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A new simulation approach of estimating the real-world vehicle performance

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Abstract

Due to the variability of real traffic conditions for vehicle testing, real-world vehicle performance estimation using simulation method become vital. Especially for heavy duty vehicles (e.g. 40 t trucks), which are used for international freight transport, real-world tests are difficult, complex and expensive. Vehicle simulations use mathematical methods or commercial software, which take given driving cycles as inputs. However, the road situations in real driving are different from the driving cycles, whose speed profiles are obtained under specific conditions. In this paper, a real-world vehicle performance estimation method using simulation was proposed, also it took traffic and real road situations into consideration, which made it possible to investigate the performance of vehicles operating on any roads and traffic conditions. The proposed approach is applicable to all kind of road vehicles, e.g. trucks, buses, etc. In the method, the real-road network includes road elevation. The traffic conditions and vehicles parameters were the inputs for traffic simulation. Based on the outputs (speed profiles and elevations) of target vehicles in the traffic simulation, then the real-world performance of the vehicle was achieved by vehicle simulation under the given traffic conditions. The fuel consumption of the vehicle calculated using this method was 34.00 L/100 km under free traffic flow conditions over highway route.

Introduction

A large amount of fossil fuel was consumed by automobiles, which partly leads to the environmental pollution [1, 2], also aggravates the dependency of fossil fuel importation. The emission factors (g/km) of exhaust pollutants and fuel consumption (L/km) for heavy duty vehicles were much higher than light duty vehicles [3, 4, 5], which led to a large contribution to the total fuel consumption and exhaust emissions of vehicle transport. In the real-driving conditions, vehicle performance changes significantly over different road situations. In order to have a globally common point of reference, new driving cycles, e.g. Worldwide harmonized Light vehicles Test Cycles (WLTC) [6] and World Harmonized Transient Cycle (WHTC) [7], were established for light and heavy duty vehicles. WLTC was divided into four segments based on vehicle speed (low, medium, high and extra high) to represent different types of road conditions. Completely different from WLTC, it is a transient engine dynamometer test for WHTC, where the engine speed and load profiles were pre-defined based on engine characteristics. Significant of work has been done to research vehicle performance based on the given driving cycles [8, 9, 10, 11]. Tsokolis [12] investigated the fuel consumption and carbon dioxide (CO_2) emission over WLTC using 12 gasoline vehicles and 8 diesel vehicles, and analyzed the differences between New European Driving Cycle (NEDC) and WLTC. CO_2 emission under NEDC ranged from 105.4 to 213.2 g/km, while it was from 125.5 to 217.9 g/km for WLTC, which was caused by the frequent changes of vehicles speed in WLTC. Frequent acceleration and deceleration lead to much energy loss. Ko et al. [9] studied NO_x emission factor of a Euro 6 compliant diesel vehicle equipped with a Lean Nitrogen Oxide (NO_x) Trap (LNT) over WLTC and NEDC. More LNT regenerations happened for WLTC than NEDC, which implied more engine-out NO_x emission for WLTC. Real-world tests [13, 14] were also done to further analyze vehicle fuel consumption and emissions under real-road situations, which indicated that the real world test conditions were complex. There are still great differences for vehicle emissions between real world test and lab results. Luján et.al [15] tested the gaseous emissions from a Euro-6 complaint light duty vehicle under real-world conditions, it indicated that acceleration at low vehicle speed caused high NO_x emission, and cold start showed strong, moderate, and low impact on carbon monoxide (CO), hydrogen carbon (HC) and NO_x emissions, respectively. Fuel consumption over WLTC is more sensitive to road load changes than NEDC [16].

As a supplementary of the tests under given driving cycles in labs and real-world, simulations also provide a significant insight into the explorations of vehicle performance under scenarios where the test are difficult to conduct. A diesel turbocharged light van was used to investigated the effect of wind speed, road grade, surface wetness, tire pressure and auxiliaries' power on fuel consumption and emissions over WLTC using simulation model [16]. The authors indicated that the road grade had the greatest impact on CO_2 emission, whose emission factor increase reached 116.8% when the road grade increases from 0% to 8%. Mansour et al. [17] estimated additional fuel consumption resulting from auxiliary needs on WLTC that cooling and heating for cabin increased the fuel consumption by 43% and 59%, respectively. Currently, vehicle simulations are based on the speed profiles suggested in emission regulations or the tested vehicle speed profiles [6, 16, 18]. However, it's difficult to conduct vehicle test under desired real-world situations, which are uncontrollable for some factors, such as traffic lights, congestion conditions, and traffic flow. Real-world vehicle performance estimation, considering the road and traffic conditions, is an alternative method to precisely investigate the vehicle performance under different real-world conditions with high precision. VECTO (Vehicle Energy Consumption calculation TOol) [19] is a new method for heavy duty vehicle simulation, which contains the road information. The tool has been mandatory for some new trucks in application to the certification legislation. In the driving cycle, parameters such as rolling resistance, aerodynamic drag, mass and inertias, gearbox friction, auxiliary power and engine performance are inputs to simulate the vehicle fuel consumption and CO_2 emission. Greenhouse Gas Emissions Model (GEM), as the other tool to simulate CO_2 emission, can effectively estimate vehicle CO_2 emission. While GEM tool does not provide the flexibility, as many parameters use the built-in default inputs and cannot be modified by the user [20].

In this paper, a real-world vehicle performance estimation using simulation approach is proposed. It considers traffic and vehicle simulations conducted under desired real-world conditions, where traffic conditions were set based on necessity. The vehicle and traffic simulations were done using GT-suite and SUMO, respectively. The heavy duty vehicle model was validated using tested data based on a real-world driving on a motorway, where the vehicle fuel consumption, speed and movement trajectory (including elevation) were recorded. The heavy duty vehicle fuel consumption was simulated and analyzed under different congested motorway. The vehicle speed was optimized under light congested scenario using model predictive control (MPC) strategy, and the fuel consumption before and after optimization was compared. This approach is applicable for all kinds of vehicles, and a heavy duty truck is taken as the example in this paper. This method can be used for the individual vehicle performance evaluations, and traffic fuel consumption and emission estimations under specific road conditions.

Methods

The methods of traffic and vehicle simulations

Majority of the vehicle simulations using commercial software are based on the given driving cycles, such as NEDC[21], Federal Test Procedure (FTP) [5], and WLTC [22]. These driving cycles only consider specific traffic conditions which are not exactly the same with the real-world driving. It was demonstrated by Solomon [23] such that fuel consumption and exhaust pollutants significantly depended on road grade. Unavailability of real-road makes it less possible to simulate the vehicle performance under real-world (traffic and road situations) conditions. Also, it is difficult to investigated the effect of traffic conditions on fuel economy. Figure 1 shows a approach of real-world performance estimation considering traffic and road conditions. The real-world performance estimation combined traffic and vehicle simulations using commercial software. The traffic simulation is performed using SUMO software [24], and the vehicle simulation is done based on GT-Suite platform. The details of the real-world performance estimation is as the follows: 1) 2D real-road network transformation; 2) integration of the road elevation and 2D real-road network; 3) targeted network extraction; 4) real-road network and traffic information loading; 5) vehicle performance simulation considering traffic and road conditions. In order to make the simulation close to the real-world simulation, the crossways of the target road with others were kept in the 3rd step. The real information of the road networks, e.g. number of lanes, road geometries, speed limitations, and priorities, was included in 2D OpenStreetMap, except for the road elevation. The road elevation data (from NASA SRTM) was integrated into the real-road network using commands indicated in osmosis-srtm-plugin instructions [25]. The traffic demands were imported using SUMO code, where the traffic flow, vehicle types, vehicle routes, maximum speed, and maximum acceleration were set. SUMO traffic simulator and Matlab were integrated in TraCI4Matlab platform [26]. The vehicle speed monitor and optimization using MPC were conducted in Matlab. Madireddy et al. [27] combined the microscopic traffic simulation model including vehicle emission, however, the emission model was set up based on the vehicle speed and acceleration. This method has a low precision, results from the lack of vehicle details, such as engine working conditions, gear shift strategies, which is different from the authors' work, where both vehicle details and traffic conditions are taken into consideration.

Vehicle model validation

Table 1 show the basic parameters of the heavy duty vehicle, which is powered by a 12.7 L diesel engine. The maximum engine power output is 368 kW, the gross mass of the vehicle is 40000 kg. Figure 2 is the brake specific fuel consumption (BSFC) map of the internal combustion engine, whose minimum value was ~190 $g\cdot(kW\cdot h)^{-1}$, the optimal fuel economy zone of the engine operation was located at the medium speed (1150 rpm~1450 rpm) and high engine load conditions. BSFC map is the basic input parameters of the vehicle model to calculate fuel consumption.

Table 1. Basic parameters of the heavy duty vehicle

Specifications		Values
Brand		Ford
Axle configuration		4×2
Cabin	Full width	2.54 m
	Total height	3.915 m
Engine	Type	Ecotorq 12.7 L
	Emission level	E6D
	Power	368 kW @ 2100 RPM
	Torque	2500 Nm @1000-1400 RPM
	Compression ratio	17
Transmission		Automated 12 speed
Gross mass		40000 kg
Rolling resistance factor		0.005
Front area/ m^2		8.5
Drag coefficient		0.5
Transmission		Automated ZF 12TX2620

Gear mechanical efficiency	96%
Axle friction torque coefficient	0.015 N·m·minute/rev

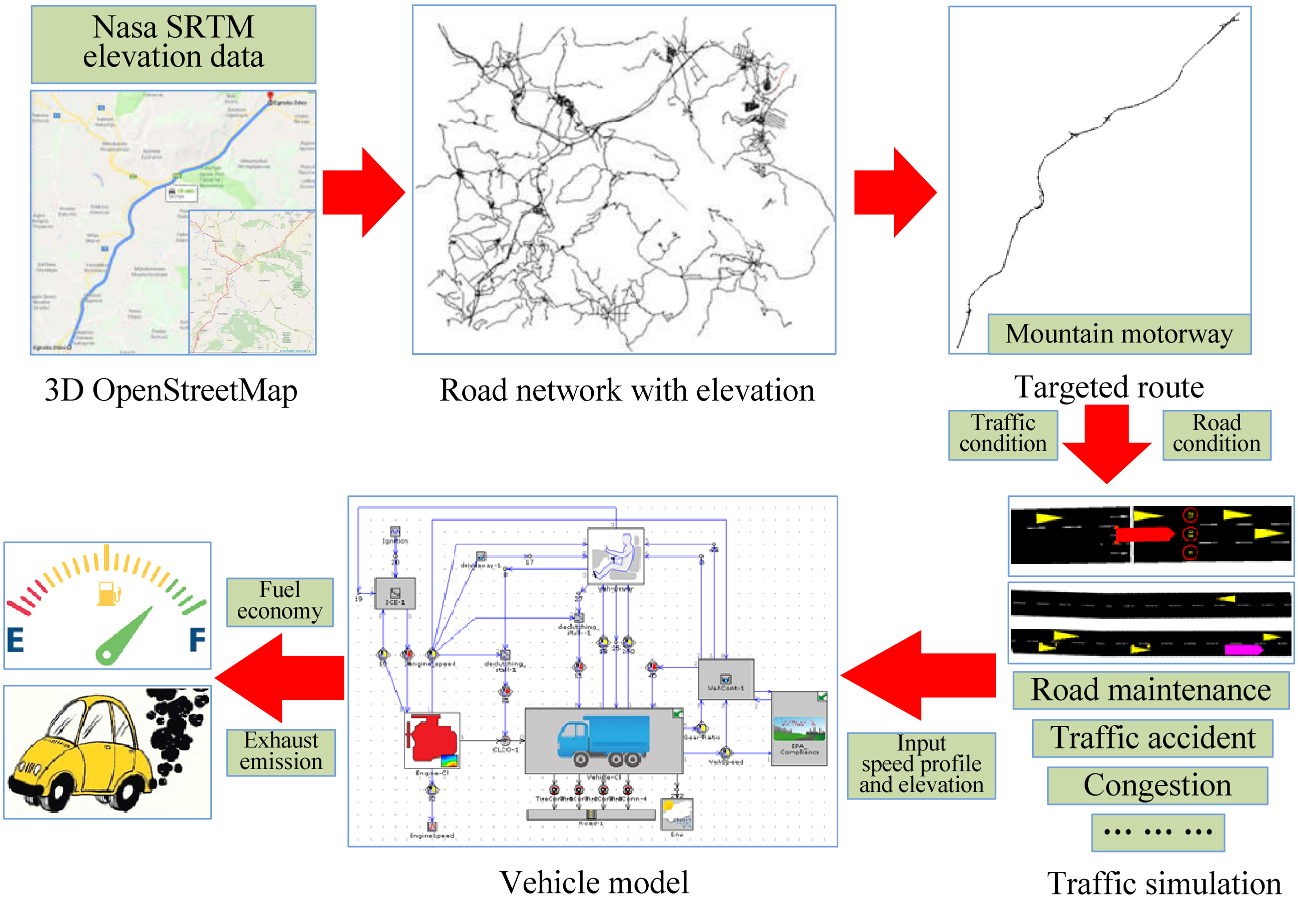


Figure 1. The method of real-world vehicle performance estimation [28]

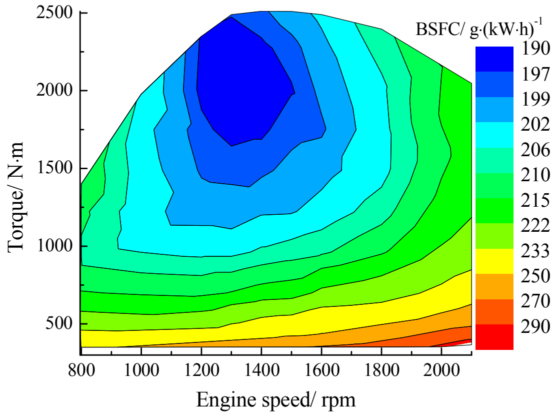


Figure 2. BSFC map

The vehicle model was validated using the real test data on a motorway of Turkey, the tested vehicle speed and road elevation are shown in Figure 3. The road elevation varies from 90 m to 150 m, and the journey lasted 60 km, which contains two segments of vehicle aggressive deceleration (smaller than -2 m/s^2), during which the vehicle speed decelerated from 90 km/h to 8 km/h in a short distance. The validation results of the vehicle model are shown in Figure 4. The vehicle fuel consumption is tested under real-world situations. As can be seen from the figure, such that the error between test data and simulation results is higher for low fuel consumption conditions than high fuel consumption. As it accounts for a high percentage of energy consumption for engine friction loss, which changes greatly with engine speed, torque and lubricating oil temperature. The R^2 reached 0.93 which indicated a high precision of the vehicle model. Due to the commercial confidential of the test results, the absolute fuel consumption was converted into the normalized fuel consumption by dividing the maximum fuel consumption during the journey.

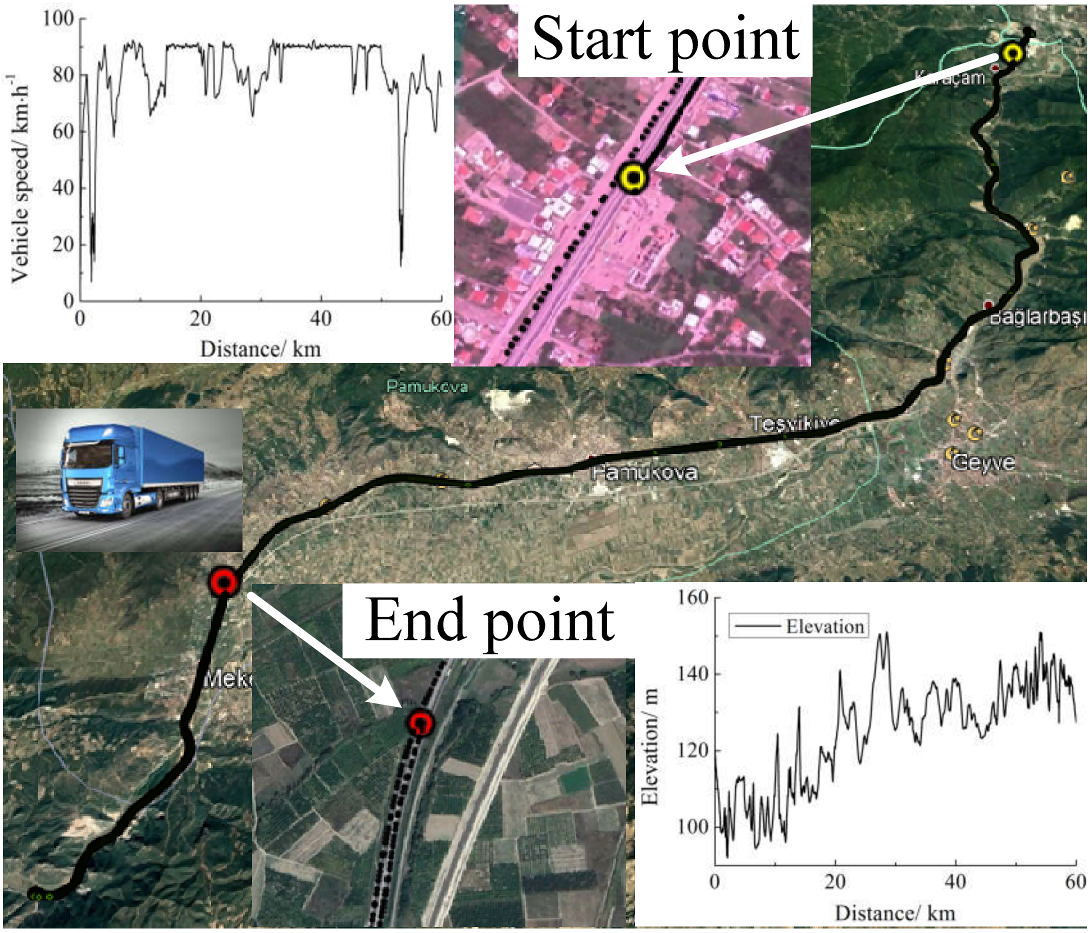


Figure 3. Real-world test on Motorway

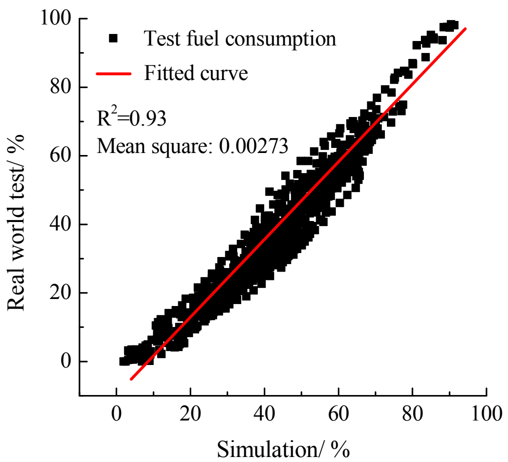


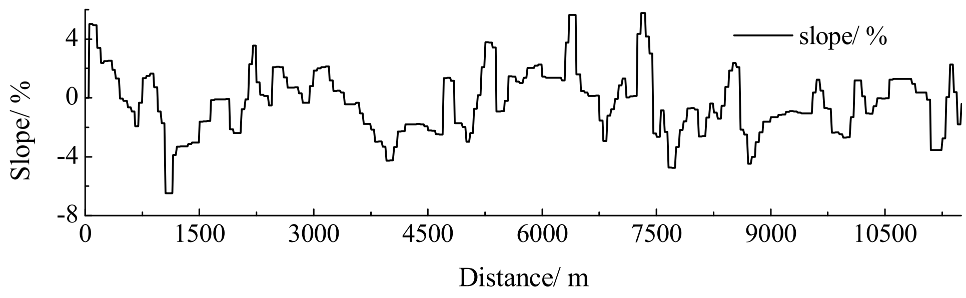
Figure 4. Vehicle model validation using the real-world test

Vehicle speed optimization

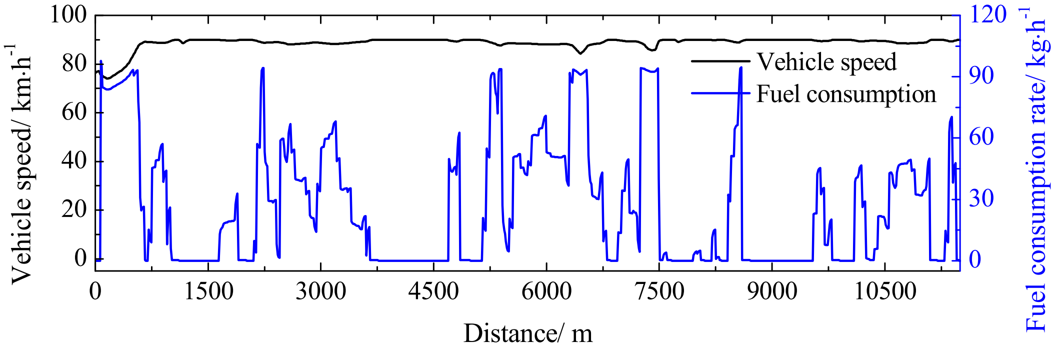
As mentioned above, SUMO was integrated with Matlab to monitor target vehicle speed. Under road congested conditions, the vehicle speed is always in the process of acceleration and deceleration, which significantly worsen the vehicle fuel economy. In this paper, MPC was also used to optimize vehicle speed. MPC is achieved by two trucks in the journey. The first truck is the baseline truck, which travelled 20 seconds in advance of the second truck, which optimized the speed from the first truck to achieve a better energy utilization (wheel energy). The interval of the two trucks are short to ensure they have similar traffic conditions. The energy consumed on the wheels is the optimized target to decrease the vehicle fuel consumption, despite there is a slight difference between energy consumption on wheels and engine. The vehicle speed optimization was done using the self-programmed code in Matlab.

Results and discussion

It is difficult to investigate the effect of traffic conditions on vehicle fuel consumption and exhaust emissions using the given driving cycles in regulations. Especially for the heavy duty vehicles, the emission regulations are focused on the second-by-second engine test, which makes it more important for real-world vehicle performance estimation, where the traffic conditions are controllable. This methodology is suitable for all kinds of vehicles, the heavy duty vehicle is taken as the example in this part. Figure 5 shows the real-world vehicle performance estimation results under the free traffic flow conditions, and the vehicle is fully loaded. The road slope varies from -6% to 6%, and it changes frequently, which increases the frequency of driver harshly pressing the acceleration and deceleration pedals. The vehicle speed was almost kept at 90 km/h, except for some sections where the road grade was nearly 6% such that the engine couldn't provide enough power to keep the high speed operation. It causes a sudden decrease of the vehicle speed in part of the journey. There are large amounts of sections where vehicle operates without fuel consumption, resulting from the joint actions of vehicle speed change and road slope. For the modern engines, the fuel cut-off technology is used to decrease the fuel consumption under some operating conditions. The high vehicle fuel consumption was mainly caused by high road slope.



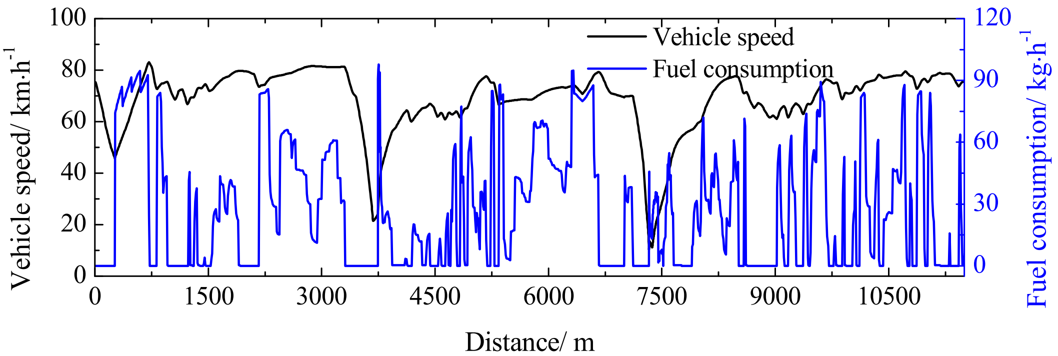
(a). road slope along the journey



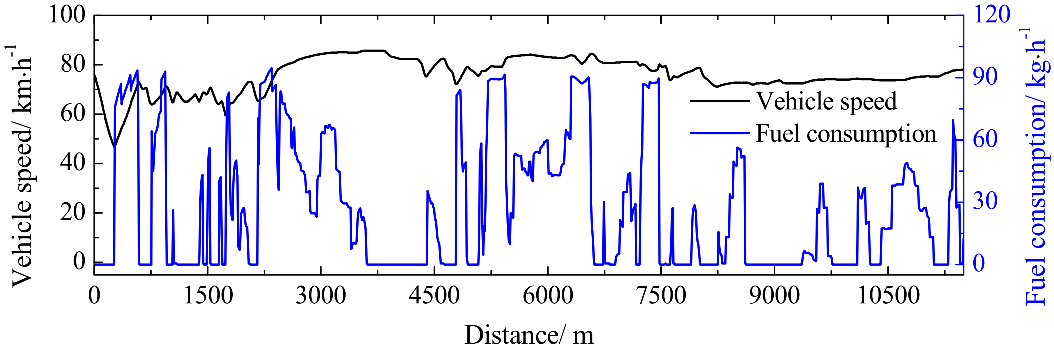
(b). vehicle speed and fuel consumption

Figure 5. Vehicle simulation under free flow traffic conditions

The vehicle speed and fuel consumption rate under real-world vehicle performance estimation are shown in Figure 6. Compared with the free traffic flow condition, vehicle speed changed frequently under real-world conditions. As indicated in Figure 6 (a), vehicle speed dropped greatly around the positions of 3700 m and 7400 m, which is caused by the sudden deceleration. Frequent and significant changes of vehicle speed led to bad vehicle fuel economy. In order to increase the fuel economy, MPC was used to optimize the vehicle speed profile synchronously, the results are shown in Figure 6 (b). Aggressive deceleration and acceleration are avoided in the optimized vehicle speed, and the overall vehicle speed is higher than that before optimization. Most of the vehicle operation points having high fuel consumption rate are caused by high road slopes and acceleration. In the authors' future work, vehicle fuel consumption will be the optimized target, which will be more accurate than the wheel energy consumption.



(a). before optimization



(b). after optimization

Figure 6. Vehicle speed and fuel consumption under light congested real-world conditions

Table 2 summarizes the vehicle performance under three scenarios. It is obvious that the vehicle fuel economy was the best under the free traffic flow conditions with the values of 34 L/100 km, and the average vehicle speed was 88.6 km/h. The fuel consumption increased significantly when light congestion happened on the road (44.44 L/100 km), and it improved by 10.76% (39.66 L/100 km) after vehicle speed optimization.

Table 2. Summary of the simulations under different traffic conditions

Scenarios	Fuel consumption/ L/ 100 km	Average power/ kW	Average speed/ $km \cdot h^{-1}$
Free traffic flow	34.00	129.9	88.6
Light congested	44.44	125.7	63.8
Optimization	39.66	133.3	75.1

Conclusion

Current vehicle performance simulations based on the driving cycles proposed in the emission regulations contain little information about the real road and traffic conditions. The real-world vehicle performance test has many limitations, as the real traffic conditions are not controllable in real world situations. To the authors' knowledge, the vehicle performance simulation approaches considering real road and variable traffic conditions are limited to data. This paper proposed a new approach of real-world vehicle performance estimation, which combined traffic and vehicle simulations. This methods can effectively simulate the vehicle performance under real-world situations with relative high precision. Also, the effect of traffic conditions on vehicle performance can be conducted. As for the targeted road in this paper, the vehicle fuel consumption rate changed significantly, which was mainly caused by road slopes. The great acceleration during vehicle operations caused high fuel consumption rate on part of road, while high negative road slope also caused zero fuel consumption rate. The fuel consumption of the vehicle was 34.00 L/100 km under the free traffic flow, and it was 44.44 L/100km for light congested situation, under which the vehicle fuel economy improved by 10.76% after vehicle speed optimization using MPC method. In the authors' future work, vehicle simulation and traffic simulation will be coupled based on Matlab platform rather than separate simulation.

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Definitions/Abbreviations

WLTC - Worldwide harmonized Light vehicles Test Cycles
WHTC - World Harmonized Transient Cycle
CO_2- carbon dioxide
NEDC - New European Driving Cycle
NO_x - nitrogen oxide
LNT - lean nitrogen oxide (NO_x) trap
CO - carbon monoxide
HC - hydrogen carbon
MPC - model predictive control
FTP - Federal Test Procedure
BSFC - brake specific fuel consumption