JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2016; 3 (3): 253–261

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

Impact of intersection type and a vehicular fleet's hybridization level on energy consumption and emissions

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ARTICLE INFO

Article history:
Available online 14 May 2016

Keywords:
Roundabout
Signalized intersection
Consumption
Emission
SUMO
Hybridization

ABSTRACT

A vehicle's energy consumption and emissions are two major constraints in sustainable development. Both of them have proportionally raised in recent decades with the exponential growth of world traffic demands. The reduction of road traffic-generated energy consumption and emissions have thus become unprecedentedly challenging and worth examining. This paper investigates energy consumption and environmental problems present at roundabout and signalized intersection to analyze the impact of the hybridization level's fleet and intersection type on vehicle consumption and pollution. Instantaneous fuel consumption and emission models coupled with simulation of urban mobility (SUMO) are in this study. The authors started with modeling energy consumption. Then, an emission model emissions from traffic (EMIT) was implemented to quantify vehicle emissions of CO_2, CO and NO_x. These models help investigate the influence of intersection type on energy consumption and environmental conditions. The authors implemented a signalized intersection and roundabout using SUMO. The input data are collected from the roundabout of Sousse (Tunisia) using video data collection. Since there is a lack of econometric models that emulate hybridized stream behavior near intersections, two energy consumption models for the roundabout and crossroad are developed using traffic flow and hybridization level as the input variables. Compared to crossroads, a roundabout can obtain more environmental improvements and substantial reductions in energy consumption and road traffic emissions.

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Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2016.05.003

1. Introduction

Road traffic encounters several problems, such as air pollution and energy consumption, which result in a major constraint for sustainable mobility. With increasing concern over urban air pollution from motor vehicles, it is imperative that vehicles take energy consumption and emission into consideration. One of the focal questions in transportation science is the evaluation of environmental and energetic impacts of vehicular traffic (Chen and Borken-Kleefeld, 2014; Sekhar et al., 2013).

Emission rates and consumption depend on road traffic characteristics, vehicle type, and road intersection type (Pandian et al., 2009). In fact, the intersection type can play a substantial role in reducing vehicle emissions. Research shows that emissions are generated in greater quantities at intersections with traffic signals than at roundabouts. Therefore, replacing a signalized intersection with a roundabout results in fuel consumption and emissions decreasing (Ahn et al., 2009; Mandavilli et al., 2008).

This paper aims to study the energy and emission problems of road traffic at intersection using computer micro simulation modeling tools (Coelho et al., 2006; Zamboni et al., 2015). Since many consumption models depend on microscopic variables, such as velocity and acceleration, one must start by modeling road traffic for simulation. The kinematic variables of traffic flow are obtained by the simulation of urban mobility (SUMO) tool (Krajzewicz et al., 2002, 2012). Thus, the authors have implemented an instantaneous energy consumption model (Demir et al., 2011) and emissions model (EMIT) (Cappiello et al., 2002).

This work contributes the integration of a microscopic simulation traffic tool with an instantaneous energy consumption and emission model. Secondly, using data collected at the roundabout of Sousse (Tunisia) the authors have studied how intersection type and traffic state influences energy consumption at a roundabout and a crossroad. Finally, this paper introduces a statistic model at a roundabout and crossroad that enables authors to estimate energy consumption while taking into account the hybridization level and traffic demand.

Since increasing traffic congestion causes complications at intersection, the authors have compared the fuel consumption and vehicle emission at a roundabout and crossroad for both congested and uncongested cases. Moreover, they have studied the influence of traffic flow on the two intersections and implemented two energy consumption models for the roundabout and crossroad that combines traffic flow and hybridization level. The hybridization level reflects the percentage of Hybrid Electric Vehicle (HEV) among the total fleet.

This work analyzes microscopic energy consumption and emission traffic models. Secondly, this work describes the implementation's geometry and vehicles dynamic of the crossroad and the roundabout. Thirdly, results are presented to illustrate the influence of intersection type on fuel consumption and emissions in both congested and uncongested cases. Also presented are details about the development of energy consumption models, which take in consideration the traffic flow and hybridization level, for the roundabout and crossroad. Finally, this study's main findings and potential for future research are summarized.

2. Related work

Many studies have investigated energy consumption and the environmental effects present at signalized intersections and roundabouts, but very few researchers have used instantaneous traffic simulation models in conjunction with microscopic energy and emission models. The main contribution of this study is the quantification of energy consumption and emissions using instantaneous models coupled with a microscopic traffic simulator at both a roundabout and crossroad intersection. Authors developed a multiple linear regression model that estimates energy consumption at two types of intersection (i.e., crossroad and roundabout) using the traffic demand and the hybridization level as input variables.

The principal objectives of this paper include studying the influence of intersection type on energy consumption and environmental effects, as well as showing the relevance of hybridization level at an intersection. A study by Mustafa and Vougias (1993) demonstrates that vehicle emissions at signalized intersections exceed emissions at roundabouts by about 50%. In fact, the hydrocarbons (HC) emitted at a signalized intersection is twice as high as what is emitted at a roundabout.

In Sweden, a study of the environmental impacts of roundabouts found that vehicle emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) at roundabouts are 20%–29% less than emissions produced at signal controlled intersections (Hyden and Varhelyi, 2000).

Varhelyi (2002) demonstrated that replacing a signalized intersection with a roundabout generates a reduction in vehicle emissions of CO and NO_x by 29% and 21%, respectively. Fuel consumption is also reduced by 28% at roundabouts.

Mandavilli et al. (2008) used the signalized and unsignalized intersection design and research aid (SIDRA) software to study the environmental impacts of roundabouts. They concluded that HC, CO, NO_x, and CO_2 emissions can be reduced by 65%, 42%, 48%, and 59%, respectively, by converting stop-controlled intersections to roundabouts.

Another study by Ahn et al. (2009) shows that roundabouts do not usually lead to a reduction in vehicle emissions and energy consumption compared to other types of intersection.

Chamberlin et al. (2011) applied the Paramics microsimulation model in combination with the motor vehicle emission simulator (MOVES) and the comprehensive modal emission model (CMEM) to estimate levels of CO and NO_x emissions at intersections. They concluded that, under congested traffic conditions, a pre-timed traffic signal can reduce vehicle emissions compared to a roundabout.

The study by Gastaldi et al. (2014) used a traffic microsimulation tool (S-Paramics) combined with an instantaneous emission estimator (AIRE) to investigate the environmental performance of two intersection types (i.e., roundabout and fixed-time signal control). The authors concluded that a roundabout can decrease pollutants more than a fixed-time signal control.

Clearly, the literature review presents diverse results regarding the energy consumption and environmental impacts at signalized intersections and roundabouts. This is due essentially to road characteristics, vehicle demands, and emission estimation methods (Gastaldi et al., 2014).

3. Modeling energy consumption and emission

There is a variety of analytical emission models, and each estimates fuel consumption differently or takes different parameters into account during the estimation (Demir et al., 2014; Liu et al., 2015). Many factors affect the rate of fuel consumption (Franco et al., 2013; Kim and Choi, 2013), and they can all be categorized into four general groups, vehicle, environment, driver, and traffic conditions. In this study, the authors concentrate on instantaneous consumption and emission models.

3.1. *Instantaneous consumption model*

This model is used to estimate the instantaneous energy consumption of each vehicle on a road section. Characterized by its simplicity and capacity to produce relevant results, this model is used in the present work. Many vehicle characteristics, such as mass, efficiency parameters, drags force, and fuel consumption components associated with aerodynamic drag and rolling resistance, are used (Demir et al., 2011). Thus, the instantaneous energy consumption of a vehicle along an urban roadway section is estimated with the following formula:

$$f_t = \begin{cases} \alpha + \beta_1 R_t v + \dfrac{\beta_2 M a^2 v}{1000} & R_t > 0 \\ \alpha & R_t \le 0 \end{cases} \tag{1}$$

where f_t is the fuel consumption per unit of time (mL/s), R_t is the tractive force, measured in kilo-Newton (kN), required to move the vehicle. It is calculated as the sum of the drag force, inertia force, and grade force:

$$R_t = b_1 + b_2 v^2 + \frac{Ma}{1000} + \frac{gM\omega}{10^5} \tag{2}$$

where a is the instantaneous acceleration ($m \cdot s^{-2}$), v is the speed (m/s) (Bowyer et al., 1985).

The energy consumption of vehicular traffic depends strongly on the vehicles' velocity profiles. Table 1 shows the parameters and respective descriptions used in this paper's model.

Table 1 – Description of energy consumption model parameters.

Parameter	Description
α	Idle fuel rate (mL/s)
β_1	Fuel consumption per unit of energy (mL/kJ)
β_2	Fuel consumption per unit of energy-acceleration ($mL/(kJ \cdot m \cdot s^{-2})$)
b_1	Rolling drag force (kN)
b_2	Rolling aerodynamic force ($kN/(m \cdot s^{-2})$)
ω	Percent grade
M	Vehicle weight (kg)

3.2. *Instantaneous emission model*

Coupled with the traffic simulation model, the microscopic emissions model quantifies vehicle emissions such as emissions from traffic (EMIT) (Cappiello et al., 2002). The EMIT model consists of the engine-out (EO) and tailpipe (TP) emission modules. The first module calculates the instantaneous engine-out emission rates of pollutant i using instantaneous speed v and acceleration a:

$$EO_i = \begin{cases} \alpha_i + \beta_i v + \gamma_i v^2 + \delta_i v^3 + \lambda_i a v & p > 0 \\ \alpha_i' & p = 0 \end{cases} \tag{3}$$

where $\alpha_i, \beta_i, \gamma_i, \delta_i, \lambda_i$ are model coefficients.

For a conventional vehicle, the only power source of tractive power p is the internal combustion engine (ICE):

$$p = Av + Bv^2 + Cv^3 + Mav + Mg\sin(\theta)v \tag{4}$$

where A is the rolling resistance coefficient, B is the speed correction to the rolling resistance coefficient, C is the air drag resistance coefficient, M is the vehicle mass (kg), g is the gravitational constant (9.81 m/s^2), θ is the road gradient.

The second module calculates the instantaneous tailpipe emission rates TP based on the first model emissions (EO_i) and catalyst conversion efficiency (CCE_i).

$$TP_i = EO_i \cdot CCE_i \tag{5}$$

where CCE_i is defined as the ratio of tailpipe to engine-out emissions for pollutant i. It is calculated in the EMIT model as:

$$CCE_i(t) = m_i EO_i(t) + q_i \tag{6}$$

Table 2 summarizes the different values of EMIT parameters for each estimated pollutant.

The tailpipe emission of CO_2 is not markedly different from the engine-out (Ma et al., 2012).

The EMIT model allows to estimate the engine emissions first and then the tailpipe emissions. In fact, vehicle emissions are greatly influenced by vehicle speed and acceleration, as well as by the vehicle's make and model.

4. Hybrid electric vehicle

Hybrid electric vehicles (HEV) are one solution to the world's need for cleaner and more fuel-efficient vehicles. In fact, HEV technology is vital to the overall automotive industry, as well as to the user, in terms of both better fuel economy and environmental effect (Mi et al., 2011). HEV uses the engine and an electric motor/generator for propulsion. Moreover, it uses the power of electronic converters and batteries in addition to mechanical and hydraulic systems (Lam and Louey, 2006; Zhao et al., 2013).

The major benefits of HEV include efficiency through improved technology, such as regenerative braking, less engine idling, and efficient engine operation. Additional benefits are better energy consumption and drivability, since electric motor characteristics better match the road load and reduce

Table 2 – EMIT parameters.

Pollutant i	α_i'	α_i	β_i	γ_i	δ_i	λ_i	m_i	q_i
CO_2	0.63284	0.15797	−0.00925	0.00039	0.17096	0.70556	–	–
NO_x	0.00030	0.01420	0.03870	−0.00240	7.37×10^{-5}	0.00530	0.00880	0.03960
CO	0.02760	12.40350	0.02500	0.00370	0.00080	0.15380	0.00150	−0.01520

vehicle emission and energy consumption (Lajunen, 2014; Lim et al., 2014). The advanced vehicle simulator (ADVISOR) (Markel et al., 2002), is used to model the energy consumption and emissions of HEV. ADVISOR was created in Matlab/Simulink tool so that each subsystem is associated to a Matlab file. Moreover, the program is more flexible for users, offering the possibility to modify blocks if needed (Markel and Wipke, 2001).

5. Description of SUMO and data collection

5.1. *Description of simulation of urban mobility*

Description of simulation of urban mobility (SUMO) is a traffic simulation tool that was implemented in 2002 (Krajzewicz et al., 2002). It is an open source road traffic simulation package based on microscopic car following models (Han et al., 2012; Krauss et al., 1997). SUMO contains a suite of applications and requires a description of road networks and traffic demand. SUMO road networks include intersections, junctions, and traffic lights. The demand file uses existing origin destination (O-D) matrices, converting them into route descriptions. Much information is needed to build a route file, such as the vehicle's physical properties and the route it takes. Moreover, specific descriptions, such as acceleration, deceleration, vehicle length and maximum speed, and should be taken into account.

5.2. *Data collection*

The authors collected available data by video in two steps. The first involves videotaping traffic movements at intersections with a video camera, and the second includes visually obtaining traffic counts from the video. The camera is designed to provide a full view when mounted above the intersection, and it was placed near the roundabout to monitor the traffic flow both coming towards and leaving the roundabout. The camera was mounted perpendicular to the ground, allowing the video image to be relatively distortion free in all directions.

The number of cars passing through each section was controlled through each section every 5 min between 06:00 and 10:00 a.m. The authors measured also the turning movements of each section for all vehicles that pass through the roundabout. To determine the passing direction, the authors measured the traffic flow from one direction to the other three directions (e.g., turning left, going straight, and turning right).

6. Implementation of crossroad and roundabout of Sousse (Tunisia) using SUMO

An intersection's geometric design is of a great interest for security. The authors of this study implemented two types of intersections—roundabout and crossroad—using SUMO. A roundabout offers simple traffic control and less traffic conflict points.

An intersection consists of incoming and outgoing edges, where an "edge" represents a road with two lanes. The geometric dimensions of the Sousse roundabout are obtained with real measurements. Fig. 1 illustrates the characteristics of the roundabout and crossroad, and Table 3 contains real dimensions of the Sousse roundabout, which is composed of four entry points and four exit destinations. It is one of the most important roundabouts in Tunisia because it is located

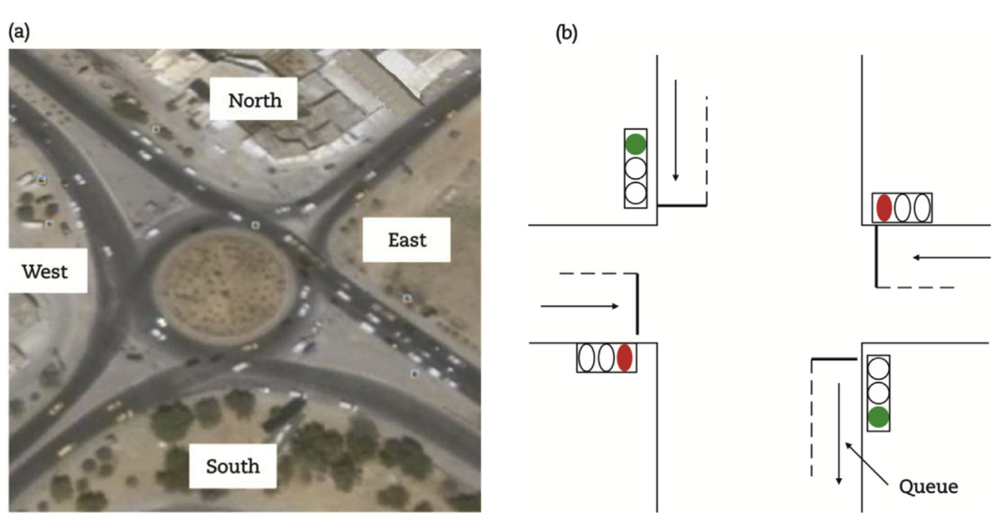

Fig. 1 – Characteristic of Sousse roundabout and crossroad. (a) Sousse roundabout. (b) Crossroad.

Table 3 – Roundabout characteristics.

General characteristics				
Inscribed circle diameter (m)	40.30			
Central island diameter (m)	36.50			
Circulatory roadway width (m)	12.80			
Approach characteristics				
Approach	North	East	South	West
Number of entering lanes	2	2	2	2
Number of exiting lanes	2	2	2	2
Entry width (m)	12.13	11.68	12.50	12.30

in an active zone near a university campus. It connects to a university hospital (Sahloul Hospital) in the west, the urban road to the east, the center of the city to the north, and industrial zones to the south. The roundabout has a central island diameter of 36.50 m, and the circulating lane widths range from 11.68 to 12.50 m.

The crossroad geometry dimensions were approximated to the Sousse roundabout dimensions in order to illustrate the influence of type intersection on energy consumption. The real dimensions of both the roundabout and crossroad are used as inputs to implement them using SUMO (Fig. 2).

To estimate fuel consumption and emissions, the micro-simulation tool that integrates an instantaneous consumption and emissions model is coupled with SUMO. The flowchart in Fig. 3 explains the coupling process. The microscopic kinematic variables, such as velocity and acceleration for each vehicle, are obtained by using SUMO to simulate the dynamic traffic flow. The traffic simulation output results are used as inputs for the instantaneous consumption and emissions models.

7. Results and discussion

7.1. *Influence of congestion on energy consumption and emissions*

The rapid rise of traffic demands has led to increasingly severe congestion. Thus, proper management of vehicle flow at intersections can significantly reduce congestion problems. Fig. 4 shows the entering flow to the Sousse roundabout during the hours between 06:00 and 10:00 a.m. To illustrate, a Tuesday has been selected to represent a working day characterized by good weather conditions. In addition, the authors present the turning flow proportion that reflects the origin-destination flow distribution throughout the intersection in Table 4.

More precisely, the authors present the evolution of traffic flow in Fig. 5 to illustrate the congested and uncongested phases. The congested phase ranges from 07:45 to 08:45 a.m., and the uncongested period lasts between 09:00 and 10:00 a.m.

Table 5 illustrates the energy consumption and emissions in congested and uncongested cases of a roundabout and crossroad. The authors estimate important pollutants (CO, NO_x, CO_2) using EMIT model.

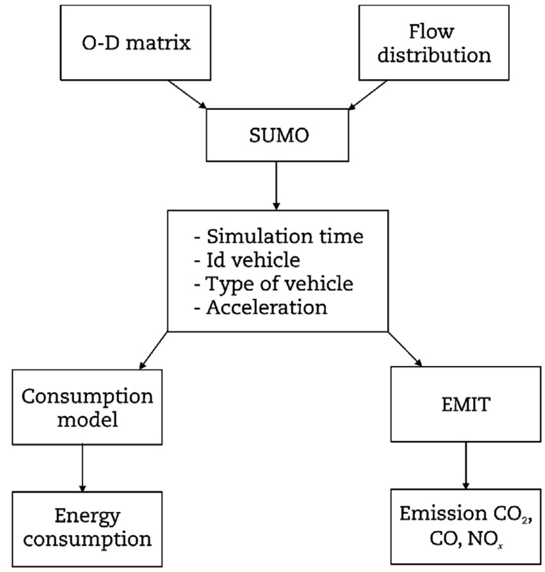

Fig. 3 – Simulation of energy consumption and emissions for roundabout and crossroad.

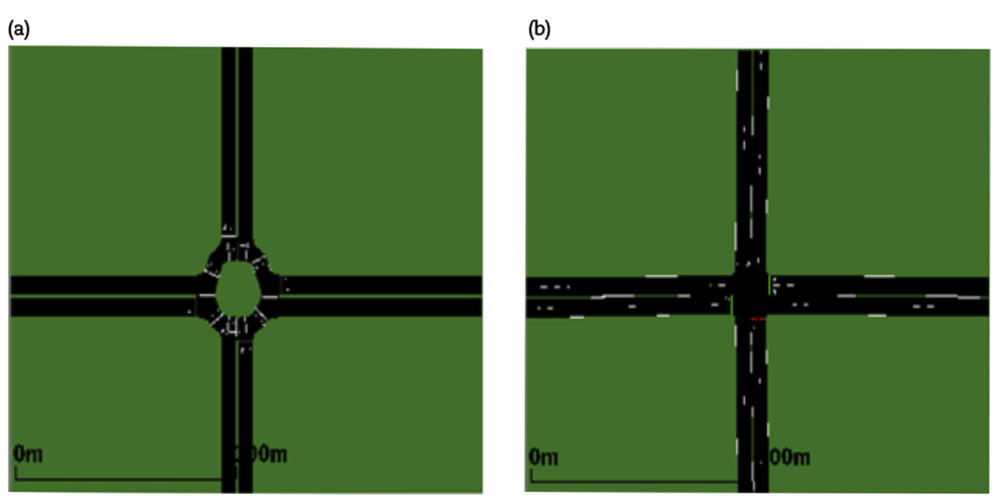

Fig. 2 – Implementation of Sousse roundabout and crossroad using SUMO. (a) Sousse roundabout. (b) Crossroad.

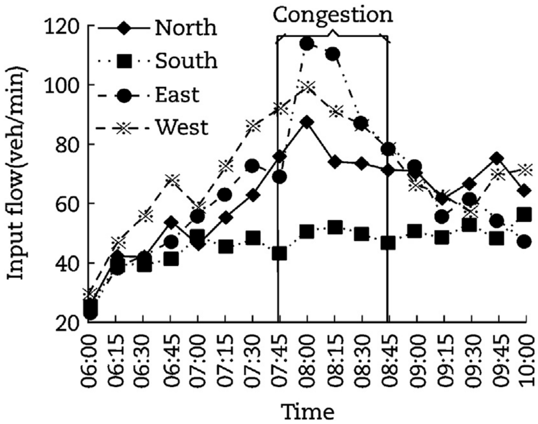

Fig. 4 – Entering flow proportion for Sousse roundabout.

The energy consumption and vehicle emissions at the roundabout are less than the crossroad for congested and uncongested cases. Thus, the geometric characteristics of the intersection type have important effects. Traffic signals require vehicles to stop at a red signal, which increases negative impacts such as delay time and vehicle consumption and emissions. However, the roundabout generates a positive impact on the environment since it is a viable alternative to reducing vehicular emissions.

The energy consumption and emissions for the congested case exceed that for the uncongested case. This is due to higher speed fluctuations and frequent stops that occur with congestion, which increases the fuel consumption and consequently results in higher emissions. When vehicles must wait at signals to cross intersections, drivers keep the engines on and, as a result, extra fuel is consumed.

Table 4 – Percentage of origin-destination flow.

Origin	Destination			
	North (%)	South (%)	West (%)	East (%)
North	0.00	87.44	3.34	9.22
South	72.16	0.00	11.70	16.32
West	14.14	10.50	0.00	74.64
East	13.50	2.06	84.96	0.00

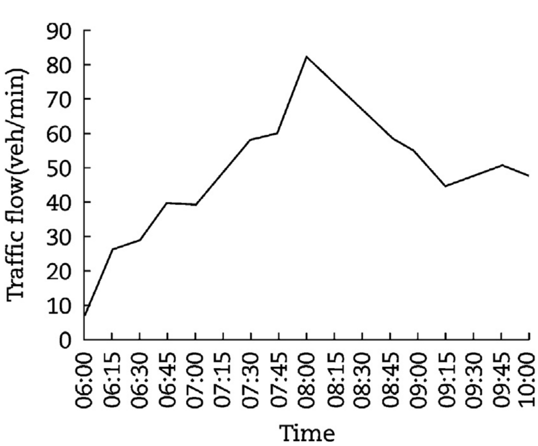

Fig. 5 – Evolution of traffic flow.

Different studies have different results. For example, studies conducted in Sweden found that turning a signalized intersection into a roundabout can produce savings in CO and NO_x emissions by 29% and 21%, respectively, and fuel consumption by 28% (Varhelyi, 2002). Another research using SIDRA software revealed that a roundabout could save HC, CO, NO_x, and CO_2 emissions by as much as 65%, 42%, 48%, and 59%, respectively (Mandavilli et al., 2008).

7.2. *Influence of traffic flow (demand) on energy consumption at a roundabout vs. a crossroad*

The authors have computed energy consumption for different flow levels (e.g., normal flow to a saturated flow). Fig. 6 describes the evolution of energy consumption versus traffic flow in two phases: before and after saturation flow. Before the saturation phase energy consumption increases with the increase of traffic flow. The increase of traffic flow leads to the raise of energy consumption until saturation flow. The second phase (after saturation) is characterized by an increase in fuel consumption versus a significant reduction in traffic flow. This is due to the saturation flow at intersections. In fact, the ever increasing vehicular flow at roundabouts and crossroads are one of the major causes of environmental and energy problems.

Comparing the two types of intersections, the authors note that energy consumption at crossroads exceeds energy consumption at roundabouts. The main cause of increased energy consumption at crossroads is the slowing and stopping of vehicles during the red phases. Thus, the engine's stop and go positions, braking, and acceleration significantly affect a vehicle's fuel consumption and emission rates. In contrast, the roundabout is an efficient type of intersection control, and can improve traffic flow by reducing intersection delays and stopped vehicles.

Fig. 6 describes the main finding that roundabouts have significant advantages in terms of energy consumption compared to crossroad intersections. Also, traffic flow greatly influences energy consumption both at roundabouts and crossroad intersections.

7.3. *Impact of hybridization level on energy consumption at roundabouts and crossroads*

A linear regression analysis was used to study the influence of hybridization level and traffic flow on energy consumption for both types of intersections (i.e., roundabout and crossroad). The data used were collected from Sousse roundabout between the hours of 06:00 and 10:00 a.m. The entering flows range from 0.2 veh/s to 0.45 veh/s for congested and uncongested cases. The following formula presents the developed regression model:

$$c_i = \beta_0 + \beta_1 F + \beta_2 H + \epsilon \quad i = \text{round, cross} \tag{7}$$

where c_{round} and c_{cross} are designed energy consumption for the roundabout and the crossroad, *F* and *H* are input variables of flow and hybridization, respectively.

The regression results in Table 6 show that the energy consumption near a roundabout or signalized intersection

Table 5 – Energy consumption and vehicle emissions for uncongested and congested cases.

Intersection type	Uncongested case			Congested case		
	Crossroad	Roundabout	Difference (%)	Crossroad	Roundabout	Difference (%)
Energy consumption (L/100 km)	16.736	11.827	41.50	25.110	21.760	15.39
CO_2 emission (g/km)	314.384	264.110	19.03	585.931	436.293	34.29
NO_x emission (g/km)	0.179	0.130	37.69	0.365	0.187	95.18
CO emission (g/km)	2.345	1.610	45.65	4.401	2.837	55.12

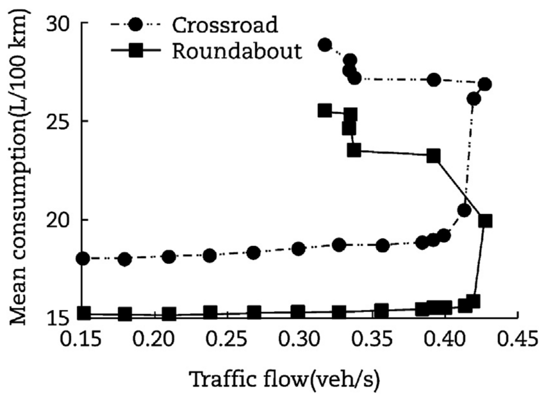

Fig. 6 – Evolution of energy consumption for different levels of traffic flow.

can be modeled as the linear combination between traffic flow and hybridization level.

The energy consumption models are statistically significant for the roundabout and crossroad. Furthermore, the fleet level of hybridization and entering flow largely affect fuel consumption. Thus, all the input independent variables (traffic flow and hybridization level) can explain the dependent variable (energy consumption).

The multicollinearity verification among variables indicates that the variance inflation factor (VIF) values are all less than 10, meaning there is no multicollinearity. Therefore, multiple linear regressions are appropriate for the energy consumption estimation at both the crossroad and roundabout.

By analyzing the results shown in Table 6, one can see that the influence of the hybridization level and flow variables on energy consumption for the roundabout exceeds that for the crossroad. This is due essentially to the geometric characteristics of the intersection type and traffic rules. As a result, the increasing delay time at crossroad intersections is due to the traffic light. However, the process of entering the roundabout only requires respecting the minimum-security distance. Moreover, the regenerative braking mode generated by the stop and go maneuver affects the fuel consumption.

In conclusion, the intersection type, hybridization level, and traffic demand are notable factors in the analysis of energy consumption and proposal of new strategies to manage and reorganize road traffic. In analyses of mean absolute percentage error (MAPE), the crossroad and roundabout error values are 2.03% and 1.45%, respectively. Residual analyses indicate that the linear regression approach is reasonable. There are no large differences between the measured and predicted values.

To illustrate the influence of hybridization level on energy consumption for the roundabout and crossroad, the authors present the evolution of mean energy consumption versus hybridization level in Fig. 7. The total mean consumption (c_{mean}) is obtained by the following equation (Boubaker et al., 2015; Zahabi et al., 2014):

$$c_{mean} = \frac{\sum_{j=1}^{N} \int_0^T c_j(t)dt}{\sum_{j=1}^{N} \int_0^T v_j(t)dt} \tag{8}$$

where $c_j(t)$, $v_j(t)$, N and T respectively represent the instantaneous energy consumption, instantaneous velocity of vehicle number j, total number of vehicle, and total time.

The hybridization level largely influences the mean energy consumption for both the roundabout and crossroad, and for both congested and uncongested case.

8. Conclusions

In recent years, significant interest in energy consumption and vehicle emissions, combined with the influence of vehicle technology, has grown globally. The present study reveals the energy and environmental impacts of a crossroad and roundabout. Hybrid electric vehicles play an important role in

Table 6 – Results of multiple linear regressions.

		Estimated value	t-statistic	R^2	$F_{statistic}$	VIF
Roundabout	β_0	15.830	91.08	0.96	576	1.23
	β_1	2.361	15.14			
	β_2	−4.150	−30.38			
Crossroad	β_0	18.640	73.30	0.95	458	1.06
	β_1	1.790	7.85			
	β_2	−5.843	−29.40			

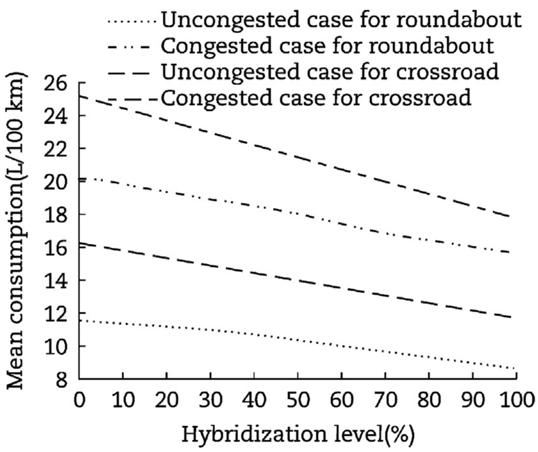

Fig. 7 – Effect of hybridization level on energy consumption for roundabout and crossroad.

reducing fuel consumption and emissions. The authors have developed instantaneous energy consumption and emission models coupled with a road traffic simulator (SUMO). As a result, the authors illustrate the influence of congestion and demand variation (traffic flow) on energy consumption and vehicle emission for crossroads and roundabouts using real data collected from the Sousse roundabout. The collected data are used as input for both the crossroad and roundabout in order to illustrate the influence of intersection geometry on energy consumption and emissions.

The authors have also developed an energy consumption model for the roundabout and crossroad, taking into account the hybridization level and traffic demand. The results underscore the importance of intersection type in reducing energy consumption and vehicle emissions. Hybridization technology also considers an important solution in reducing consumption and emissions. Future research, such as studying energy consumption and emissions at road traffic networks, can enhance this paper's contribution. In addition, the authors can integrate the hybridization and electrification of the vehicular fleet to promote sustainable consumption.

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