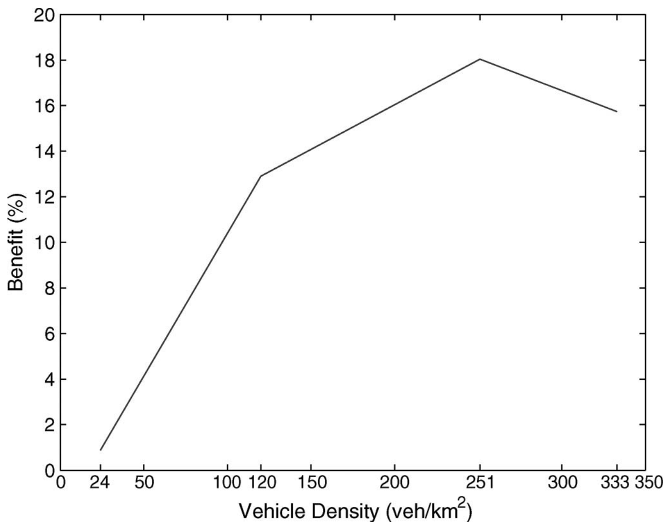

Fig. 8. Improvement in terms of CO_2 emissions due to the implementation of the VTL system in function of the vehicle density.

Fig. 8 depicts the percentage of improvement in terms of CO_2 emissions as a function of the vehicle density. The implementation of the VTL system is beneficial in terms of CO_2 emissions for all the traffic densities that were studied. In addition, as the car density increases, the mitigation in terms of CO_2 becomes more evident. For the selected vehicle densities, the benefit varies between 1% and 18%. Eventually, if we increase the densities to higher values (which are unrealistic for the capacity of the current traffic control system of the city), the benefit would start declining, as the theoretical capacity of the road network, independent of the intersection control scheme that is used, starts to be reached.

Note that there is also a significant increase on the average vehicle velocity between 26% (low density) and 41% (high density). In urban scenarios, however, this case does not lead to increased emissions, because the optimal cruising speed is never reached. The mitigation of carbon emissions occurs due to self-organized ubiquitous traffic control enabled by VTL. At high vehicle densities, the absence of traffic signals at intersections exacerbates the congestion problem, which leads to increased emissions in the physical-TL case. The results presented herein are in accordance with the results published in [6], where the vehicle traffic flow was studied.

VII. Conclusion

The advent of wireless intervehicle communication, which should be available in the near future, opens a variety of opportunities to increase the safety and efficiency of road utilization. With regard to efficiency, an important aspect of its optimization will involve the mitigation of pollutants emission to fight global warming and climate change. In this paper, we have addressed the evaluation of the environmental impact of a challenging application of intervehicle communication, called VTL. Such a system will have to overcome complex problems that are intrinsic to the critical control of the right of way of vehicles in an intersection through a distributed system based on wireless communications. In particular, VTLs face the hurdle of requiring 100% deployment in motorized vehicles to work. However, this penetration problem is a common issue for a variety of other V2V or V2I applications; safety-related applications are a main example that requires high penetration rates for effectiveness and are pushed forward for their evident advantages. Reaching this level of deployment requires governmental commitment to mandate the existing motorized vehicles to install VTLs as an after-market equipment.[7] To tackle this issue, studies must be performed to investigate whether changes can be made to the original VTL system to allow lower penetration rates and the coexistence with the current TL system.

In addition to the significant improvements in traffic flow that have been reported in the work of Ferreira *et al.* and to the increased safety of semaphore-controlled intersections, where accidents can be reduced by more than 30%, this paper has reported a reduction of 18% for the CO_2 emissions of a realistic number of vehicles that travel in a large-scale urban scenario when using the VTL system. Considering only the CO_2 component of the annual circulation tax that is in place in Germany, for example, 2€/g/km, would justify the cost of an after-market VTL system for any car owner.

This paper has been performed for internal combustion-engine vehicles. As further work, we plan to investigate the energy savings that arise from the implementations of ITS measures for hybrid or electric vehicles, which currently have limited autonomy. Furthermore, the simulator should be extended to include alternative emissions-modeling approaches and also modified to perform the calculation in real time of the energy/fuel consumption rather than postprocessing the information. This approach would allow testing innovative algorithms where parameters are changed online, depending on the current energy consumption or emissions. Another interesting topic to study in more detail is pedestrian–vehicle interaction and human–computer interaction.

The inclusion of urban traffic control (UTC) systems in simulation can provide additional insights into the intersection control problem. More specifically, the benefit of the VTL approach compared to such centralized control systems will be studied. In the city of Porto, such UTC systems have been deployed to control part of the traffic signals. We are currently integrating in our simulation platform a replication of the functioning of this UTC based on simulated inputs that correspond to activations of virtual inductive-loop sensors. This line of research involves joint work with the company that develops the UTC system to have a virtual replication of the system that mimics the exact behavior of the traffic signals that are in place in the city of Porto.

Acknowledgment

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[7]Electronic tolling systems and in-vehicle parking meters are examples of systems that have been the subject of legislation in some parts of the world.

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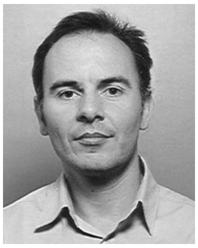

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