

Article

# A Single Intersection Cooperative-Competitive Paradigm in Real Time Traffic Signal Settings Based on Floating Car Data <sup>†</sup>

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**Abstract:** New technologies such as “connected” and “autonomous” vehicles are going to change the future of traffic signal control and management and possibly will introduce new traffic signal systems that will be based on floating car data (FCD). The use of floating car data to regulate traffic signal systems, in real time, has the potential for an increased sustainability of transportation in terms of energy efficiency, traffic safety and environmental issues. However, research has never explored how not “connected” vehicles would benefit by the implementation of such systems. This paper explores the use of floating car data to regulate traffic signal systems in real-time in a single intersection and in terms of cooperative-competitive paradigm between “connected” vehicles and conventional vehicles. In a dedicated laboratory, developed for testing regulation algorithms, results show that “invisible vehicles” for the system (which are not “connected”) in most simulated cases also benefit when real time traffic signal settings based on floating car data are introduced. Moreover, the study estimates the energy and air quality impacts of a single intersection signal regulation by evaluating fuel consumption and pollutant emissions. Specifically, the study demonstrates that significant improvements in air quality are possible with the introduction of FCD regulated traffic signals.

**Keywords:** traffic management; transportation sustainability; real time traffic signal settings; traffic simulation; cooperative intelligent transportation systems (ITS); ITS; traffic flow

## 1. Introduction

Co-operative intelligent transportation systems (C-ITS) can be used to share information between drivers and road management. Various co-operative systems have been proposed in Europe and have obtained research in funded projects, among them SAFESPOT [1], EuroFOT [2] and DRIVE C2X [3].

According to the European Commission traffic congestion costs are an important issue and road transportation accounts for more than 25% of the total energy consumption in the EU. Traffic signal regulation can be a major cause of delays in urban travelling and often, especially in Italy, traffic signals are regulated without adjusting them dynamically to real changing traffic conditions. Static signal plans adopted according to simple traffic surveys are extended to all other days and hours of the week resulting in great unnecessary delays for travellers.

Imperfect regulation of traffic lights sometime is perceived by drivers and can also cause the lack of respect for the rules (i.e., southern Italy); red-light running violations are also a serious problem in the USA [4]. In other countries like The Netherlands and Germany, traffic signals were, experimentally,

completely eliminated, showing that congestion was reduced and safety increased [5,6]. Cassini [7,8] also presents a fascinating case where traffic signals were installed improperly causing residents to protest, without success, until the moment the lights went off for a technical failure and the traffic jams magically disappeared.

While these experiences hint that regulating traffic signal systems properly is an important and actual problem, mobile internet coupled with Global Navigation Satellite System (GNSS) localization systems are creating disruptive innovations in the transportation sector. A real technical revolution has started, driven by the convergence of mobile internet, GNSS and the introduction of “connected” vehicles.

Intelligent Transportation Systems (ITS) can take advantage in the use of Floating Car Data (FCD) for managing traffic flow or to extract traffic flow parameters and many large scale deployments of such systems based on Floating Car Data (FCD) are already showing the use of mobile phones [9–12] and wireless communications [13,14] combined with GNSS technologies.

Smartphones (and connected vehicles) can obtain localization and speed information from GNSS systems such as Galileo, GPS and Glonass. GPS sensors embedded in smartphones provide an economical method to obtain vehicular travel times [15] and to evaluate traffic scenarios [16,17]. Smartphones also allow the estimation of traffic safety parameters [18] and route choices [19]. Mobile devices have also been used to assess safety and risks by insurance companies [20] and for traffic safety [21,22] and fuel consumption estimation [23].

Cooperative systems based on smartphones are spontaneously spreading in ordinary use (BlaBla Car, Uber, etc.). Cooperative systems based on smartphones for pedestrians and bicycles are also emerging [24]. All these concepts will be further developed with the introduction of connected vehicles. Some of the complications connected with the implementation of ITS systems are discussed in [25] and [26]. The methodology of this paper can be implemented easily just with smartphones yet results are general and can be applied to any connected vehicle that can be the base of an FCD system.

The problem of traffic signal synchronization was studied starting in 1967 by Newell and others [25–30]. The problem of adaptive synchronization of traffic lights was then explored in 1980 by Sims [31] for the city of Sydney, which suffered from severe congestion problems. On that occasion the SCAT system was conceived in which a series of road signals are adaptive and coordinated allowing optimizing the use of the city road network. The Sydney SCAT system consisted of a central server and eleven distributed computers in different parts of the city, which managed to control up to 200 control units each, and over 1000 sensors and traffic light stations distributed over 1500 square kilometres of the city. Subsequently, the SCOOT system was created and then the TRANSYT method used to set up green wave systems [32]. Both in TRANSYT and in SCOOT it was important to reduce the sum of the average queues present in the area assigning the green as fast as possible. These systems estimate the length of the queue, and consequently regulate the traffic lights. TRANSYT estimates traffic conditions every hour while SCOOT does so every 4 s. Both systems assume a standard speed and dispersion for the vehicle platoons and a known and constant saturation flow rate during the green phase.

Sehgal et al. [33] proposed a similar system in which a series of sensors measure road traffic information and send them to a central monitoring station that modifies the traffic light cycles in the network dynamically. Their method was based on the simple idea of assigning the priority of green to the main flow. However, Sehgal highlights some shortcoming of the method where a change in traffic light applied too early can lead to congestion on other roads and a change too late could lead to traffic jams on the main road.

A variant of the SCAT and SCOOT systems was proposed in 2013 by Faye [34] developing the TAPIOCA algorithm, which regulates the traffic light cycles on the basis of data collected from wireless sensors, cameras, and a network of sensors located in the intersections. However, this system is applied only to virtual data of the French city of Amiens simulated through SUMO. The regulation of all intersections works with a local adaptation logic. This is done to limit the huge data exchange between the various intersections.

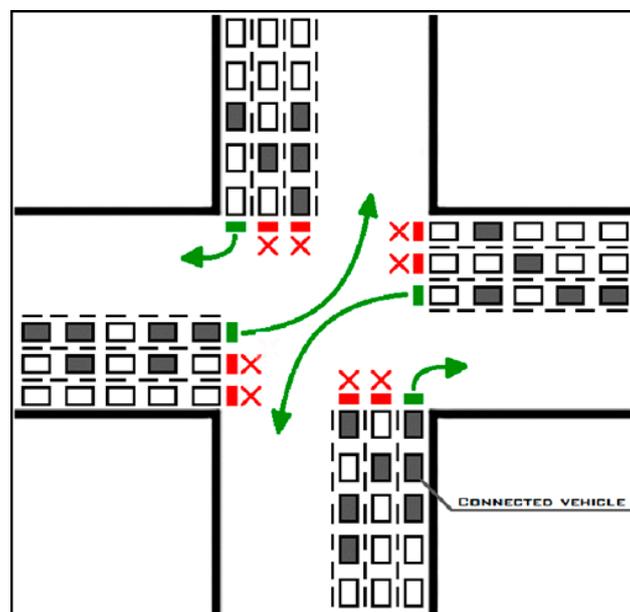
Choosing a different approach Clempner and Poznyak [35] analyzed the problem of synchronizing a traffic light network using game theory based on the extraproximal method. For them, too, the goal at an intersection is to minimize the queuing delay and set the green time for each phase, but the light controllers are considered as players in a Markov chain system.

More traditionally, in 2016 Ghazal [36] affirmed that for smart traffic lights, it is not advisable to use video sensors or fuzzy algorithms because this would only involve a waste of calculation resources.

Traffic light regulation can be done effectively knowing the exact position of vehicles at intersections. This information is useful to allocate green and red times improving real time regulation. Some works have been published on the use of Radio-Frequency Identification (RFID) tags or FCD data to regulate traffic lights [37–40]. Research has been carried out to obtain traffic light green times from FCD data coming from smart-phones [41,42]. The following works have introduced the idea to use FCD for traffic light regulation and the concept of FCD Adaptive Traffic Signals (FCDATS): [43,44]. In FCDATS all “connected” vehicles send localization information to a central traffic signal controller.

FCDATS systems regulate traffic lights according to the known position of some percentage of total vehicles. The traffic signal regulation algorithms would tend to minimize queuing and delays at intersections. To obtain this result it is useful to know the queue length for every group of lanes that is coupled with a turning manoeuvre. In the case of intersections with a single lane for each incoming road, the accuracy of smart-phone GNSS data is usually enough to establish the length of the queue and apply queue based control algorithms. Instead in the case of multiple lanes this is cannot be taken for granted.

As an example, in a situation such as that depicted in Figure 1, a FCDATS systems would be more accurate to reduce traffic delays at intersection by knowing the exact lane distribution of instrumented vehicles (dark shaded vehicles) in queues.



**Figure 1.** An example of signalized intersection, where, exact lane position information would be useful for FCDATL systems (X symbolizes manoeuvres that cannot move in the current phase).

The accuracy of GNSS smartphone data has become the object of research in [45], in a study on the reconstruction of signal cycles from FCD data. The GNSS position was compared to the simulated one and an error area was used, with a radius given from a Gaussian distribution with average 0 and s.d. 25 m. This assumption derives from [46] in which the GPS position was corrected with Bayesian filters using data from different sensors. However, the study was intended for pedestrian GPS position correction and not vehicles. Speeds were, in fact, between 0 and 2 m/s.

Prior to these studies Angermann [47] also hypothesized that the position of GNSS data could be simulated with Gaussian distribution with standard deviation between 20 and 30 m. In other studies conducted on GPS signal reception problems [14,48–52] it was discovered that in an location where there are constructions and solid obstacles to satellite signals the error grows. GNSS can fail among tall buildings in situations that are defined as “urban canyons”. The need to recognize the lane occupancy of a car is also useful in autonomous driving. In this case, cameras are used to identify the lane lines on the road pavement. A summary of the state-of-the-art of camera methods can be found in [53]. Algorithms have been developed to correct satellite data and obtain an accurate positioning on the road e.g., in: [54] or [55]. The problem in most GNSS car positioning systems is that the accuracy is insufficient to identify lane occupancy. Solutions have been proposed to bring the accuracy to a level that would allow lane identification: [56] and [57] by using, for example differential GPS (D-GPS). Recent works on lane determination are: [58] and [59]. In [60], a simple method for smartphone GPS to determine the lane position of a car is proposed.

One paper, [61] proposes a fuzzy set procedure to identify occupied car lanes using GNSS data obtained from mobile phones. The proposed method was applied to three intersections in an Italian city. The paper shows the efficacy of the fuzzy set method when the actual car lane positions and those determined by the method are confronted.

FCDATS systems, such as that presented in [44], are based on the principle of a cooperative-competitive paradigm since “connected” drivers who are part of the system are granted green priority on other vehicles (competition), yet “connected” vehicles are also source of useful information for other vehicles (cooperation). The cooperative-competitive paradigm arising from FCD-based adaptive traffic signals, though, was not extensively explored in [44] or in any other work. An introduction to this topic in the simple case of signal cycle offset regulation can be found in [62] and the topic is further developed in this paper considering an extensive set of traffic scenarios for a single intersection. While it is clear, in a traditional adaptive traffic signal system, how to evaluate benefits for vehicles that are moving on a regulated network (in terms of reduced travel time). The same evaluation in an FCDATS system instead becomes not trivial since different percentages of “connected” vehicles could turn into different benefits (or damages) among different users. With an FCDATS system there is an intrinsic difference with all other adaptive traffic signal systems: some vehicles are “connected” and are considered in traffic signal regulation while other vehicles are not detected and accounted by the system. The evaluation of FCDATS systems performance must be based on the more complex assessment of travel times for both categories of vehicles: those “connected” and those “not connected”, with different percentages of “connected” vehicles”.

Since, in all past scientific works, there was no formal definition of cooperation and competition, in traffic signal settings, we will give a definition in this paper with the aim of evaluating different scenarios in terms of cooperation-competition. With traffic signal regulated intersection there is an obvious rivalry, between different categories of vehicles, for the right to move first at the intersection. So we will assume this general definition for competition at traffic signals: “Rivalry between different vehicles groups in the use of the scarce resource of green time at a signal regulated intersection” (which could be extended and generalized to the general case of road traffic use: “Rivalry between different vehicles in the use of the scarce resource of space on a traffic network”). With traditional traffic signals there is competition between vehicles using different lanes and receiving green in different phases. In FCDATS systems “connected” vehicles are in competition with “not connected” vehicles since regulation algorithms will regulate traffic signal according to the detected “connected” vehicles. This regulation may take green time from “not connected” vehicles and advantage “connected” vehicles. In this paper we will consider only competition between “connected” and “not connected” vehicles.

In FCDATS cooperation is also present since all “connected vehicles” are cooperating to produce an improved real time representation of traffic situation in the central server. This representation does not take into account “not connected” vehicles.

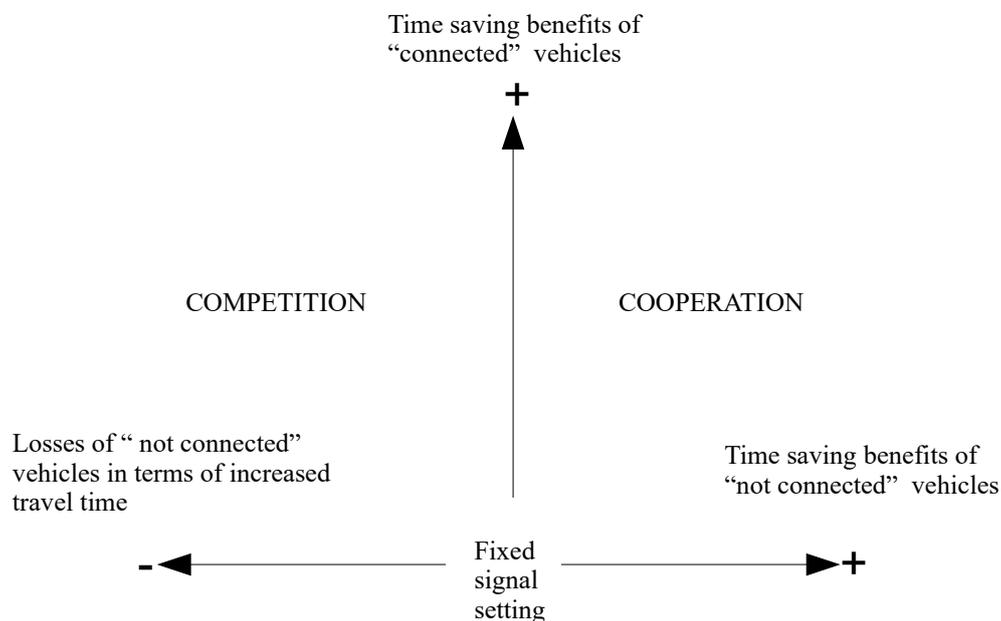
What is realistically expected is that if the percentage of “connected” vehicles is low they would get more green time than “not connected” vehicles. In practice they would cooperate among themselves competing at the same time with “not connected” vehicles, actually, stealing green time from them whenever possible.

Since FCDATS systems are systems in which competition and cooperation are both present at the same time we define them as “coopetitive” systems. Once a FCDATS system is introduced, drivers have the possibility of joining the system and becoming “connected”. Is this choice a selfish choice or also an altruistic choice? To what extent and in what cases would the introduction of an FCDATS system contribute to create competition or cooperation among drivers? Answers to these questions are given in a single intersection scenario by applying a competition-cooperation diagram which is introduced in Section 2. Some simulation results in terms of the competition-cooperation diagram are presented in Section 3.1. The last section of the paper (Conclusions), also presents more insights into the above-described issues.

## 2. Materials and Methods

An evaluation of FCDATS systems in terms of competition-cooperation is proposed which is based on the dual utility diagram put forward by Cipolla [63] which assigns an action to four quadrants depending on whether the action brings benefits or losses to others or to themselves. Since in FCDATS systems there are only two groups of drivers which can benefit (or lose) in terms of travel time gains (or losses) such a diagram seems able to capture the level of cooperation-competition.

Since it presents level of competition and cooperation at the same time we will call this diagram “Coopetition diagram”. The diagram is structured as shown in the following Figure 2. The x axis is the percentage gain or loss in term of average travel time, with respect to a non-controlled situation, for “not connected” vehicles while the y axis is the percentage of gain for “connected” vehicles.

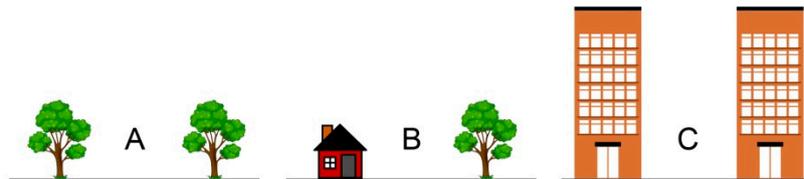


**Figure 2.** Coopetition (competition-cooperation) diagram.

This research is based on the results of [64], where some issues relative to the accuracy of the GNSS smart-phone were explored by conducting an experimental survey. GNSS device error was correlated to a number of factors such as the occlusion of the sky. The study produced a first algorithm to be inserted into micro-simulators in order to correctly simulate FCD data.

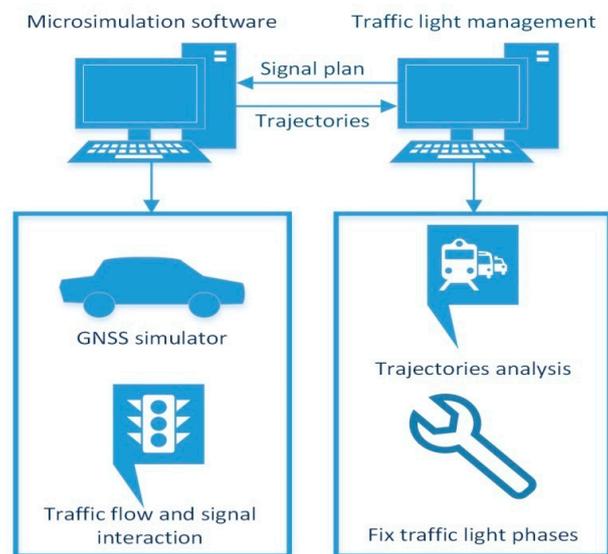
Experiments were performed in three different scenarios. Figure 3 shows the three types of scenarios in which experimental data were gathered. Case A represents a scenario where the satellite

localization is almost perfect as the sky is almost completely clear. Case B represents a scenario where sight disturbances can reduce satellite signals. Case C is a scenario where there are tall buildings at least 18 m on the side of the street (urban canyon). The experimental survey was conducted in the urban area of Cosenza (Italy) fully representing the three above-described scenarios. A high precision GPS system was used to assess the accuracy of five different smart-phones in the three mentioned scenarios. In accordance with GNSS localization theory Rayleigh distribution was used as a reference for distance error and uniform distribution for angle error. Based on these experimental data a procedure was developed to reproduce GNSS error in traffic simulations and applied in this work.



**Figure 3.** Experimental scenarios.

To evaluate performances of FCDATS systems we developed a special laboratory prototype in which to carry out experimental tests. Our laboratory prototype (Figure 4) is composed of a central server which is able to regulate traffic signals from connected vehicles data (such as one that can be used in real time in the field connected with real traffic signals) and another computer that creates a virtual reality environment by microsimulation combined with a module that simulates the GNSS errors. This laboratory implementation makes it possible to evaluate realistically the performances of the proposed system before a real implementation in the field. We applied the standard practice of using simulation to test the effectiveness of the FCDATS system because, in most academic studies, traffic light regulation and traffic signal optimization were designed and analyzed in simulated environments [65–68]. Once the results have been analyzed, if they are promising, the system can be tested in a real environment.



**Figure 4.** Traffic signal algorithms testing lab.

The virtual reality environment is created, with a micro-simulation module based on the Tritone microscopic traffic simulator [69,70]. Some details are presented in the following on: localization error simulation model, map-matching algorithm, car-following model, traffic emission model and fuel consumption model.

The localization errors are generated in a dedicated module for post-processing of vehicles trajectories. This module is very important for correctly assessing performances of a traffic settings algorithm.

Localization error model: the simulation procedure as in [70] assigns the first vehicle localized position on the network when the vehicle is generated (in the microsimulation), according to localization errors. This is done addressing separately distance error (which is a positive variable theoretically distributed as a Rayleigh variable) and angle error (which follows a uniform distribution). A distance error is generated, according to one of the three case scenarios, with a different Rayleigh distribution.

After the first time step, the error in distance is generated following a normal distribution with mean and standard deviation that are relative to one of the three scenarios and also relative to the error absolute value in the preceding time step (this is an empirical procedure that introduces some approximation). The experimental data showed, in fact, that autocorrelation translates into a different standard deviation of the error at time  $t+1$  according to the absolute value of the error at time  $t$ .

A similar procedure is carried out for the angle simulation where instead the autocorrelation can be reproduced by just using a normal distribution for each of the three scenarios fully in accordance with theory. This can be done exactly following theory since the angle distribution, not considering autocorrelation, is a simple uniform distribution.

The procedure above described is useful to generate a sequence of distance and angle errors and allows applying microsimulation to test generic ITS algorithms and strategies that are based on FCD data.

Generated position data are transferred via an internet protocol to the central signal regulating server. The central server of the system elaborates positions, by correcting introduced random localization errors with a map-matching algorithm. Elaborated position data are then fed into the adaptive traffic signal algorithm (FCDATS).

To carry out the above-described simulations, the GNSS error generation module, the map-matching algorithm and the algorithm for traffic light control were implemented using the microscopic traffic simulation model Tritone [71]. The use of Tritone allowed automatic simulation of 20 repetitions for every scenario. Inside Tritone specific car-following, emission and fuel consumption models were used as described in this section.

Car-following: one of the major concerns for considering signalization at intersections is the modelling of rear-end interactions involving vehicles travelling along the approaches. Approaching a slower leading vehicle (car-following regime) the driver must recognize consciously some action points, and consider others unconsciously. The conscious actions is determined by the speed difference, relative distance to the leading vehicle, and driver-dependend behaviour. The Car-following Model that was selected to represent the interactions among vehicles of the traffic stream is Wiedemann 99 [72]. In Tritone, the car-following model parameters are set up according to [73], that calibrated the Wiedemann 99 model in an urban intersection located in Southern Italy.

In their study, Gallelli et al. established that the parameters significantly influencing driver behaviour are: "Desired Speed" (average) (km/h) that represents individual free flow speed, "Observed vehicle ahead" that affects drivers' capacity to regulate their speed/distance according to the number of lead vehicles, "Standstill distance" (m) (CC0) that defines the desired distance between stopped cars, "Headway time" (s) (CC1), "Following variation" (m) (CC2) threshold for the entering "following" (CC3), "Positive following" threshold (CC5)," Speed dependency of oscillation" (CC6), "Oscillation acceleration" (CC7) and "Standstill acceleration" (CC8). The parameters values considered in TRITONE are reported in the following Table 1.

Traffic emission modelling: In this research the traffic emissions are modelled according to a consolidated emission model [74]. The emission model was calibrated on experimental evidence and takes into account the instantaneous kinematic values of single vehicles considering: the driving style and the vehicle characteristics. For all pollutant emission it was considered a general function

which takes into account instantaneous speed and acceleration of vehicles. The pollutants modelled are nitrogen oxides (NO<sub>x</sub>), volatile organic compounds (VOC), carbon dioxide (CO<sub>2</sub>) and particulate matter (PM). This choice is based on their potential health impacts and external costs.

**Table 1.** Car following parameters.

Calibration Parameter	Value	Unit
Desired Speed (average)	25.43	(km/h)
Observed vehicles ahead	4	
CC0	0.50	(m)
CC1	0.52	(s)
CC2	2.21	(m)
CC3	−7.06	
CC6	8.01	
CC7	0.27	
CC8	3.48	

The pollutant emission function which was applied is:

$$E_n(t) = \max \left[ E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t) \right] \quad (1)$$

This function was derived in [74] by Panis et al. and takes into account instantaneous speeds and accelerations:  $v_n(t)$  and  $a_n(t)$  are the speed and acceleration of vehicle  $n$  at time  $t$ .  $E_0$  is a lower limit of emission (g/s) defined for each vehicle and pollutant type, and the  $f_1$ – $f_6$  coefficients, which are relative to vehicle and pollutant, are determined by the regression analysis. The exact coefficients, which were obtained using non-linear multiple regression technique, for each single vehicle type can be found in [74].

Fuel consumption model: The fuel consumption model considered is the Akcelik model [75]. The choice is due to highly accurate fuel consumption estimates for traffic analysis.

The vehicle parameters in the fuel consumption model include: Fuel type (percentage of diesel vehicles), maximum engine power, power to weight ratio, number of wheels and tyre diameter, rolling resistance factor, frontal area and the aerodynamic drag coefficient.

The model is applied on the vehicles trajectories obtained from microsimulation and is applied differently for each of the four-mode elemental (modal) travelling cases: cruise, acceleration, deceleration and idling.

### 3. Results

A case study is presented where a simple greedy algorithm (more extensively described in [44]) is applied for the optimization of traffic settings based on FCD data. The algorithm is among the few control algorithms for FCDATS that have been introduced in the literature. Most preceding scientific works on adaptive traffic signals were based on traffic flow variables as input. FCDATL algorithms are based on the known positions of some of the vehicles and thus FCDATL control algorithms are conceptually different.

The control algorithm: the algorithm establishes in real time the phase sequence, the green times and the total cycle time. It is based on the evaluation of the number of “connected” vehicles that are detected on every approaching street at the intersection. The algorithm at every cycle establishes the sequence of phases by choosing first the phases with more “connected” vehicles. Every phase receives a green time which is enough to clear the queue of “connected” vehicles. Vehicles that are not “connected” are not considered and the signal setting may change before some of them are able to exit the intersection. If there is no “connected” vehicle on some of the approaches the algorithm falls back on a reference pre-established cycle establishing green times according to the pre-established fixed times of green. The algorithm guarantees at least 4 s of green for every phase (according to UK traffic

light rules). It must be noted that this simple algorithm can be used only on intersections that have one single lane for every approach.

The above described algorithm, intuitively, appears to give an advantage to “connected” vehicles. It is, in fact, expected that it would bring a high level of competition between “connected” and “not connected” vehicles in the sense that green times would be given to “connected” vehicles at the expense of “not connected” vehicles. The first case study was specifically designed to evaluate numerically these issues with the objective of shedding some light on competition-cooperation issues in FCD based regulation.

In this case study the simulated intersection is a typical symmetrical intersection with four approaching roads. Three different flow distributions were provided assuming that one direction is the main traffic direction: 60/40, 70/30 and 80/20. Approaching road links are of 200 m each. The direction of links 2-3 and 3-2 (see Figure 5) is considered the main direction. The distribution, of the various manoeuvres for a single approach, is uniform with 1/3 of the vehicles turning left, right or proceeding straight.

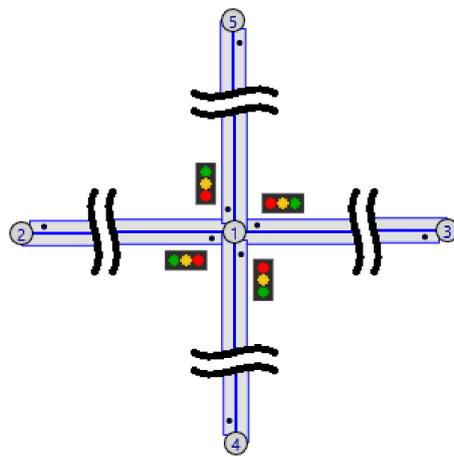


Figure 5. Simulated road intersection.

For the traffic demand a distribution such as that of the HCM 2010 [76] for the distribution of average daily traffic in urban areas is used. The distribution (Figure 6) was then approximated in order to obtain only four daily flows, 680, 424, 278 and 93 veh/h.

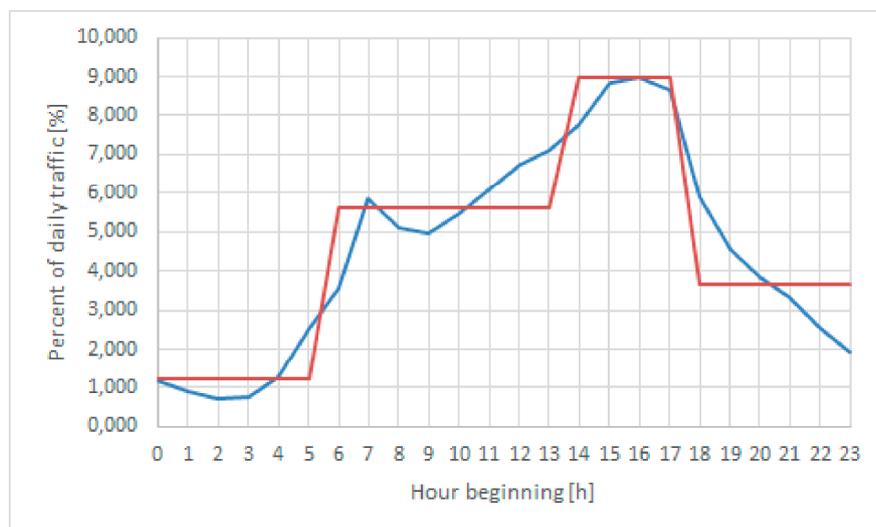


Figure 6. Daily flow for local route (in blue real data, in red the constant piecewise approximation that was used in the simulations).

Two basic signal settings have been used as reference for the algorithm as in Figure 7.

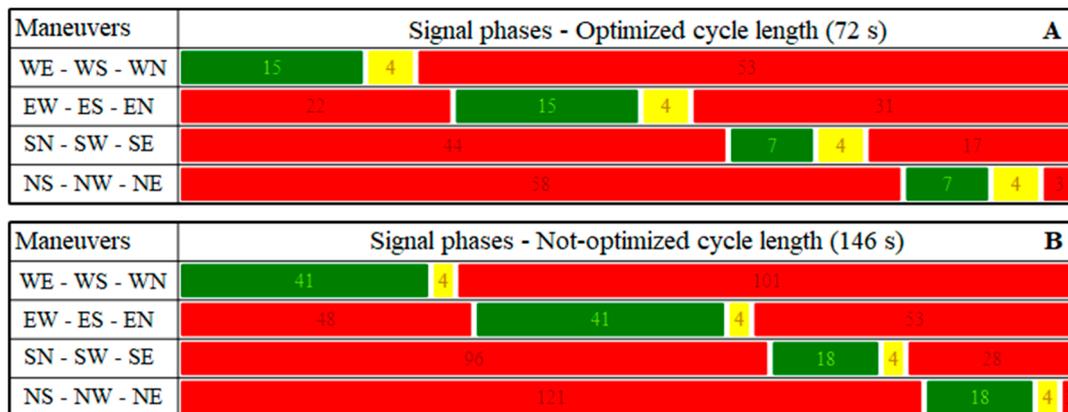


Figure 7. Traffic light Cycle A and B.

The static traffic light setting A was established, according to the HCM 2010 methodology, for peak traffic and a 70/30 distribution of flows, while the second setting B is the optimum for the same configuration but with double total traffic. The B signal setting variant was created to evaluate the hypothesis in which the traffic light system is poorly regulated, in the first place, to assess how the FCD-based algorithm system automatically works to improve the way green is established.

A preliminary analysis was carried out based on the evaluation of the Ratio of Travel Time Saving (RTTS) both for “connected” and “not connected” vehicles expressed as follows:

$$RTTS_C = \frac{TTO - TT_C(p)}{TTO}, \quad (2)$$

$$RTTS_{NC} = \frac{TTO - TT_{NC}(p)}{TTO}, \quad (3)$$

where  $RTTS_C$  is the Ratio of Travel Time Saving for “connected” vehicles;  $RTTS_{NC}$  is the Ratio of Travel Time Saving for “not-connected” vehicles;  $TTO$  is the overall average travel time of the intersection four entry links (including service time) assuming that no vehicles are “connected” (no regulation of the traffic signal is applied);  $RTTS_C$  is the Ratio of Travel Time Saving for “connected” vehicles and  $TT_C(p)$  is the average travel time of the “connected” vehicles of the entry links of the intersection (including service time) assuming that penetration rate of “connected” vehicles is  $p$ .

Simulations were performed by varying the percentage of “connected” vehicles, also to establish which is, for this specific scenario, the minimum number of “connected” vehicles needed to have an optimal regulation. For this reason the same scenario was replicated by simulating different percentages of “connected” vehicles from 5% to 100% in increments of 5%.

### 3.1. Competition-Cooperation Diagrams

In the following Figures 8–11 results in terms of “cooperation” diagram (above defined) are presented. Four different values of total flow and three different directional distributions were considered for Cases A and B (20 repetitions of each scenario were performed) for each percentage of “connected” vehicles (21 different cases) for a total number of 10.080 simulations (20 repetitions of each scenario were performed).

For the sake of brevity only results relative to a directional flow distribution 60/40 and 80/20 are presented in Figures 8–11 for Cases A and B. Results show that the FCDATS systems always impact positively on Travel Time Saving of “connected” vehicles especially in Case B where confrontation is carried on in a inefficiently regulated intersection.

It should be noted that the marginal utility of “connected” vehicles, expressed in terms of Travel Time Saving, decreases with the increasing in the percentage of “connected” vehicles, in all cases (when the percentage of users is low they get a substantial advantage which in most cases is at least over 30% of average time saving, when percentage increases this differential advantage tends to fade).

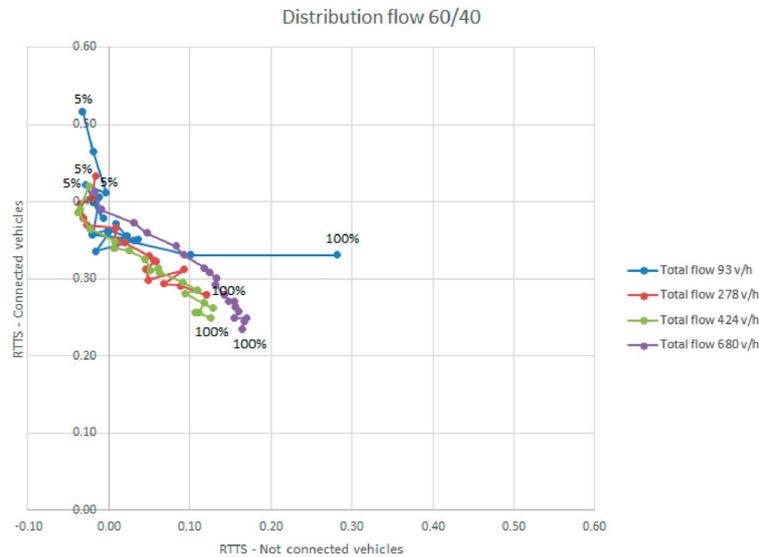


Figure 8. Ratio of Travel Time Saving for traffic light cycle A (Distribution of flow 60/40).

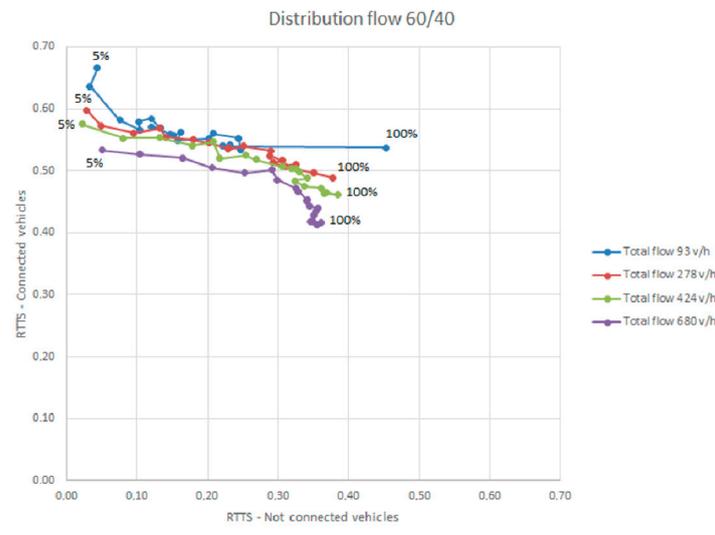


Figure 9. Ratio of Travel Time Saving for traffic light cycle B (Distribution of flow 60/40).

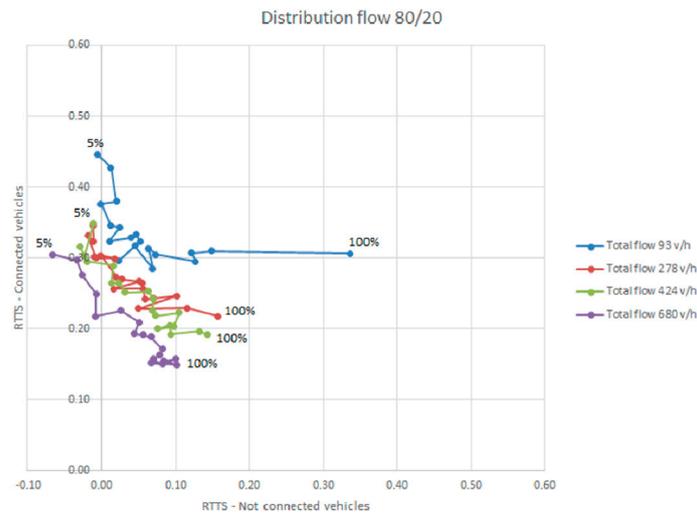


Figure 10. Ratio of Travel Time Saving for traffic light cycle A (Distribution of flow 80/20).

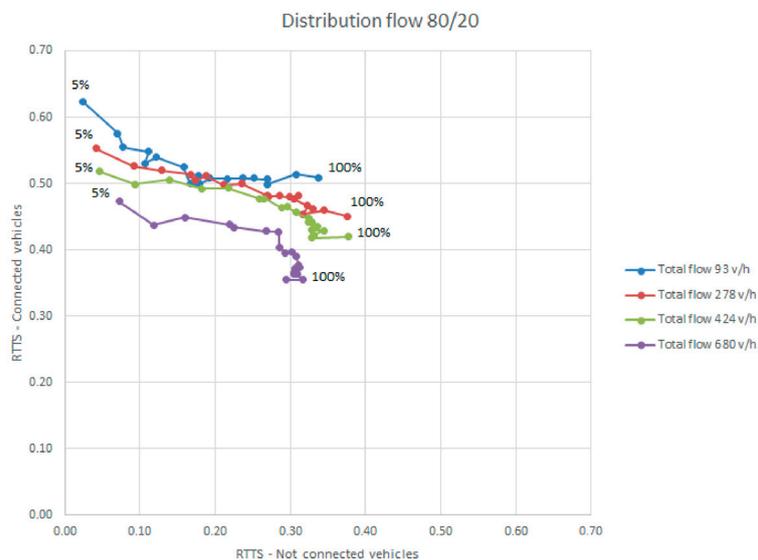


Figure 11. Ratio of Travel Time Saving for traffic light cycle B (Distribution of flow 80/20).

In Case A (Figures 8 and 10), no travel time saving (TTS) is observed for “not-connected” vehicles when the percentage of “connected” vehicles is less than 20%. With a low percentage of “connected” vehicles the situation is that of a clear competition between “connected” vehicles and “not connected” vehicles, “connected” vehicles are taking green time away from “not connected” vehicles and the points in the “coopetition” diagram are on the left of the y axis. This disadvantage for “not connected” vehicles disappears when more vehicles become “connected”. The marginal utility of the “not-connected” vehicles increases for all simulated scenarios with an increase of “connected” vehicles”.

On the other hand, when the basic traffic light cycle is inefficiently regulated, in the first place (traffic light Cycle B), “not-connected” vehicles benefit from an improvement in travel times even in the presence of very low percentages of “connected vehicles” both for balanced distributions and for unbalanced distributions of traffic volumes on the main and the secondary directions (Figures 9 and 11). Overall, we can observe an improved optimization of travel times through the proposed FCDATS compared to static-flows based regulated traffic light cycles (i.e., traffic light Cycle A).

It should be noted that FCDATS advantages seems to decrease with the increase in total flow. In most cases (also with flow distribution 70/30 which is not in presented in the figures), the curves in the “cooperation” diagram shift left and down when the intersection is more saturated (total flow increasing). The only exception we found in our simulation is in case A with a 60/40 distribution of flow.

### 3.2. Average Results of a Typical Day

Results based on averaging the simulation for a typical day are based on the distribution of total flows of Figure 6 as in Table 2 (a typical day is composed of 24 h of simulation with flows that are distributed as in the above presented Figure 6):

**Table 2.** Distribution of daily flow.

Flow (veh/h)	Hours
93	6
278	6
424	8
680	4

The following Tables 3 and 4 show the average travel time for Cases A and B.

**Table 3.** Average travel time [sec.], in a typical day, for Case A.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	47.42	46.60 [1.73] *	42.97 [9.38]	38.44 [18.94]	36.06 [23.96]	34.29 [27.69]
70/30	46.25	45.13 [2.42]	42.78 [7.50]	38.18 [17.45]	36.06 [22.03]	34.88 [24.58]
80/20	45.30	44.39 [2.01]	41.88 [7.55]	38.05 [16.00]	36.79 [18.79]	35.70 [21.19]

\* relative savings [%] compared to the static cycle.

**Table 4.** Average travel time [sec.] in a typical day for Case B: inefficiently regulated intersection.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	65.14	58.41 [10.33] *	47.90 [26.47]	39.59 [39.22]	35.97 [44.78]	33.93 [47.91]
70/30	63.90	57.00 [10.80]	47.05 [39.01]	38.97 [39.01]	36.06 [43.57]	34.56 [45.92]
80/20	61.95	54.78 [11.57]	46.05 [25.67]	39.52 [36.21]	36.62 [40.89]	35.06 [43.41]

\* relative savings [%] compared to the static cycle.

The results of Tables 3 and 4 are also presented in Figures 12 and 13 in terms of RTTS for all vehicles as a function of percentage of “connected” vehicles.

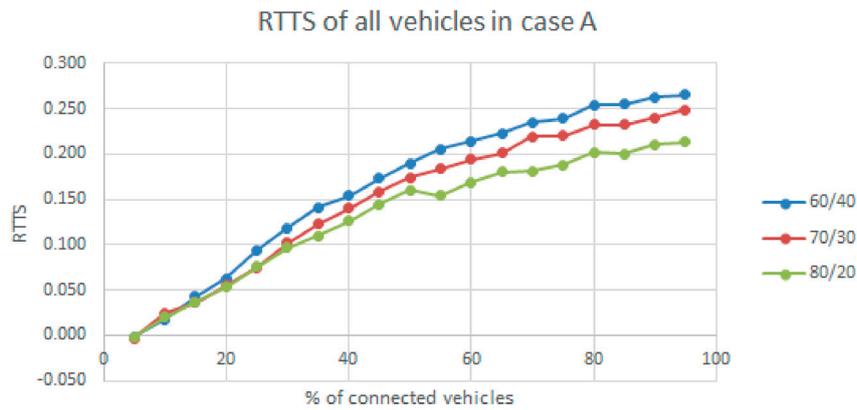


Figure 12. RTTS for all vehicles in Case A.

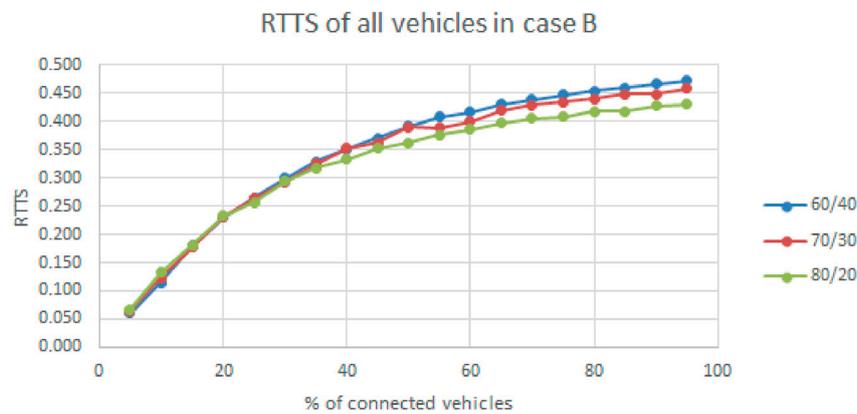


Figure 13. RTTS for all vehicles in Case B.

Tables 5 and 6 show the average values of fuel consumption for Cases A and B.

Table 5. Average fuel consumption [l/km], in a typical day, for Case A.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	0.235	0.232 [1.28] *	0.221 [5.96]	0.209 [11.06]	0.205 [12.77]	0.200 [14.89]
70/30	0.238	0.234 [1.68]	0.225 [5.46]	0.212 [10.92]	0.208 [12.61]	0.204 [14.29]
80/20	0.240	0.236 [1.67]	0.229 [4.58]	0.218 [9.17]	0.215 [10.42]	0.212 [11.67]

\* relative savings [%] compared to the static cycle.

Table 6. Average fuel consumption [l/km], in a typical day, for Case B.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	0.276	0.257 [6.88] *	0.229 [17.03]	0.209 [24.28]	0.201 [27.17]	0.198 [28.26]
70/30	0.280	0.259 [7.50]	0.232 [17.14]	0.213 [23.93]	0.204 [27.14]	0.201 [28.21]
80/20	0.276	0.257 [6.88]	0.234 [15.22]	0.217 [21.38]	0.211 [23.55]	0.208 [24.64]

\* relative savings [%] compared to the static cycle.

Tables 7 and 8 show the average values of CO<sub>2</sub> pollution.

**Table 7.** Average CO<sub>2</sub> pollution [g/km], in a typical day, for Case A.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	89.946	89.373 [0.64] *	85.875 [4.53]	82.111 [8.71]	81.424 [9.47]	79.695 [11.4]
70/30	91.566	90.957 [0.67]	87.793 [4.12]	84.334 [7.90]	83.212 [9.12]	81.402 [11.1]
80/20	94.134	93.077 [1.12]	90.909 [3.43]	87.834 [6.69]	86.957 [7.62]	85.177 [9.52]

\* relative savings [%] compared to the static cycle.

**Table 8.** Average CO<sub>2</sub> pollution [g/km], in a typical day, for Case B.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	102.795	97.619 [5.00] *	89.392 [13.00]	82.127 [20.10]	80.126 [22.60]	79.161 [23.00]
70/30	106.503	99.765 [6.30]	91.211 [14.40]	85.744 [19.05]	82.035 [23.00]	80.865 [24.10]
80/20	107.129	101.32 [5.40]	93.110 [13.10]	87.532 [18.03]	85.710 [20.00]	84.160 [21.40]

\* relative savings [%] compared to the static cycle.

FCDATS show a general reduction in travel times, fuel consumption and pollutant emissions in all scenarios compared with values obtained from static signal regulation. Tables 3–10 show that FCDATS perform better in Case A than in Case B in terms of absolute values when the percentage of “connected” vehicles is equal or less than 50%. This happens since the initial conditions are different. The algorithm in Case A is based on a properly calculated static reference signal cycle. The algorithm in cases where there are no “connected” vehicles, at the intersection, falls back on this basic static reference cycle and this means that in the scenarios of Case B sometime the wrong static reference signal cycle is applied bringing higher travel times and lower performances. This problem disappears when the percentage of connected vehicles is 75% or 100% since there would be fewer situations where the algorithm cannot rely on “connected” vehicles to adjust signal phases.

Improvements of FCDATS with respect to the static cycle derive mainly from the reduction in travel time on the links entering the intersection, but also from the reduced number of stop-and-go events near the traffic light, which consequently reduces the number of sudden braking and deceleration/acceleration.

The overall results compared to the static reference signal cycle are positive in all cases showing that FCDATS system can be implemented with benefit in all situations. The expected performances are to a larger extent better at intersections where the static signal cycle is not well established. The following Tables 9 and 10 show the average values of NO<sub>x</sub> pollution:

**Table 9.** Average NO<sub>x</sub> pollution [g/km], in a typical day, for Case A.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	1.152	1.147 [0.43] *	1.092 [5.21]	1.026 [10.9]	0.999 [13.28]	0.977 [15.19]
70/30	1.159	1.156 [0.26]	1.113 [3.97]	1.047 [9.66]	1.020 [11.99]	1.004 [13.37]
80/20	1.189	1.176 [1.09]	1.144 [3.78]	1.080 [9.17]	1.062 [10.68]	1.040 [12.53]

\* relative savings [%] compared to the static cycle.

**Table 10.** Average NO<sub>x</sub> pollution [g/km], in a typical day, for Case B.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	1.422	1.322 [7.03] *	1.168 [26.09]	1.051 [26.09]	0.997 [29.89]	0.973 [31.58]
70/30	1.431	1.322 [7.62]	1.175 [25.23]	1.070 [25.23]	1.018 [28.86]	1.000 [30.12]
80/20	1.437	1.336 [7.03]	1.206 [23.31]	1.102 [23.31]	1.065 [25.89]	1.041 [27.56]

\* relative savings [%] compared to the static cycle.

And finally Tables 11 and 12 show the average values of PM pollution in a typical day.

**Table 11.** Average PM pollution [g/km], in a typical day, for Case A.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	0.013	0.012 [7.69] *	0.012 [7.69]	0.011 [15.38]	0.011 [15.38]	0.011 [15.38]
70/30	0.013	0.013 [0.00]	0.012 [7.69]	0.012 [7.69]	0.012 [7.69]	0.012 [7.69]
80/20	0.014	0.014 [0.00]	0.013 [7.14]	0.013 [7.14]	0.013 [7.14]	0.013 [7.14]

\* relative savings [%] compared to the static cycle.

**Table 12.** Average PM pollution [g/km], in a typical day, for Case B.

Total Daily Flow 8838 veh		% of GNSS Vehicles				
Distribution	Static Cycle	10	25	50	75	100
60/40	0.014	0.013 [7.14] *	0.012 [14.29]	0.011 [21.43]	0.011 [21.43]	0.011 [21.43]
70/30	0.014	0.013 [7.14]	0.012 [14.26]	0.012 [14.29]	0.012 [14.29]	0.012 [14.29]
80/20	0.015	0.014 [6.67]	0.013 [13.33]	0.013 [13.33]	0.013 [13.33]	0.012 [20.00]

\* relative savings [%] compared to the static cycle.

### 3.3. Average Results of a Typical Day in Terms of Competition-Cooperation

The competition-cooperation diagram was calculated in Section 3.1 for some specific cases. This section shows results for the average day considering an intersection which has a fixed signal cycle for all day. Averaging travel times over all the day was done to evaluate real competition-cooperation in the common situation where traffic signals keep the same regulation during the day without adjusting to changing conditions. Figures 14 and 15 show RTTS for “connected” and not “connected” vehicles in the “cooperation” diagram. Results show that at intersections where the cycle is correctly calculated (Figure 14) there is some competition for lower values of the percentage of “connected” vehicles. Connected vehicles are obtaining better travel times on a daily average at the expense of not “connected” vehicles. When the percentage of “connected” vehicles goes over 30% in all cases the effects of competition disappear since RTTS becomes positive also for not “connected” vehicles.

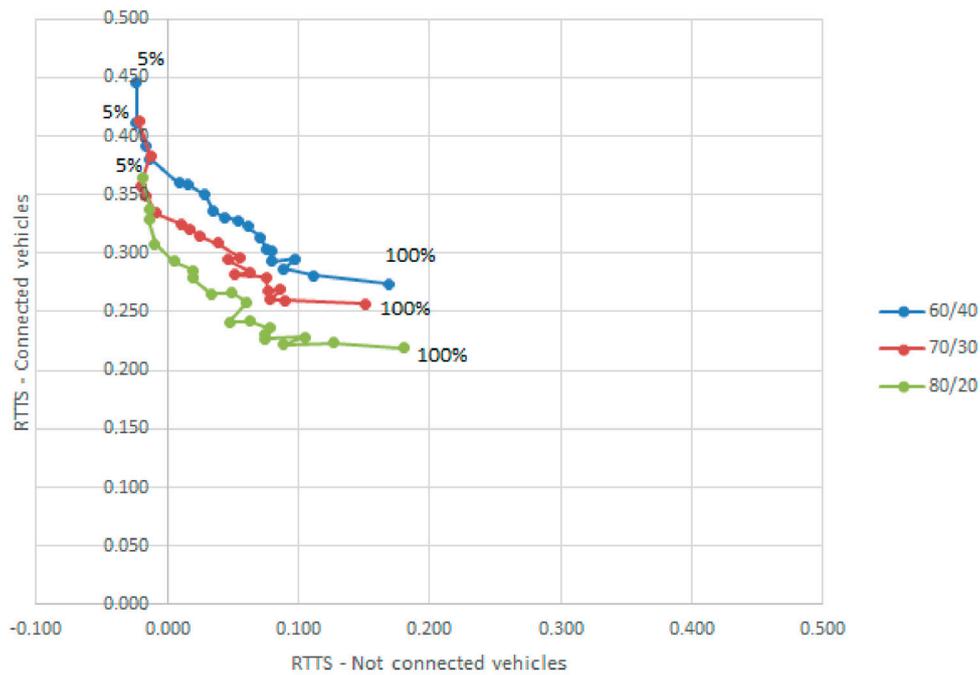


Figure 14. Competition-Cooperation diagram on a daily base in Case A.

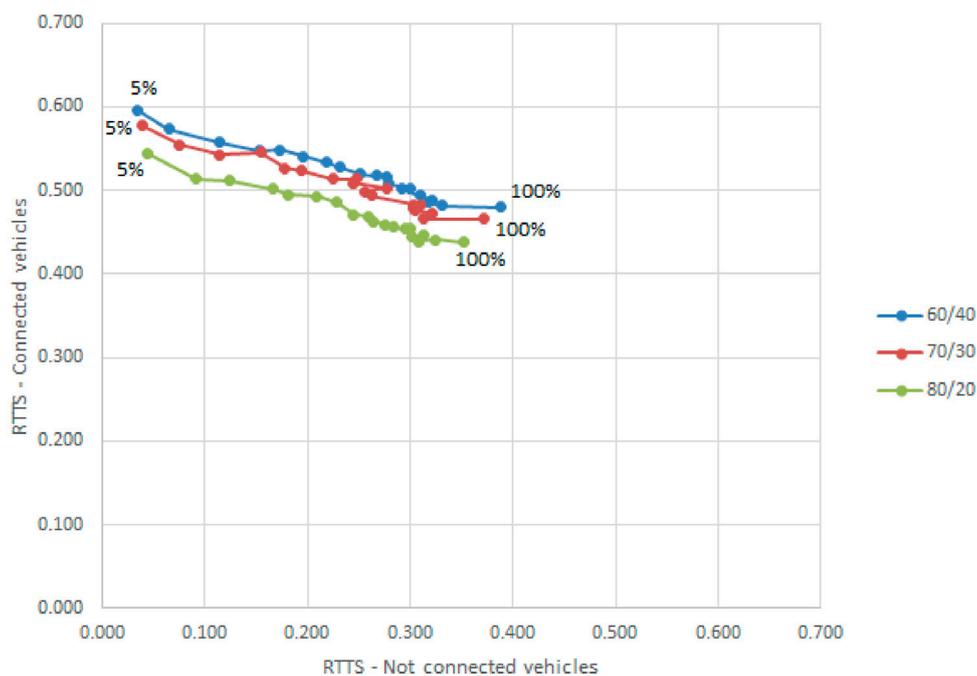


Figure 15. Competition-Cooperation diagram on a daily base in Case B.

Results for the intersection, which is starting from an improper signal cycle, are instead always positive also for not “connected” vehicles, RTTS is always positive for both categories of vehicles as shown in Figure 15.

#### 4. Discussion

The paper gives a first assessment of the penetration rate of “instrumented” vehicles that is necessary in order to obtain a good real time regulation in an FCDATS system and on the meaning of competition-cooperation in such a system.

This work is based on realistic assumptions on the control infrastructure and the quality of data that can be obtained from FCD. After experimenting for 15 years with mobile phones localization data we developed a dedicated Microsimulation Lab. The lab was developed specifically to test FCDATS algorithm with realistic assumptions on data quality that can be obtained from the field. For this reason one key element in our procedure is the introduction of a localization error and the consequent map-matching algorithm. Most research works on ITS assume the exact positioning of vehicle which is not necessary true. Moreover, everything that was done in this paper can be easily introduced in the field with standard mobile phone devices on vehicles.

The choice of microsimulation to test algorithms has a long historical background: traffic signal regulation has been verified and evaluated in simulation since the well-known Webster formula for delays which was evaluated in 1966 with the first computer traffic simulations.

Results of the simulations show a good performance of the simple implemented greedy algorithm even with a low percentage of “instrumented” vehicles: even on a well-regulated intersection (case A) FCDATS always improve traffic performances and can improve up to 25% travel time savings and reduce up to 10% fuel consumption and pollutant emissions. The disadvantages for not “connected” vehicles are contained and are an issue only in some cases and for a low percentage of “connected” vehicles. A driver who would choose to adopt these systems would compete with not “connected” vehicles only when the system is in its very initial start-up phase. As more and more drivers accept these systems they would cooperate also with not “connected” drivers for an improved general traffic signal regulation

All other performance measures, in terms of average travel time, fuel consumption and pollutant emissions, improved compared to the values of the original static signal cycle. Some level of competition among different classes of vehicles was revealed in some of the scenarios. Vehicles which are not “connected” may suffer disadvantages in terms of travel time with traffic regulation from FCDATS, for the benefit of “connected” vehicles, especially when the percentage of connected vehicles and the total flow at intersection is low.

General results prove that FCDATS systems can be an effective new solution, among smart city innovations, to increase transportation sustainability.

The algorithm used in the simulation is one of the very few control algorithms for FCDATS presented in the literature. It is a simple algorithm that allows other researchers to reproduce results. Future research efforts can be dedicated to developing specific algorithms to apply in more complex specific cases.

The work presented in this paper represents the first approach to analyze the traffic light regulation of a four legs intersection using FCDATS in terms of cooperation-competition. Future research efforts can also be devoted to test more general optimization algorithms in terms of cooperation-competition once new algorithms will be formalized so to perform a good regulation in FCDATS. Genetic algorithms may be a candidate for a superior solution to the problem given the complications involved that do not allow a simple analytical representation.

## 5. Conclusions

The competition between “connected” vehicles and not “connected” vehicles is a real problem which could hold back the use of innovative traffic signal regulation systems based on Floating Car Data. This paper has shown that practically, in all simulated scenarios of a single intersection, the advantages for the community of the introduction of FCDATS compared with traditional fixed time regulation are in terms of reduced consumption, reduced pollutant emissions and reduced travel time. The paper, however, does not analyses more complex intersection configurations and different levels of service (i.e., asymmetric approaching roads, higher traffic volumes, uneven turning manoeuvres, etc.). Furthermore, a simple greedy algorithm is applied to optimize the traffic settings based on FCD in order to demonstrate the advantages of the proposed system into a simulated environment. In this

way, the authors investigated the validity of urban traffic regulation systems based on connected vehicles, regardless of the technology used, but limited to a simulated scenarios.

More efforts have to be spent to implement the proposed system in a real context and evaluate its reliability by using an integrated hardware/software platform which allows the drivers to connect themselves to the traffic control system through their smartphones. As GNSS-embedded smartphones are widespread, especially in traffic congested areas, as previously described, they can be used as FCD to optimize travel times and queue lengths not only for isolated intersections, but also for wider areas including several traffic lights.

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