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Original Article

Research on the Forecast of Fuel Consumption of Cars by a Combination of Simulation and Experiments

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Abstract - *The paper presents a study on the fuel consumption of passenger cars using a combination of simulation and experimentation. The study used MATLAB/Simulink software to simulate the fuel consumption of gasoline-powered sedan cars under three operating conditions: urban, highway and mixed. The simulation results show that the corresponding fuel consumption is 6.86 L/100 km under urban conditions, 5.21 L/100 km under highways, and 6.00 L/100 km under mixed conditions. Road experiments were conducted over five driving cycles with a total distance of 169.3 km; from the measured fuel consumption, the average fuel consumption of the converted vehicle is about 5.78 L/100 km. The experimental results also show that fuel consumption gradually increases from highway, steep, suburban, mixed to urban road conditions, with the urban driving cycle showing the highest fuel consumption. Comparisons between simulations and experiments show that fuel consumption is consistent, with a difference between the mixed simulation value and the average experimental value of 3.68%. The research results confirm that the method of combining simulation and experiment in evaluating and forecasting the fuel consumption of cars under actual operating conditions is appropriate and reliable.*

Keywords - *Driving cycles, Fuel Consumption, Matlab/Simulink Software, Road tests, Vehicle Driving Resistance Model.*

1. Introduction

The fuel consumption of passenger cars is an important indicator in evaluating the efficiency of exploitation, operating costs and the environmental impact of vehicles. Many studies show that fuel consumption is simultaneously influenced by vehicle technology, driving cycles, traffic conditions, route characteristics, and drivers' driving style [1, 2]. In addition, operational data analysis and machine learning methods are also being developed to improve the ability to forecast fuel consumption under actual operating conditions [2, 16].

In fact, standard driving cycles such as the FTP-75 are widely used to evaluate a vehicle's fuel consumption and emissions. Many studies have shown that laboratory results often differ significantly from actual operations due to the influence of traffic conditions, slopes, road surfaces, loads, and driving behavior [3, 5, 7, 8, 13, 15]. In addition, studies on actual driving cycles and eco-driving strategies also show that speed characteristics and operating conditions can significantly change the fuel consumption of vehicles [4, 11, 12].

In terms of methodology, simulation models based on the longitudinal dynamics of the vehicle, with parameters such as vehicle mass, rolling resistance, aerodynamic resistance, and powertrain performance, are directly related to the vehicle's fuel consumption. The studies also emphasize that vehicle mass, the structure of the powertrain and operating conditions are determinants of fuel efficiency [5, 6, 9, 10, 14].

Recent advances in Digital Twin technology and intelligent vehicle systems also provide promising opportunities for integrating simulation and real-time operational data to improve fuel-consumption prediction accuracy. Although such approaches are beyond the scope of this study, they represent an important direction for future research.

From the published works, it can be seen that a combination of standard cycle simulation and experimental verification on the road is necessary to more accurately assess the fuel consumption of cars. Therefore, this study focuses on determining the fuel consumption of sedans using gasoline engines through simulations with the FTP-75 standard driving cycle, and then compares the results with experimental results on mixed roads. This approach aims to assess the relevance between simulation and reality, and serves as a basis for research and solutions to reduce fuel consumption in the operation of cars. Although there have been many studies on automotive fuel consumption based on simulations, real-world operating data, and road experiments, the majority of these studies have focused on either simulation or experimentation. Therefore, this study focuses on integration a fuel consumption simulation model in MATLAB/Simulink with on-road experimental results. The study allows a direct assessment of the agreement between simulation and reality for a 1.5 L gasoline-powered sedan, including: developing a fuel consumption assessment process that combines simulation and experimentation; validating the model through testing on a 169.3 km route; and quantifying the prediction error between simulation and experiment.

From that basis, this paper studies the evaluation of fuel consumption of cars in actual operating conditions by combining simulations and experiments. Specifically, the study uses a model in MATLAB/Simulink software with the FTP-75 cycle as the input, which is then verified by experiment on a mixed route for a 1.5 L gasoline sedan. thereby clarifying the applicability of the method in forecasting and controlling fuel consumption in cars (see Figure 1).

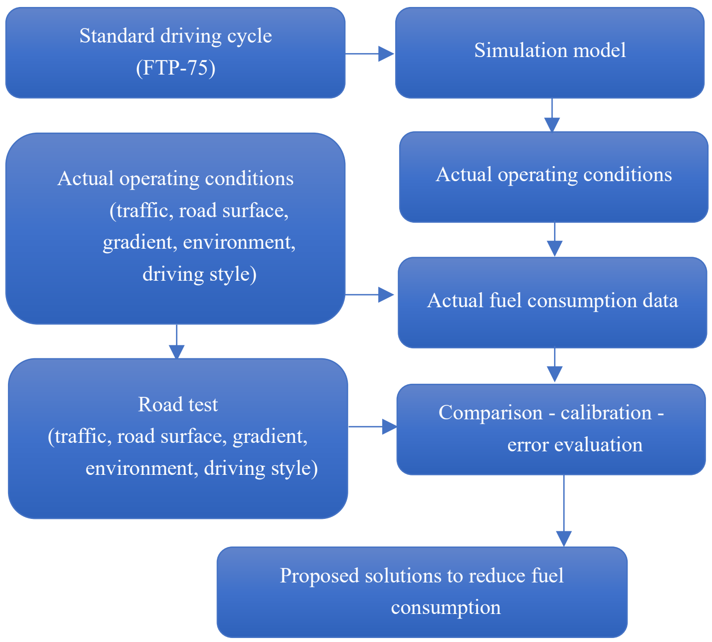

Fig. 1 Overall diagram of the automobile fuel consumption assessment study

2. Theoretical Basis and Computational Model

2.1. Building a Dynamic Model with Motion Resistance Forces

The study used a longitudinal dynamics model of the vehicle to determine fuel consumption [6, 11, 15].

Figure 2 shows the longitudinal forces acting on the vehicle during motion. The longitudinal force balance equation of the vehicle can be written as follows:

$$F_k = F_f + F_w + F_i + F_j \quad (1)$$

In which: F_k is the tangential traction at the active wheel; F_f is the rolling resistance; F_w is the aerodynamic resistance ; F_i is the slope resistance; and F_j It is the inertial force when the vehicle accelerates or decelerates.

$$F_f = f_r .m.g.\cos\alpha \quad (2)$$

$$F_w = \frac{1}{2}.\rho.C_d.A.v^2 \quad (3)$$

$$F_i = m.g.\sin\alpha \quad (4)$$

$$F_j = \delta.m.a \quad (5)$$

In which: m is the total mass of the car; g is the gravitational acceleration; f_r is the rolling resistance coefficient; ρ is the density of air; A is the frontal bumper area; C_d is the aerodynamic drag coefficient; a is the vertical acceleration; δ is the rotational volume inertia conversion coefficient.

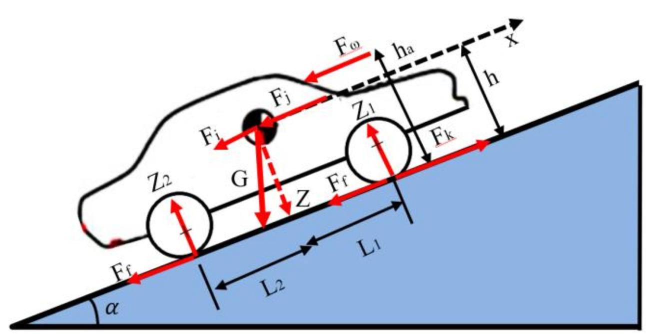

Fig. 2 Diagram of the force applied to the car in motion

2.2. Power Calculation and Fuel Consumption

The fuel consumption of a vehicle is considered as a function of vehicle mass, speed, time, rolling resistance coefficient, road slope, aerodynamic characteristics, accelerator pedal impact level and the number of brake impacts, which can be generalized as follows [6, 11, 15]:

$$FC_k^{(stat)} = f(G, v, t, f_G, \alpha, W_d, n_{ga}, i_{ph} \quad (6)$$

In which: k is the survey cycle; G is the vehicle volume; v is the vehicle velocity; t is the running time; f_G is the rolling resistance coefficient; α is the road surface slope angle; W_d is the aerodynamic coefficient; n_{ga} is the accelerator impact level; và i_{ph} is the number of times the brake impact.

From the equation of total resistance, the required power at the wheel is determined:

$$P_w = F_k \cdot v \quad (7)$$

The power required at the engine is inferred through powertrain efficiency:

$$P_e = \frac{P_w}{\eta_{tr}} \quad (8)$$

Fuel flow by volume can be approximately represented as follows:

$$\dot{m}_f = \frac{P_e}{\eta_e H_{you}} \quad (9)$$

In which:

P_w is the capacity at the wheel; P_e is the useful power engine supply; η_{tr} is the powertrain performance; H_{you} is the low calorific value of fuel; η_e is the useful performance of the motor.

When the specific mass of the fuel is known ρ_fInstantaneous fuel volumetric flow is:

$$\dot{V}_f = \frac{\dot{m}_f}{\rho_f} \quad (10)$$

From there, the amount of fuel consumed over the entire cycle is determined and converted to L/100 km units according to the formula:

$$FC = \frac{100\, V_f}{S} \quad (11)$$

In which V_f is the total volume of fuel consumed in the cycle, and S is the distance traveled by car.

3. Materials and Methods

3.1. Building a Simulation Model

In this study, using the FTP-75 driving cycle [17], which is one of the commonly used standard cycles to evaluate the fuel consumption of gasoline engine passenger cars, the model is built into the “Conventional Vehicle Spark-Ignition Engine Fuel Economy and Emissions” tool of the Matlab/Simulink software version R2023b (23.2.0.2365128). The FTP-75 driving cycle represents urban, highway and mixed road conditions (55% urban roads and 45% highways). The block diagram is represented as shown in Figure 3.

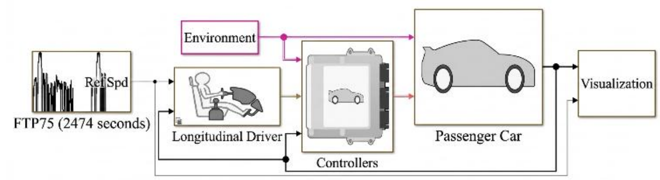

Fig. 3 Simulink diagram simulates the fuel consumption of a passenger car for the FTP-75 driving cycle

The main parameters of the model include vehicle mass, engine capacity, driving cycle, fuel characteristics, aerodynamic drag coefficient, rolling resistance coefficient and powertrain parameters. During the simulation, the model calculates vehicle speed, acceleration, traction force, rolling resistance, aerodynamic resistance, engine power demand, instantaneous fuel flow, and cumulative fuel consumption over the entire driving cycle.

The model calculates instantaneous acceleration, then determines the motion resistance components, traction power at the wheels, the required power of the engine, and the instantaneous fuel flow. The results for each individual cycle are aggregated in a 55/45 operating ratio to obtain a mixed value that represents the actual use conditions of the vehicle.

3.2. Experimental Research

The subject of the study was a 5-seater Toyota sedan using a 1.5 L forced ignition gasoline engine, with a total weight of 1170 kg. The experimental research vehicle is shown as shown in Figure 4.

Fig. 4 Experimental vehicles

The total length of the test route was 169.3 km and consisted of various sections, including urban roads, mixed roads and expressways (see Figure 5).

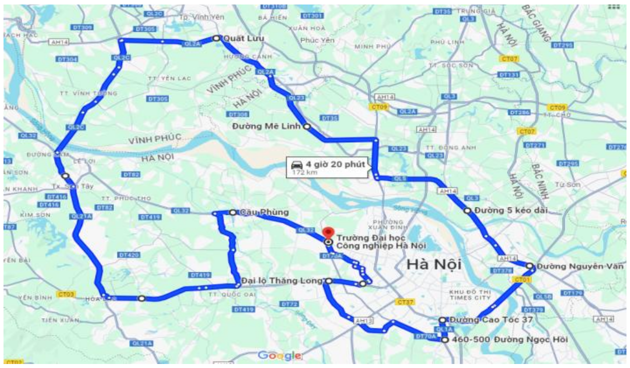

Fig. 5 Experimental routes

The experiment was conducted by placing the test fuel tank on an electronic scale and continuously recording the volume of fuel consumed during the journey. At the same time, signals of vehicle speed, throttle opening, and braking impact were collected to synchronize with the operating state. The experimental data after processing are converted to L/100 km units for direct comparison with the simulation results.

4. Results and Discussion

4.1. Simulation Results According to the FTP-75 Cycle

Perform a simulation for the FTP-75 steering cycle in MATLAB/Simulink software. The FTP-75 driving cycle represents urban, highway and mixed road conditions (55% urban roads and 45% highways). The simulation results, as shown in Figure 6, show that the vehicle's fuel efficiency reached 34.29 mpg in urban conditions, 45.18 mpg in highway conditions, and 39.19 mpg in mixed conditions. When converted to fuel consumption units, these values correspond to 6.86 L/100 km for urban roads, 5.21 L/100 km for highways, and 6.00 L/100 km for mixed conditions. This trend is in line with the operating conditions of cars using 1.5L gasoline engines, in which urban conditions always have greater consumption due to frequent acceleration, deceleration and stop-departure, while highway conditions have lower consumption due to more stable velocity.

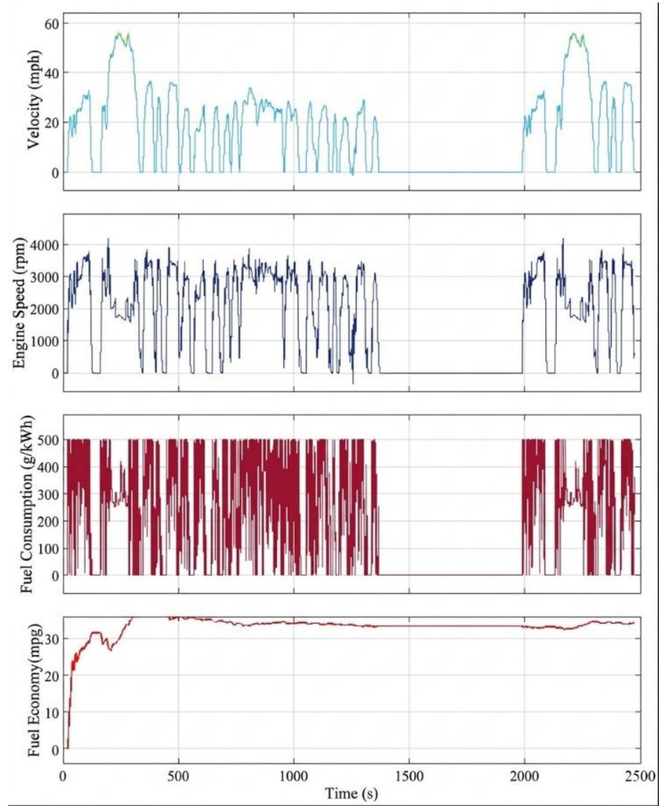

Fig. 6 Fuel consumption results for the five-seat sedan

4.2. Experimental Results

The on-road experimental tests were conducted over five representative driving cycles. For each cycle, the recorded parameters included running time (s), distance (km), fuel used (g), and Fuel Consumption (FC).

The driving cycles represented five typical road conditions, namely highway, hilly road, suburban road, mixed road, and urban road. A summary of the experimental results is presented in Table 1.

Table 1. Summary of the five experimental driving cycles

Item	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Running time (s)	3600	3602	3600	3600	3606
Distance (km)	34.4	34.4	34.4	34.4	31.7
Fuel used (g)	1457	1409	1425	1482	1565
FC (L/100 km)	5.65	5.46	5.52	5.74	6.58
Road type	Highway	Hilly road	Suburban road	Mixed road	Urban road

Table 1 presents the empirical results of the five operation cycles with different road conditions, including highways, sloped roads, suburbs, mixed, and urban. The total test distance reached 169.3 km, of which each cycle had a relatively uniform length (31.7-34.4 km) and an operating time of about 60-66 minutes. The results showed that the amount of fuel consumed in each cycle ranged from 1409 g to 1565 g. Cycle 2 (sloped roads) has the lowest consumption with 1409 g, while cycle 5 (urban roads) has the greatest consumption with 1565 g. The difference between the largest and smallest values reached 156 g, or about 11.1%, indicating that the actual operating conditions have a significant effect on the fuel consumption of the vehicle. Calculated over the entire experimental journey, the total fuel consumption was 7338 g, corresponding to an average fuel consumption of about 5.8-5.9 L/100 km. This result shows that the vehicle has relatively stable fuel consumption under different actual operating conditions.

Based on a measured average fuel consumption of 5.78 L/100 km and a standard emission factor for gasoline of about 2.31 kg CO_2/L, the corresponding CO_2 emissions are estimated to be 13.35 kg CO_2/100 km, equivalent to 133.5 g CO_2/km. This estimated result suggests that the model can be further developed to assess CO_2 emissions in subsequent studies. The average fuel consumption of 5.78 L/100 km obtained in the study is in line with the reported values for 1.5L gasoline-powered passenger cars, where fuel consumption under mixed driving conditions typically ranges from 5.5-6.5 L/100 km.

Using a gasoline density of 0.75 kg/L, the experimentally measured fuel consumption was approximately 5.65 L/100 km for the highway cycle, 5.46 L/100 km for the hilly-road cycle, 5.52 L/100 km for the suburban-road cycle, 5.74 L/100 km for the mixed-road cycle, and 6.58 L/100 km for the urban cycle. The highway, mixed-road, and urban-cycle results were selected for direct comparison with the corresponding simulation results, as presented in Table 2.

Table 2. Comparison between simulation and experiment

Driving condition	Simulation (L/100 km)	Experiment (L/100 km)	Deviation (%)
Urban	6.86	6.58	4.26
Highway	5.21	5.65	7.79
Mixed	6.00	5.74	4.53

Table 2 shows reasonable agreement between the simulation and experimental results under the three comparable driving conditions. The simulated fuel consumption was 6.86 L/100 km under urban conditions, 5.21 L/100 km under highway conditions, and 6.00 L/100 km under mixed conditions. The corresponding experimental values were 6.58, 5.65, and 5.74 L/100 km, respectively. Using the experimental values as the reference, the deviations were 4.26%, 7.79%, and 4.53%, respectively. The smallest deviation occurred under urban conditions, whereas the largest deviation occurred under highway conditions. These results indicate reasonable agreement between the simulation and experimental measurements, although the degree of agreement varies with the driving condition.

The results show that the research model not only predicts average fuel consumption but also accurately reflects the variation in fuel consumption under different road conditions. This provides an important basis for further application of the model in vehicle operation optimization, assessment of driving-cycle effects, and the development of fuel-consumption reduction strategies under real-world operating conditions. Overall, the deviations ranged from 4.26% to 7.79% across the three comparable driving conditions, indicating reasonable agreement between the simulation and experimental results.

This result is equal to or better than those reported in some published studies. Specifically, Tsiakmakis et al. [13] reported that, using a simulation method combined with calibration based on experimental data, the prediction error ranged from approximately 1.0% to 4.5%, while the prediction based on the WLTP driving cycle had an error of about 4.5%. In addition, Fontaras et al. [8] showed that fuel consumption under real-world conditions often differs significantly from laboratory test results due to the influence of traffic conditions and driver behavior. Compared with these studies, the error of 4.53% achieved in the current study shows that the method of combining MATLAB/Simulink simulations with on-road experiments is highly reliable and can be effectively applied to forecasting the fuel consumption of gasoline-powered passenger cars.

Although the proposed method showed a match between simulation and experimental results, the study was conducted only on a gasoline-powered passenger car and a representative mixed route. The simulation uses the FTP-75 driving cycle and does not specifically consider factors such as traffic congestion, weather conditions, vehicle wear and tear, or driver behavior. Therefore, future studies need to be validated under different operating conditions.

5. Conclusion

The study developed and evaluated a method for forecasting the fuel consumption of passenger cars by combining simulations in a MATLAB/Simulink environment with on-road experiments. The simulation results show that the fuel consumption of the vehicle reaches 6.86 L/100 km in urban conditions, 5.21 L/100 km on the highway and 6.00 L/100 km in mixed conditions.

The experimental results from five driving cycles covered a total distance of 169.3 km. The measured fuel consumption was 5.65 L/100 km under highway conditions, 5.46 L/100 km under hilly-road conditions, 5.52 L/100 km under suburban-road conditions, 5.74 L/100 km under mixed-road conditions, and 6.58 L/100 km under urban conditions. For the three conditions directly compared with the simulation, the deviations were 4.26% for urban conditions, 7.79% for highway conditions, and 4.53% for mixed conditions.

These results indicate reasonable agreement between the simulation model and the experimental measurements and show that the model reproduces the general variation in fuel consumption under the tested operating conditions. This result shows that the simulation model is accurate and reliable. Thus, the combined method of simulation and experimentation is considered suitable for evaluating and forecasting the fuel consumption of cars. The research results provide a basis for further development directions, such as perfecting the model, supplementing the influence of real-time traffic, etc., route slope, and driving style, thereby further improving the accuracy of forecasting and supporting the proposal of solutions to reduce fuel consumption in automotive operation. Further studies will focus on different types of vehicles, integrating machine-learning techniques to improve prediction accuracy under real-world driving conditions. Future work will also investigate uncertainty analysis, Digital Twin technology, and advanced data-driven approaches to enhance the applicability of the proposed methodology further.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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