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Optimum Driving Pattern for Minimizing Fuel Consumption of On-road Vehicles

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Abstract –

The consumption of fossil fuels by on-road vehicles is the greatest source of air pollution and the second largest source of greenhouse gases (GHGs) globally. The emitted pollutions have caused major problems such as respiratory diseases. Also, as the sources of these types of fuels are diminishing, their price is projected to steadily increase. This necessitates developing strategies and policies to ameliorate the environmental, economic and health impacts of such fuels. This paper aims to present a process to minimize fuel consumption through optimizing driving pattern. Four acceleration, speed, slope and payload parameters were investigated as operational parameters affecting fuel consumption. This paper developed engine load parameter as the surrogate of used power of engine linking operational parameters to fuel consumption. Through conducting ordinary least square and multivariate regression analysis on the field data collected from six on-road vehicles, the relations among operational parameters, engine load and fuel consumption were developed. In the next step, the optimum driving pattern was developed by investigating the effect of operational parameters in the fuel consumption developed model. The result analysis shows for driving a vehicle without payload and zero acceleration in a levelled route, the optimum speed is around 50km/hr for having minimum fuel consumption per kilometre. Also, the investigations on the road slope parameter shows by increasing this factor optimum speed decreases while the minimum used fuel increases.

Keywords –
Fuel Consumption; Statistical Modelling; Fuel Efficiency; On-road Vehicle; Instrumentation

1. Background

Today, there are over one billion vehicles in operation throughout the world consuming approximately five trillion litres of petroleum annually [1]. The rate at which petroleum is being consumed and the external costs that result from its use are extremely unsustainable [2]. Despite this, the demand for vehicles and petroleum is steadily increasing, the global on-road vehicle population is expected to reach two billion by 2050 [3]. With increasing demand and diminishing sources of fossil fuels, supplying the required fuels is one the main challenges in transportation field.

The fossil fuels are the main source of pollutants including carbon dioxides (CO_2), carbon monoxides (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matters (PM). The pollution produced by on-road vehicles is one of the greatest killers today. The annual deaths associated with air pollution far exceed that of any currently ongoing conflict. Each year, 53,000 people die in the U.S alone due to vehicular air pollution [4]. Arguably of more concern is the fact that road transport accounts for more than 12% of the world's CO_2 emissions [5]. Based on the report prepared by Clean Energy Regulator Agency, by decreasing 10% of fuel consumed by on-road vehicles, only in Australia of over 3 billion litres of fuel is saved and over 8 million tonnes of CO_2 is produced less. By considering the increasing demand, reducing supplies and the impact of emitted pollution, developing strategies and schemes for decreasing fuel consumption is necessary.

Many studies have been conducted to develop strategies for optimising features of the road environment that are generally outside of a drivers control such as vehicle routing, platooning, road surface choice, intersection configuration, ambient weather conditions, vehicle load, vehicle condition and speed limit recommendations. However the greatest savings come from the studies that focus on driving patterns which are collectively known as eco driving. These studies have investigated the effect of acceleration rates, cruising speed, idling and speed variability on fuel consumption. It is estimated that as much as 70% of fuel economy is affected by driver decisions [6]. Eco driving strategies focus on driving behaviour and involve eliminating unnecessary sources of energy loss, they advise minimising time spent in acceleration as well as accelerating in a smooth and rapid manner, looking ahead to avoid unnecessary stops and reducing time spent in the wrong gear and idling [7]. A large number of studies on eco driving can be found however the reported savings differ substantially between experiments. For on road vehicles the savings from eco-driving vary from 5-30% [6, 7].

By considering the aforementioned studies, this paper aims to optimize driving pattern to minimize the fuel consumption of on-road vehicles. A comprehensive methodology is first developed to instrument, collect field data and analyse the results. Then, the effect of four operational parameters on fuel consumption is investigated through conducting regression analysis on the filtered data. The effect of operational parameters is finally considered on the presented fuel consumption model to develop optimum driving pattern.

2. Methodology

As was discussed, the main objective of this study is minimizing fuel consumption of on-road vehicle through optimizing driving pattern. In this section, a comprehensive methodology is developed for collecting and analysing field data. As Figure 1 shows, the required instruments are first developed for collecting required data. In the next step, the gathered field data are processed through data mining, and are analysed to develop fuel consumption model. The developed fuel consumption model is finally investigated to optimize driving pattern.

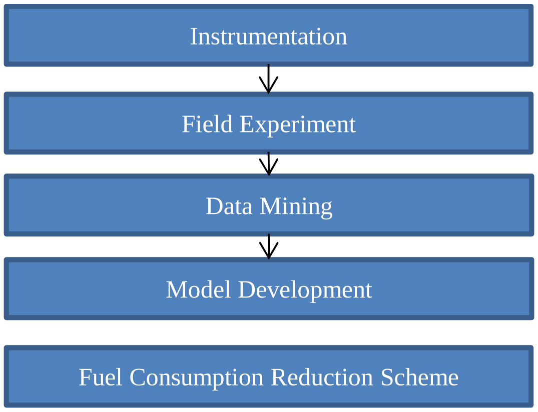

Figure 1. Methodology for developing fuel consumption reduction scheme

There are numerous parameters affecting fuel consumption. On the whole, these parameters can be classified to engine attributes and operational factors. Engine size, engine load are two main engine parameters having significant effect on fuel consumption. Also, engine age and engine tier are the other two engine attributes influencing fuel consumption, but due to their minor effect, they are not been investigated in this study. Operational parameters influencing fuel consumption can be categorized to four acceleration, speed, road slope and payload factors. Based on the research conducted by Barati and Shen [8], there is direct multi-linear relation between operational parameter and engine load. Figure 2 shows the schematic relations between operational parameters, engine attributes and fuel consumption.

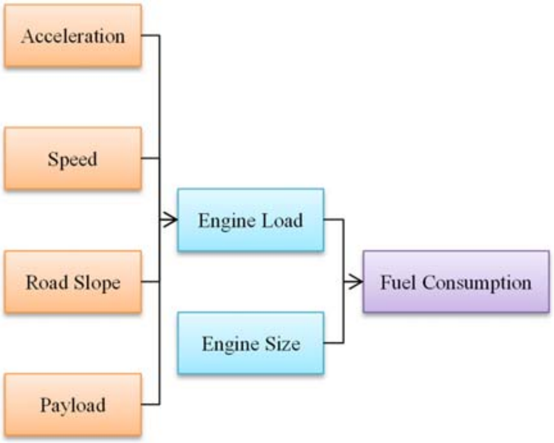

Figure 2. Schematic relations between operational parameters, engine load and fuel consumption

By identifying parameters affecting fuel consumption of on-road vehicles, required instrument needs to be developed to collect field data. Three engine data logger, GPS aided inertial navigation system (GPS-INS) and industrial Tough Pad instruments developed to collect and store required real-world engine and operational data. The main used instrument in this study was engine data logger. This instrument was connected to OBDII port of vehicle under the dashboard and collected real-world fuel consumption rate and engine load from engine control unit (ECU) in each second. The utilized engine data logger in this study is Bluetooth Vgate OBDII adapter. GPS-INS was another instrument used for collecting operational parameters investigated in this research. This tool combines accelerometers, gyroscopes and magnetometers with a commercial grade GPS receiver. By embedding this instrument on the dashboard, three-dimensional position, speed and acceleration of vehicle and slope of road were measured second by second. The GPS-INS system used for this study is SPATIAL-EK manufactured by Advanced Navigation Pty Ltd.

The measured data by engine data logger and GPS-INS instruments were transmitted through RS-232 serial data communication port to the industrial Tough Pad. Panasonic FZ-G1 is the industrial Tough Pad utilized to store and analyse the collected field data.

Using developed instrument, field experimentation were conducted on different on-road vehicles to collect real-world field data. Data collection in this research was conducted in two steps of laboratory and field experiments. The laboratory experiments need to be conducted to verify the performance of instruments, adopt the employed instruments and synchronizing the collected data. Around ten passenger and utility cars were experimented as laboratory test. The data of the laboratory experiments used for developing the initial framework of fuel consumption model.

In the next step, six vehicles were used as field data collection. The specifications of the vehicles used for field experiments are presented in Table 1. Also, Figure 3 shows some sample photos of the conducted field experiments on vehicles. Before starting experimentation, engine would be hot stabilised. To achieve this, the vehicle would be left in idling mode for the time that the cool engine indicator on the dashboard is deactivated. Each vehicle was driven for around 60 minutes, and the driving routes were designed so that each vehicle would spend a substantial amount of time in cruising, accelerating, decelerating and idling mode. Both engine data logger and GPS-INS instruments have a measurement rate of 1 Hz

Table 1. The specification of vehicle used for experimentation

Vehicle	Engine Size (kW)	Model	Tier	Fuel	Experiment Time (min)
Hyundai i30	107	2012	EU V	Petrol	68
Honda Civic VTi	103	2004	EU III	Petrol	57
Toyota Camry Atara	135	2013	EU VI	Petrol	55
Honda CR-V 4WD	120	2001	EU III	Petrol	66
BMW 120i	125	2012	EU V	Petrol	50
Toyota Echo	63	2004	EU III	Petrol	62


(a) (b) (c) (d)

Figure 3. Sample photos of vehicles used for data collection: (a) Toyota Camry Atara, (b) Honda CR-V 4WD, (c) LX Holden and (d) Honda Civic VTi

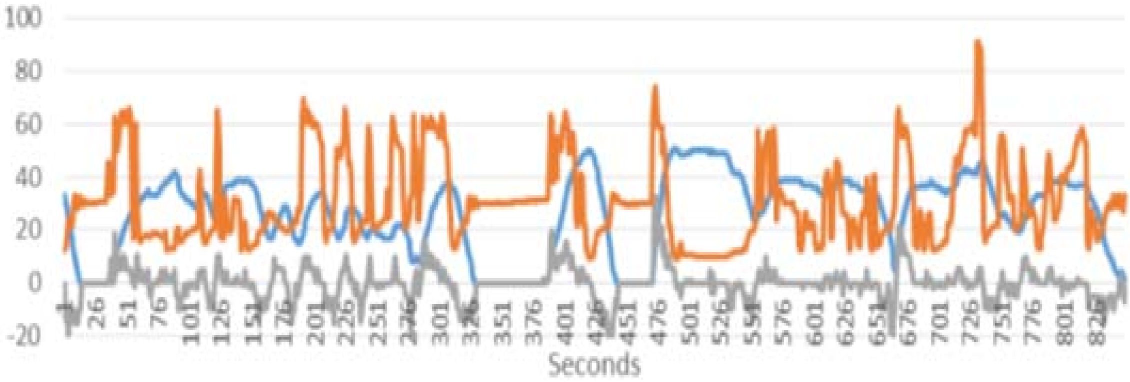

Figure 4. Samples of raw data collected by engine data logger and GPS-INS Instruments

generating 3600 data points per hour. The vehicles were driven for a portion of the time over planned drive cycles and for the remainder on unplanned routes extending over longer distances and traffic conditions. Over the course of the field experiment, a maximum speed of 116 km/hr was recorded. Acceleration rates ranged between -3 to +2.5 m/s^2 and the slopes encountered spanned -10 degrees to +10 degrees. It was ensured that a significant amount of time was spent in all driving modes and that a continuous array of data would be available for all conditions so that no gaps in the data would appear requiring interpolation. Figure 4 presents some sample data collected by GPS-INS and engine data logger instruments.

The collected data amounted to over 20,000 data points. The data was subsequently analysed and all data that did not meet a strict standard of quality was rejected. 25% of the data was rejected leaving 15,000 points deemed to be representative of the true conditions. The process of data filtering was done carefully and in a manner that would not bias the data. Sources of potential error were identified and the associated data points were filtered out.

3. Result Analysis and Discussion

In this section, an exploratory analysis is conducted on the field collected data to develop fuel consumption model and optimum driving pattern. As was discussed, two main engine data logger and GPS-INS instruments were used to collect fuel consumption, engine load and operational parameters. The collected data need to be synchronized and filtered in data mining process [9]. Conducting this procedure, the quality of raw gathered data was assured and outliers were removed. IBM SPSS Statistics V22 and Microsoft Excel Software were used to conduct an exploratory analysis on the gathered data.

The relation between engine load and instantaneous fuel consumption (IFC) was developed through conducting ordinary least square regression analysis on the collected data. Among different functions were correlated, it was found that exponential curve has the highest correlation coefficient (R^2) value for all experimented vehicles. Then, by combining the collected data from all vehicles, the Equation (1) was developed as the relation between IFC and engine load. The R^2 of developed model is 0.94 which shows there is high correlation between engine load and IFC, and developed model has high level of accuracy. Figure 5 shows the result of ordinary least square regression analysis conducted in Microsoft Excel Software.

$$IFC = 0.0126e^{0.036EL} \quad (1)$$

Where:
IFC: Instantaneous fuel consumption (l/kW.sec)
EL: Engine load of vehicle in (%)

As Figure 6 shows, there is exponential relation between IFC and engine load. This means that as engine load increases, the rate of IFC change per 1% variation of engine load increases. Based on developed curve, for decreasing IFC, we need to drive at the lowest engine load rate. It also shows the variation in engine load value must be minimized.

The effect of operational parameters needs to be considered in the next step. Barati and Shen developed multivariate linear relation between four acceleration, speed, road slope and payload parameters and engine

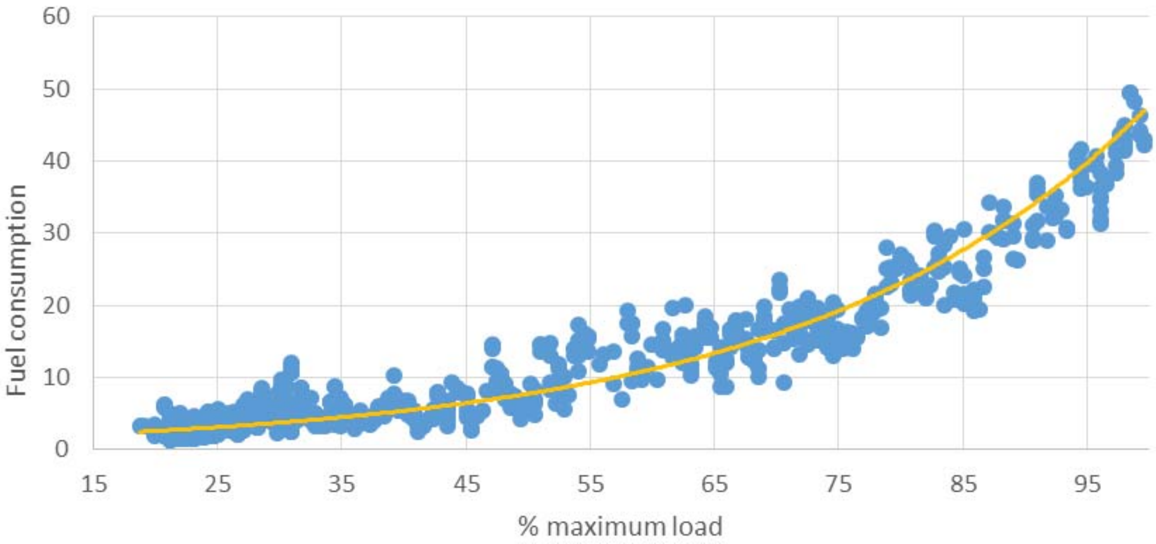

Figure 5. Ordinary least square regression analysis on IFC and engine load relation

load [8]. Actually, payload is a separate factor influencing the effect of the other three investigated parameters on engine load. So, this parameter does not have coefficient in the presented model, but its effect on engine load is considered in the coefficients of the other parameters. Also, the engine load of vehicles in idling mode needs to be considered in model which is around 18% for on-road vehicles. The developed engine load model is presented in Equation (2). Also, Table 2 presents the coefficients of acceleration, slope of road and speed parameters in the developed model. Load factor (LF) represents the payload parameter. The coefficients of this parameter show the current payload as a percentage of maximum allowable payload of vehicle.

$$EL = (C_{AC}*AC) + (C_{SL}*SL) + (C_{SP}*SP) + C \quad (2)$$

Where:
EL: Engine load of vehicle (%)
AC: Acceleration of vehicle (m/s^2)
SL: Slope of road (degree)
SP: Speed of vehicle (m/s)
C: Engine load of vehicle in idling mode which is around 18%.
C_{AC}, C_{SL}, and C_{SP}: The coefficients of acceleration, slope and speed respectively (unit less)

In the next step, we aim to develop optimum driving pattern to minimize the fuel consumption of on-road vehicles. As was noted, payload does not have any coefficient in the developed model, but its effect is considered on engine load through the coefficient of other parameters. The optimization process needs to be done for different payloads. For simplifying the analysis, as an example, we develop the optimization process for vehicles without any payload (LF=0). So, the fuel consumption model for vehicles without payload is presented as Equation (3). As can be seen, this is the combination of Equations (1) and (2).

$$IFC = 0.0126*e^{0.036(13.9AC + 1.2SP + 2.1SL + 18)} \quad (3)$$

Optimum driving pattern is developed by minimizing fuel consumption per moved distance for on-road vehicles. Based on Equation (3), three acceleration, speed and slope parameters affect fuel consumption at the same time. Equation (3) covers negative values of acceleration and slope of road as well which means the developed fuel consumption model is valid for deceleration and driving in downhills. In this step, we first focus to determine the effect of speed on fuel consumption to find optimum speed for driving with zero acceleration and payload in levelled route. For conducting optimization process, the value of three main parameters of IFC, instantaneous speed and moves distance is required for

Table 2.The coefficients of parameters in engine load model

Model	Coefficients			
LF	0	0.33	0.67	1
C_{AC}	13.9	16.10	19.15	24.30
C_{SL}	2.10	2.65	3.35	4.25
C_{SP}	1.20	1.40	1.60	1.90

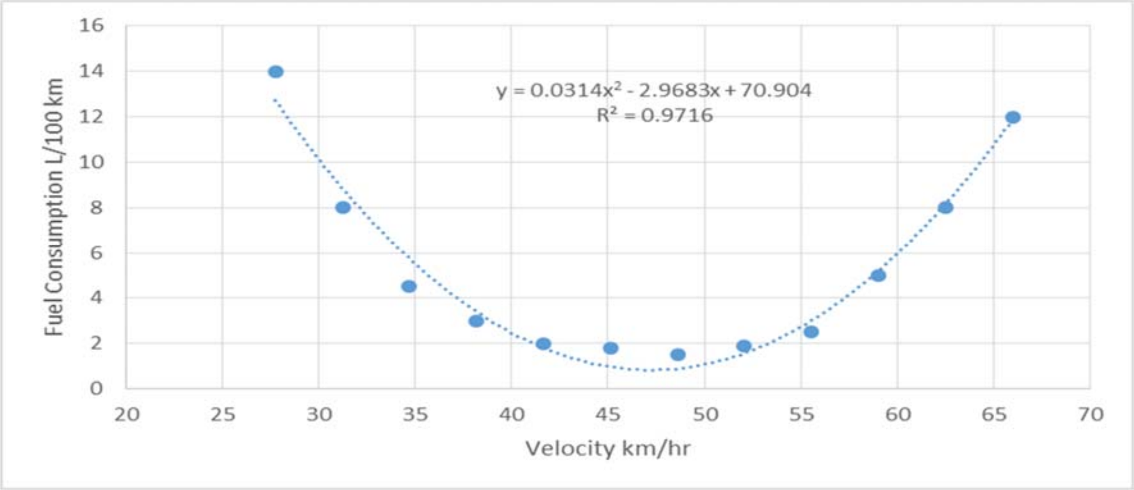

Figure 6. Relation between speed and fuel consumption

each second. IFC is measured by Equation (3), and speed and distance parameters are measured by GPS-INS instrument. As Figure 6 shows, the fuel consumption was calculated per 100 moved kilometers based on different fixed speeds. Ordinary least square analysis was conducted to develop this relation. As Equation (4) presents, there is highly correlated parabolic relation ($R^2 = 0.972$) between consumed fuel and speed of vehicle.

$$FC = 0.0314SP^2 - 2.968SP + 70.904 \qquad (4)$$

Where:
FC: Fuel consumption (l/100km)
SP: Speed of vehicle (km/hr)

As Figure 6 indicates, for a vehicle with zero acceleration and payload driven in a levelled route, the speed of around 50 km/hr is optimum for having minimum fuel consumption. This figure indicates that driving with the speed of less than 50 km/hr, in spite of decreasing engine load, fuel consumption increases decreases due to having longer trip time. Also, for driving with the speed of higher than 50 km/hr increases the fuel consumption because of high change in the engine load value.

The result analysis on investigating the effect road slope shows this parameter has significant effect on the relation between optimum driving speed and fuel consumption. As Figure 7 indicates, by increasing the slope of road, the optimum speed decreases, but there is sharp increase in the amount of minimum fuel consumption. For example, in a road with 6 degree slope, optimum speed reduces to around 30 km/hr, while the minimum fuel consumption increases to about 6 l/100km.

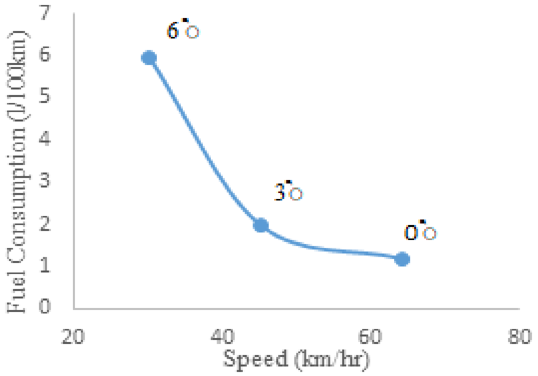

Figure 7. Effect of road slope on the relation between optimum speed and fuel consumption

4. Conclusion

The fuel used by on-road vehicles is the main source of pollution in urban area causing numerous respiratory diseases for inhabitants. Also, the sources of fossil fuels are diminishing because of huge use by vehicles globally. This paper optimized driving pattern to minimize fuel consumption used by on-road vehicles. A comprehensive methodology was first developed to collect required field data, model fuel consumption and optimize driving behaviour. Two main engine data logger and GPS-INS instruments were developed to collect real-world field data of six on-road vehicles through experimentation. After data mining and filtering, and removing outliers, ordinary least square and multivariate linear regression analysis were conducted on the data to investigate the relationship between operational parameters, engine load and fuel consumption. The result analysis indicates the developed relations have high accuracy ($R^2 > 0.90$). In the next step, by using developed fuel consumption model and field data measured by GPS-INS instrument, the driving pattern was optimized by investigating the role of speed and road slope parameters.

To simplify the optimization process, in the first step, acceleration, road slope and payload parameters were assumed to be zero, and the effect of speed was investigated. Based on the archived results, the speed of 50 km/hr is optimum for having minimum fuel consumption per distance. Also, the effect of road slope was investigated on the optimum speed and its correspondent fuel consumption. It was shown that as slope of road increases, the optimum driving speed decreases, while there is sharp increase in the amount of minimum fuel consumption.

For future studies, based on developed methodology, this research focuses on fuel modelling of off-road vehicles including construction and mining equipment. This is the first step for developing schemes and guidelines for minimizing the used fuel of these huge machineries. Also, the relation between fuel consumption and emission rates needs to be investigated for decreasing the emission produced by such equipment.

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