Optimal Travel Routes of On-road Vehicles Considering Sustainability

N. Mehrvarz[a], Z. Ye[a], K. Barati[a], and X. Shen[a]

[a]School of Civil and Environmental Engineering, University of New South Wales, Australia
E-mail: n.merhvarz@unsw.edu.au , zhilin.ye@student.unsw.edu.au, Khalegh.barati@unsw.edu.au, X.shen@unsw.edu.au

Abstract –

Transportation is one of the major contributors in global energy consumption and greenhouse gas emissions. Currently, there are approximately 1.32 billion on-road vehicles around the world, which is expected to be doubled by 2040. This increase has triggered deep concerns over the global issues of climate change and sustainable development. Current GPS navigation systems determine the best travel route in terms of time or distance. However, there are significant challenges to determine an optimal travel route considering sustainability. This paper aims to develop an automated system in order to evaluate different travel routes and suggest the most sustainable one. In this paper, a mathematical model is proposed to estimate the travel time and fuel consumption given different travel route options. Five operational and engine variables of acceleration rate, speed, road slope, engine load, and fuel consumption rate are incorporated in the quantitative analysis. Remote data acquisition was conducted using a GPS-aided inertial navigation system (GPS-INS) and an engine data logger for seven days. The results indicate that the fastest route selected by the current navigation system may not be the most sustainable option. It was also found in the field experiments that the most sustainable route could potentially save on average 5% fuel consumption compared to the fastest route.

Keywords –

Sustainability; Route Selection; Vehicle; Fuel Consumption; GPS-INS

1 Introduction

The transportation field has been widely regarded as one of the major sections of energy consumption, which has produced a significant amount of greenhouse gases (GHGs) worldwide, leading to negative impacts on the environment as well as the climate. There are more than 1.3 billion vehicles in operation throughout the world, which can consume approximately five trillion liters of petroleum annually [1]. The rate related to which petroleum is being consumed and the external costs that result from its use are incredibly unsustainable [2].

Family vehicles play an important role in the total use of global fossil fuels in the transportation field. There is still a rapid increase in the number of family vehicles in the current situation. It is predicted that the number of global on-road vehicles and cars will reach two billion by 2050 [3]. Therefore, it is of great importance to provide quantitative models with high accuracy to estimate the amount of fuel use and emissions caused by on-road vehicles.

There are several GPS navigation systems for vehicles such as Google Maps, which can show the best route in terms of time to users; however, this selected route may not be the best way in terms of sustainability. For this reason, how to measure the best route in terms of sustainability requires to be taken into critical consideration.

The main purpose of this study is to provide a comprehensive model to compare the sustainability of each travel path quantitatively. Furthermore, this research will confirm that the best route offered by current navigation systems may not be the most sustainable route, as well as to potentially develop an updated concept of GPS navigation systems. A comprehensive framework of methodology has been developed to model the fuel use of vehicles as well as evaluate the sustainability of route choice. Three experimental parameters including speed, acceleration, and road slope have been identified and investigated in this study. Two main instruments called GPS-based inertial navigation system (GPS-INS) device and on-board diagnostics (OBD) engine data logger have been employed to collect real-world data. At the end of this study, research limitations as well as recommendations for the future studies are provided.

2 Literature Review

This section focuses on the parameters which can affect the traffic modeling and the fuel use modeling of on-road vehicles.

The value of speed can be used to measure the service level of traffic. As is known, the on-road vehicles can keep the speed around a relatively high value without interruption, e.g. running on a freeway, which means that the traffic condition is on the highly satisfying level [4]. In addition, flow is a relatively macroscopic parameter in traffic modeling, which can help controlling the traffic condition under a macroscopic view. California Department of Transportation (Caltrans) Freeway Performance Measurement System (PeMS), a widely used traffic modeling, can offer 30 seconds or 5 minutes per-loop averages of lane occupancy, flow, speed, and delay for various links in the roadway network [5].

Ahn and Lee developed the operation efficiency parameter to consider idling and non-idling emission coefficients [6]. Besides, Barati and Shen chose both engine attributes (size and load) and operational parameters (operation efficiency, cycle time, and operator skill) as affecting parameters on fuel use [7]. Lewis and Hajji presented a model to estimate the total fuel use, unit cost, activity duration, and emissions of vehicles. Using multiple linear regression (MLR) method, the impact of different affecting parameters including distance and speed was modeled on the fuel use and cost [8].

3 Methodology

This section introduces a comprehensive framework which has been developed to model the fuel use of vehicles as well as evaluate the sustainability of available routes. This methodology can be applied to estimate the fuel consumption of vehicles at the operation level and to appraise the routes sustainability. It can help drivers to identify the best route in their daily trips in terms of sustainability rather than the time.

The fuel use model in this study can be developed in three steps. As the first step, instantaneous engine load value is estimated based on collected operational and environmental parameters. Then, the fuel use in each second can be predicted considering the engine attributes. The fuel use for each trip is eventually measured having instantaneous fuel consumption (IFC) and travel time.

As Figure 1 presents, five steps should be followed to develop the model. Instrumentation and data collection phases are to obtain real data from the field. Raw data should be synchronised and filtered to remove potential errors. The processed data must be finally analysed to estimate the fuel consumption and evaluate the available routes in terms of time and sustainability.

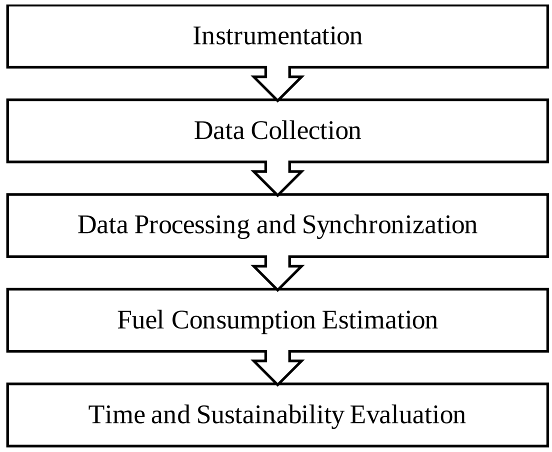

Figure 1. Research framework for selecting most sustainable route

3.1 Parameters Identification

The parameters related to engine size and engine load have been widely regarded as two essential attributes affecting fuel consumption and consequently emissions. The engine load can be defined as the ratio of the used power in different working conditions comparing to the maximum power as a percentage [9]. As for engine size, the greater capacity of the engine generally means more fuel use and emissions. The operational parameters which can influence engine load are acceleration and speed. In addition, the vehicle may use more power of engine at an upward slope than a levelled route. Therefore, the effect of road slope, as an environmental variable, cannot be ignored on engine load estimation. Further, gross vehicles' weight (GVW) is a major variable impacting the effect of other operational parameters on engine load.

The fuel use of a vehicle has a direct relationship with its engine load and size. Having the values of engine load and engine size, the instantaneous fuel use of vehicles can be estimated.

3.2 Instrumentation

There are two main instruments called GPS-INS device and OBD engine data logger employed to collect real-world data of identified parameters. The V-gate iCar Pro OBD2 Scanner is an OBD instrument used to collect field data of engine attributes in this research. It can satisfy almost all the required parameters except acceleration and road slope. JY-GPSIMU is a three-axis inertial navigation GPS-INS device, which can collect, measure, and record the accurate position, speed, acceleration by using an attitude and heading reference system (AHRS). This GPS-INS instrument is installed inside the cabin of vehicle on a leveled surface, and it should be fixed on a surface with minimum vibration and without any lateral movement to increase the accuracy of data collection. In order to collect data of higher accuracy as well as keep better satellite signal connection, the antenna of GPS-INS is installed on the roof of the vehicle cabin and connected to the main unit via a wire. Finally, all the data collected by OBD engine data logger and GPS-INS device will be stored, synchronised, and analysed in a Toughpad.

3.3 Data Collection

In this research, the data collection has been completed in two preliminary testing and field experimentation parts. The preliminary tests in this study were completed by three selected family vehicles to check and evaluate the performance of instruments. Completion of the whole preliminary experiments took around six hours, and more than 20000 data points have been collected. The field experimentation was conducted by the same vehicles used in the preliminary experiments. The total field experimentation took about 20 hours with more than 80000 collected data points. In order to collect more reliable data during experimentation, several deliberate arrangements have been applied to make the location and time of each experiment different. Moreover, there were significant differences among different routes in each experiment. For example, some had longer distances and fewer traffic lights, some had shorter distances and more traffic lights, and some routes included part of highways.

Table 1 summarises four conducted experimentations. Table 2 demonstrates the samples of the operational parameters collected by instruments. Photos of instrumentation and experimentation, as well as an operation interface version of master computer software are shown in Figure 2a-d. There are five parameters identified to be used for measuring the experiments in this research. Three of them, i.e. acceleration, speed, and road slope, are collected by the GPS-INS device. The other two parameters, i.e. engine load and fuel use rate, are recorded by the OBD engine data logger.

Table 1. A summary of conducted experimentation

Experiment	Vehicle Model	Experiment Location	Experiment Time	Model Year	Engine Size (kW)	Empty/Total Weight (kg)	Number of Data Points
1	Honda Civic	Suburban	Evening Peak	2016	104	1255/1505	15832
2	Honda Civic	Suburban	Midnight	2016	104	1255/1505	17251
3	Toyota Corolla	City	Midnight	2010	81	1060/1210	17449
4	Honda Sylphy	City	Evening Peak	2012	86	1220/1445	20558

Table 2. Samples of field data collected by instruments

Time	Angle X (deg)	GPS V (km/h)	Acceleration (m/s^2)	Calculated Engine Load (%)	Fuel Use (L/100km)
12:54:32 AM	8.09	19.083	0.6508	60.4	8.4
12:54:33 AM	7.40	21.518	0.6764	59.9	7.9
12:54:34 AM	7.34	23.174	0.4600	54.7	6.2
12:54:36 AM	6.39	26.626	0.4408	55.5	6.5

(a)

(b)

(c)

(d)

Figure 2. Sample photos of instrumentation and experimentation, (a) the GPS-INS device, (b) external antenna of the GPS-INS device, (c) the OBD engine data logger, and (d) the operation interface version of OBD Auto Doctor.

4 Result Analysis

The aim of this section is to develop a model to estimate fuel consumption as well as the most sustainable route selection of on-road family vehicles by the analysis of operational parameters collected in the experimentation. As one of the essential sections of this research, this section presents the estimation of fuel use among different routes and the results of model validation.

4.1 Model Development

This section examines how to estimate the total fuel use of a trip. As mentioned in section 3.1, engine load can be described as a function of acceleration, speed, road slope, and vehicle load factor (LF). As for LF, it is the ratio of current vehicle weight to its GVW. The LF of the three selected vehicles, Honda Civic, Toyota Corolla, and Honda Sylphy, are 0.67, 0.4, and 0.6, respectively, and their engine size are 104kW, 81kW, and 86kW, respectively. The highest speed of these vehicles during the experiment are 64.35 km/h, 70.29 km/h, and 49.18 km/h, respectively. The acceleration fluctuation range of these vehicles in the experimentation are between -2.37 m/s^2 and 3.15 m/s^2 (-8.52 km/h.s to 11.3 km/h.s), -3.08 m/s^2 and 3.22 m/s^2 (-11.1 km/h.s to 11.6 km/h.s), -3.08 m/s^2 and 3.22 m/s^2 (-11.1 km/h.s to 11.6 km/h.s), respectively. The parameter of road slope in the selected routes varied from -17.9° to +16.7° (-19.9% to 18.5%).

4.1.1 Engine Load Estimation

Barati and Shen developed a model based on the real-world data to estimate of engine load by acceleration, slope, speed, and the LF. In addition, they also offered the relationship among these coefficients and LF (Equation (1)) [7]. Table 3 presents LF and three experimental coefficients of vehicle acceleration (C_{AC}), slope of road (C_{SL}), and vehicle speed (C_{SP}). Using linear interpolation technique, a relationship between C_{AC}, C_{SL}, C_{SL}, and LF can be developed (Equations (2-4)).

$$\mathrm{EL} = (\mathrm{C_{AC}} * \mathrm{AC}) + (\mathrm{C_{SL}} * \mathrm{SL}) + (\mathrm{C_{SP}} * \mathrm{SP}) + \mathrm{C} \qquad (1)$$

where:

EL Engine load of vehicle (%)
AC Acceleration of vehicle (m/s^2)
SL Slope of road (degree)
SP Speed of vehicle (km/h)
C Engine load of vehicle in idle mode which is around 20%.

Table 3. The coefficients of parameters in the engine load estimation model

Model	Coefficients			
Load Factor	0	0.33	0.67	1
C_{AC}	15.65	16.36	24.8	27.37
C_{SL}	1.12	1.29	1.67	1.86
C_{SP}	0.41	0.52	0.57	0.64

$$\mathrm{C_{AC}} = 12.163\ \mathrm{LF} + 15.713 \quad , \mathrm{R}^2 = 0.985 \qquad (2)$$

$$\mathrm{C_{SL}} = 0.749\ \mathrm{LF} + 1.096 \quad , \mathrm{R}^2 = 0.0.986 \qquad (3)$$

$$\mathrm{C_{SP}} = 0.221\ \mathrm{LF} + 0.424 \quad , \mathrm{R}^2 = 0.973 \qquad (4)$$

4.1.2 IFC Estimation by Engine Load

According to the field data provided by Klein et al. there is an exponential relation between IFC and engine load (Equation (5)). In other words, a small increase in engine load may result in a significant growth of IFC [9]. Figure 3 shows all the results of IFC estimation and engine load of experimented vehicles in this study.

$$\mathrm{IFC} = 0.126 * \mathrm{e}^{0.036*\mathrm{EL}} \qquad (5)$$

where:

IFC Instantaneous fuel consumption (L/sec)
EL Engine load of vehicle (%)

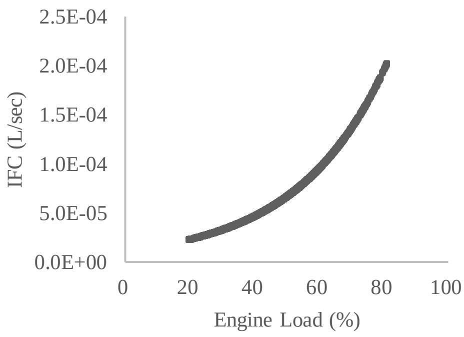

Figure 3. IFC results based on engine load

4.1.3 Total Fuel Consumption Estimation by IFC

The last step of fuel consumption estimation is the calculation of the total amount of fuel used in one trip. The total fuel consumption in a small unit of time can be regarded as the product of IFC and one unit of time. The amount of total fuel consumption in one route is the sum of IFC (Equation (6)).

$$\mathrm{TFC} = \sum(\mathrm{IFC}) \qquad (6)$$

where:

TFC Total fuel consumption (L)
IFC Instantaneous fuel consumption (L/sec)

4.2 Time and Sustainability Evaluation

A vehicle navigation system equipped with GPS-INS can use a significant amount of real-time information for route planning. On the one hand, this GPS-INS system first searched the origin and destination of the trip and used positioning information and internal program algorithms to find several alternative routes. On the other hand, the real-time mega data will be used to simulate the running condition of each route and make an evaluation, which can finally select the best route in terms of time. The GPS-INS system can provide drivers with the best route in terms of time; however, this route might not be the best choice in terms of sustainability. Figure 4 makes a comparison of time and sustainability evaluation.

As an example, in experiment 3, route 1 took the least time but with the most fuel consumption, which means that this route is the most unsustainable one in all three routes. Although the route 3 took a relatively long time to arrive at the destination, it is the best route selection in terms of sustainability. In addition, in experiment 5, route 2 seems to spend almost the longest time; however, the fuel consumption of this route is significantly lower than the other two paths. The experimental results also confirmed three rules, which can be regarded as the principle of sustainable traveling. First and foremost, it is more sustainable to travel during off-peak hours rather than peak hours in both urban and suburban areas. Secondly, it is more sustainable to travel in suburban areas rather than urban areas. Thirdly, it is more sustainable to select the route which has less road slope fluctuation as well as traffic signals.

In conclusion, according to the results of this experimentation, the best route in terms of time provided by the GPS-INS system is not the best route in terms of sustainability sometimes. For the concept of reaching a higher level of sustainability, it is essential to develop another algorithm in the GPS-INS system, which can make simulation and calculation to choose the best route in terms of sustainability.

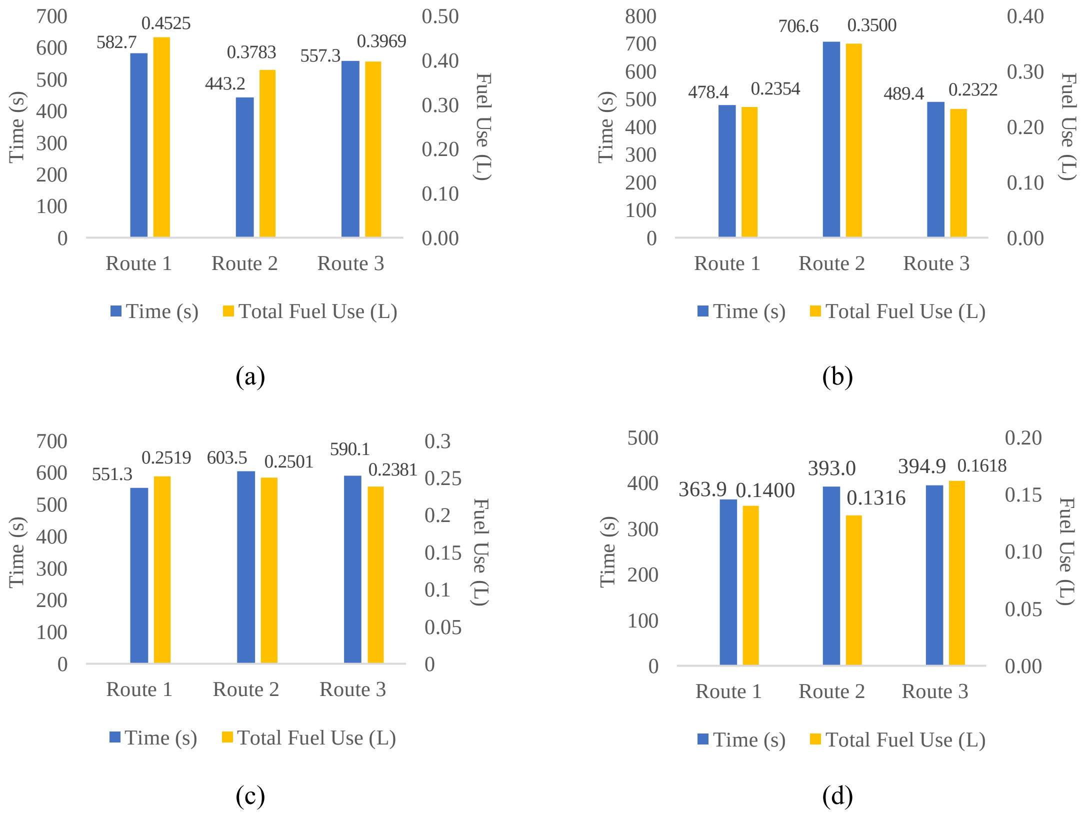

Figure 4. Time and sustainability evaluation of the four conducted experiments, (a) experiment 1, (b) experiment 2, (c) experiment 3, and (d) experiment 4.

5 Conclusion

The transportation field has been widely considered as one of the major sections of energy consumption, such as the use of fossil fuels by vehicle engines. The widespread use of fossil fuels has also produced a significant amount of air pollutants worldwide. It requires a quantified model to estimate family vehicle fuel consumption and select the best route. An assumption has been presented that the best route offered by current navigation systems, which cost the shortest time may not be the most sustainable route. This paper mainly concentrates on confirming the validity of this assumption as well as developing a comprehensive methodology to quantify the total fuel consumption in alternative routes.

The model used in this study can be divided into three steps: engine load estimation by operating parameters, instantaneous fuel consumption estimation by engine load, and total fuel consumption estimation by instantaneous fuel consumption. The concept of this modelling can be applied to all on-road family vehicles. The GPS system can be updated to provide the best route selection in terms of sustainability based on the model in this study.

The experimentation and the results of this research confirmed that the total fuel consumption of each alternative route can be calculated by the identified parameters. Due to the fact that the GPS navigation systems can make simulation and calculation with the support of GPS real-time mega data, it can make the modelling reach a more practical level and be widely applied. It is strongly recommended that the GPS navigation systems should perform the normal route selection as well as the best route selection in terms of sustainability based on the model concept in this study at the same time. Moreover, the GPS navigation systems can present both these two plans of route selection to the user interface for operators to determine. Furthermore, the GPS navigation systems can even simulate the travel of a short period of time in the future to provide better travel recommendations. For example, the evening peak will last for half an hour, and then the updated GPS navigation system can present the total fuel consumption of the current travel and the deferred travel after the simulation and calculation. The simulation may show that a 30 min deferral in a travel can save significant time and fuel. The core concept of this research is to make the traditional navigation systems combine with sustainability and make operators take sustainability into consideration in their daily life.

References

[1] Dargay J., Gately D. and Sommer M. Vehicle Ownership and Income Growth. *The Energy Journal*, 143-170, 2007.

[2] Khan, M.A., Khan, M.Z., Zaman, K., and Naz, L. Global estimates of energy consumption and greenhouse gas emissions, *Renewable and Sustainable Energy Reviews,* (29): 336-344, 2014.

[3] Sperling D. and Gordon D. *Two billion cars: driving toward sustainability*. Oxford University Press, 2014.

[4] Transportation Research Laboratory (TRL). A Review of Instantaneous Emission Models for Road Vehicles. *Project Report PPR*, 267, 2007.

[5] Boriboonsomsin K., and M. Barth. Modeling the Effectiveness of HOV Lanes at Improving Air Quality. Draft Final Report. *California Department of Transportation*, 2006.

[6] Ahn C.R. and Lee S.H. Importance of Operational Efficiency to Achieve Energy Efficiency and Exhaust Emission Reduction of Construction Operations. *Journal of Construction Engineering and Management*, 139(4), 404-413, 2013.

[7] Barati K. and Shen X. Operational level emission modelling of on-road construction equipment through field data analysis, *Journal of Automation in Construction*, (72): 338-346, 2016.

[8] Lewis M.P. and Hajji A. Estimating the Economic, Energy, and Environmental Impact of Earthwork Activities, In *Proceedings of Construction Research Congress*, pages 1770-1779, Indiana, USA, 2012.

[9] Klein, J., Shen, X., and Barati, K., Optimum driving pattern for minimizing fuel consumption of on-road vehicles, Proceedings of the 33rd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2016), Auburn, USA, 2016.