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A Rule-Based Intelligent Energy Management System for an Internal Combustion Engine Vehicle

Hamid Khayyam, Abbas Z. Kouzani, Khashayar Khoshmanesh, and Eric J. Hu
School of Engineering and IT, Deakin University, Geelong, VIC 3217, Australia
hkhay, kouzani, kkho, erichu@deakin.edu.au

Abstract- An intelligent energy management system (IEMS) is developed to improve fuel efficiency of an internal combustion engine vehicle. It helps determine the best approach to run the engine system through dynamically analysing various factors relating to vehicle. The energy balance technique is implemented and utilised. The simulation outcome of the IEMS is compared against that of a conventional system under the same driving factors. The results show that the IEMS reduces the fuel consumption around 5.6% for the tested conditions.

I. INTRODUCTION


Despite the existing research work, there is a gap in understanding of the performance of fuel consumption of the vehicles. This paper uses the analysis and simulation method to develop an Analytical Model of Intelligent Energy Management System (IEMS) Fuel Consumption for an internal combustion engine vehicle. It calculates the energy distribution and power flows in the power train of the vehicle and related losses. It formulates the ways to minimise the vehicles' fuel consumption under various driving conditions. It learns during operation, and applies proper adjustments to the way it operates to ensure that fuel consumption reduction is achieved.

II. PROPOSED IEMS

A. Model

A.1. Conventional vehicle: The power flow model from tank to wheel is demonstrated in Fig. 1. There exit several efficiency terms that signify the effect of different losses from tank to wheel:

\[ (Q_{\text{combustion}}) \times \eta_{\text{mec}} \times \eta_{\text{motor}} \times \eta_{\text{trans}} \times \eta_{\text{actuator}} = P_{\text{out}} \]

\[ = P_{\text{combustion}} + P_{\text{motor}} + P_{\text{trans}} + P_{\text{actuator}} + P_{\text{braking}} \]

(1)

where:

\[ P_{\text{out}} \] = Power output of engine

\[ \eta_{\text{mec}} \] = Mechanical efficiency

\[ \eta_{\text{motor}} \] = Motor efficiency

\[ \eta_{\text{trans}} \] = Transmission efficiency

\[ \eta_{\text{actuator}} \] = Actuator efficiency

A driver first determines the drive strategy, selects the engine specifications, starts the vehicle motion, and controls the mass flow rate of fuel in to ICE by changing the pedal, gear, brake, and clutch.

A.2. IEMS: This is a methodology proposed to reduce fuel consumption. In this unit, as shown in Fig. 1, two data flow path parts are employed:

1. Slope Prediction Unit (SPU): This unit employs an sensor and a vision algorithm to calculate the slope angle of the road ahead within the distance of 50 meters away from the vehicle, and forward this information to the IEMS.

2. Friction Management Unit (FMU): This unit includes the following modules:

   i. Current Road Slope Module (CRSM): This module specifies the actual slope angle of the road at the current location of the vehicle.

   ii. Road Friction Module (RFM): This module gives road friction coefficient, gravity acceleration, and motion angle.

   iii. Combustion Module (CM): This module employs the combustion process from the vehicle as described below, and calculates and returns the amount of combustion energy needed.

\[ Q_{\text{combustion}} = m_{\text{fuel}} \times q_{\text{combustion}} \]

(2)

where \[ q_{\text{combustion}} \] is the combustion energy. The fuel is assumed to be \[ C_{4}H_{10} \] [14]. The complete combustion of \[ C_{4}H_{10} \] with \( I+k \) percent theoretical air is:

\[ 8CO_{2} + 7.48H_{2}O + 11.74(k-1)O_{2} + 11.74 \times 3.76 \times k \times N_{2} \]

(3)
iv. Wind Drag Module (WDM): This module provides the following wind parameters: wind speed, wind direction, and drag coefficient.

v. Accessory Module (AM): This module represents the accessories embedded within the vehicle such as electrical devices and air conditioning.

vi. Vehicle Efficiencies Module (VEM): This module defines the values of the Otto cycle, real fuel air engine, mechanical and heat loss efficiencies associated with the conventional vehicle.

B. Algorithm

The overview of the simulation algorithm for the IEMS is sketched in Fig. 2. The simulation initialises normal power and primal kinetic energy for a moving vehicle. The data include arrays of 24000 elements (steps). One iteration occurs in each step representing the time interval of the duration 0.05 sec. Then the slope prediction data is retrieved from the SPU. If the predicted slope angle is different from the current slope angle, the STI block increases or decreases the amount of power. Then the vehicle/environment/friction data is retrieved from the FMU. If the current total friction energy is different from the energy associated with the slope prediction, the FTI block is triggered calculating the amount of power for all frictions. Otherwise, the OPP block is entered. The OPP optimises the fuel consumption with respect to the vehicle/efficiencies, speed, acceleration, gear data, and the power information from last block in an iterative manner. In each iteration, Eq. (2) is calculated first. Then the results are used to compute Eq. (3), producing a value for \( \text{fuel} \). The vehicle speed should remain constant and thus the fuel consumption of vehicle is expected to remain constant. However, due to changes in various frictions, the required power may become larger than the normal power. In this case, more fuel will be consumed to maintain the speed and acceleration within their desired ranges. On the other hand, if certain frictions are reduced, the required power becomes smaller than the normal power. In this case, less fuel will be consumed to keep the speed and acceleration within their specified ranges.

The result of OPP is compared against the drive strategy. In each iteration, the following are calculated:

\[
P_{in} = [F_{frem} + F_{drag} + F_{eng}] \times V_1 + \frac{1}{2} \times m \times (V_1^2 - V_0^2)
\]

The acceleration of the vehicle in \( \Delta t \) time can be calculated as:

\[
a_t = \frac{V_f - V_i}{\Delta t} = \frac{dV}{dt}
\]

Also, the distance of traversed by vehicle in \( \Delta t \) is:

\[
x = \frac{1}{2} \times a_t \times (V_f + V_i) \times \Delta t
\]

The results are then compared with the drive strategy data. If the comparison is satisfied then these data will be forwarded to the next block where they overwrite the results of the previous iteration. Otherwise, the power of engine is corrected by decreasing or increasing it in the increase/decrease power block. Once either of speed or acceleration is found greater than the desired limit, then the engine power is reduced. On the other hand, when either of speed or acceleration becomes smaller than the desired limit, the engine power is increased.

In the assignment block, old data is overwritten with the new data. Also a copy of the information is stored into the database. These steps are repeated maintaining both the speed and acceleration within their desired ranges.

![Figure 1. Overview of the developed power flow analysis for vehicles.](image-url)
C. Slope

Several geometric design methods could be used [15] to smoothen physical slope of a real road. A method called "vertical curve comfort" is used. In our work, $K$ is chosen as 3, and thus for the acceleration of 0.1g (0.98 m/s$^2$), the speed of should be 60 km/h (16.6 m/s).

D. Drive Strategy

Moreover, in this work, we have considered a vehicle with the engine specification as given in Table I.

Table I. ENGINE SPECIFICATION

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine size (litre)</td>
<td>1.9</td>
<td>6.0</td>
<td>3.6</td>
</tr>
<tr>
<td>RMP (rev / min)</td>
<td>4000</td>
<td>6000</td>
<td>5000</td>
</tr>
<tr>
<td>Engine power (kW)</td>
<td>9.9</td>
<td>12.0</td>
<td>10.1</td>
</tr>
</tbody>
</table>

We have employed the highway method where the road has no bends and traffic lights. We have formulated a set of rules called "Drive Strategy" as shown Table II.

Table II. DRIVE STRATEGY PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>16.38</td>
<td>16.94</td>
<td>16.66</td>
</tr>
<tr>
<td>Acceleration (m/s$^2$)</td>
<td>-0.98</td>
<td>0.98</td>
<td>0.5</td>
</tr>
<tr>
<td>Travel Time (s)</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Travel Distance (m)</td>
<td>20000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the fuel map diagram presented in [9], for a 2 litre conventional engine, more than 70 kW is considered as uneconomic engine operating condition.

III. RESULT AND DISCUSSIONS

A. Simulations

A.1. Simulation 1: In the first simulation, the IEMS was tested on a set of data associated with a sloping-windy condition. The road was set to be sloping with various slope angles within the range $-20^\circ \leq \theta \leq +25^\circ$. Moreover, the environmental wind was assumed to be non-zero. The wind angle of attack was varied as follows: $\theta_1=0^\circ$, $\theta_2=90^\circ$, and $\theta_3=180^\circ$. Considering the wind velocity, however, four different conditions were implemented: $V_2=0$, $V_2=1$, $V_2=1.5$, $V_2=2$. In our simulation, the following parameters were also considered: road-friction, combustion, and constant accessory. Fig. 3 shows the slope angle and the wind-speed data used.

A.2. Simulation 2: In the second simulation, the IEMS was tested on a set of data associated with a sloping-windy employing slope prediction information. The road was set to be sloping with various slope angles within the range $-20^\circ \leq \theta \leq +25^\circ$. Moreover, the environmental wind was assumed to be non-zero. The wind angle of attack was
varied was varied as follows: $\theta_1=0^\circ$, $\theta_2=90^\circ$, and $\theta_3=180^\circ$. Considering the wind speed, however, four different conditions were implemented: $V_2=0$, $V_2=10$, $V_2=15$, $V_2=20$. In this simulation, the SPU would see the slope ahead and measure it within a 50 meter distance from the front of the vehicle. The following parameters were also considered: road-friction, combustion, and constant accessory. Fig. 3 shows the slope angle as well as the wind-speed data used in this simulation.

B. Discussions

B.1 Simulation Result 1: The power and fuel consumption results for the first simulation are shown in Fig. 4-top. Initially 8635 watt of energy is given to the vehicle so that the initial speed of 16.6 m/s is achieved. The energy consumption remained constant at 8635 watt where the condition was flat-windless (e.g. Steps 0-3000). Using:

$$m_{\text{fuel}} = \frac{1}{T} \int m_{\text{fuel}} \, dt$$

where $T$ is the total numbers of steps involved in the simulation, the average fuel consumption for Simulation 1 was found to be around 9.843 liter/100 km.

B.2 Simulation Result 2: The power and fuel consumption results for the second simulation are shown in Fig. 4-bottom. The IEMS uses slope information and increases $\dot{m}$ about 50 meters prior to reaching a hill. In addition, the IEMS decreases $\dot{m}$ about 50 meters prior to reaching the top of the hill because the vehicle would have adequate kinetic energy to pass the hill. Fig. 5 shows that the slope friction has a significant impact on the fuel consumption. The reason is that it requires more fuel in a transit time. Slope friction takes up to 5 times more fuel consumption than other frictions in short times, depending on the slope angle and slope parabolic vertical curve distances. The outcome of this simulation shows the vehicle speed and acceleration is significantly smoother than that of Simulation 1. Using Eq. (7), the average fuel consumption for Simulation 2 was 9.287 liter/100 km.

V. CONCLUSIONS

Analysis and simulation of the behaviour of a conventional vehicle under varying environmental conditions are presented. Several frictions were included. The slope friction takes 2-5 times more fuel consumption than other frictions in short times. The results show that for using more than 70 kW of engine energy, the fuel consumption is increased about 0.06% g/s. The simulation results show that employing the IEMS which uses the slope prediction strategy has helped reduce the fuel consumption around 5.6% per 100 km.

ACKNOWLEDGMENT

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REFERENCES

Figure 3. (top) Slope angle data and (bottom) wind-speed data used.

Figure 4. Power and fuel consumption results for (top) Simulation 1, and (bottom) Simulation 2.

Figure 5. All power consumption results for Simulation 2.