International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1020

A RECEDING HORIZON ECO-DRIVING STRATEGY FOR ELECTRIC VEHICLES CONSIDERING TRAFFIC FLOW AND SIGNAL INFORMATION

Lijun Zhang*, Xianming Ye, Farshad Barzegar, Xiaohua Xia

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

ABSTRACT

A real-time eco-driving strategy for electric vehicles is presented with the objectives of minimizing the travel time and energy consumption. The strategy is developed following a receding horizon approach such that it can take real-time traffic flow information in terms of speed limits into account when planning the vehicle's speed profile. The problem is tackled by dividing it into two sub-problems, a travel time minimization problem and an energy consumption minimization problem. Analytic solutions to the travel time minimization problem is provided to facilitate real-time application. Simulation is done over a 10 km road to demonstrate the strategy's effectiveness.

Keywords: Eco-driving, speed advisory, receding horizon optimization, electric vehicles, traffic flow, traffic signal

NONMENCLATURE

Abbreviations	
TMP	Time minimization problem
EMP	Energy minimization problem
Symbols	
$\overline{x}$	Upper limit of x
$\underline{x}$	Lower limit of x
k	Index of road sections

1. INTRODUCTION

Although electric vehicles (EVs) have made their way to road applications, the limited mile range per single charge is still the main bottleneck limiting their widespread adoption. Eco-driving that reduces energy consumption per distance travelled is one of the key techniques having the potential of extending the driving range of EVs [1].

Either as an offline speed advisory system or online real time driver assistance speed planner, the eco-driving system's main function is to optimize speed profile of the vehicle over a distance covering one or several traffic lights ahead of it [2]. Most of the published works on eco-driving focus on light duty fossil fuel powered vehicles with a few of them investigated heavy duty city transient buses [3] and electric vehicles [1].

From methodology perspective, researchers have tried to apply rule as well as optimization based methods to reduce fuel consumption of road vehicles by means of reducing the average speed, sharp acceleration, and waiting times at traffic lights [2].

However, these studies all assumed that the speed limit is constant throughout the trip or at least in a road segment between two traffic lights. This is not always true for highly populated urban cities. In a real-world scenario, the speed limit of the vehicle is affected by both legal speed limit that is constant and the traffic flow density, which is time varying. Under such circumstances, the speed optimized by the reported eco-driving systems might no longer be optimal or even feasible in real-time applications. To tackle the speed advisory problem under changing speed limits, this paper proposes a receding horizon optimization approach for EVs aiming at

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

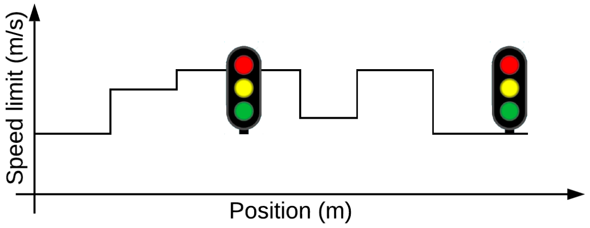

Fig 1 Vehicle speed limits over multiple segments

minimizing both the energy consumption and trip time of the vehicle.

2. MODELLING OF THE ECO-DRIVING SYSTEM

The general form of the eco-driving system presented is graphically illustrated by Fig 1, in which the vehicle has to adhere to speed limits that are different in different sections within a segment of the road (the road covering the complete distance between traffic lights).

Under the situation that the speed limit over a road segment is constant, which might be true for low traffic density roads, the speed planning in eco-driving only needs to plan the acceleration of the vehicle according to a single speed limit. However, when the speed limit within a road segment changes over distance, the speed planning problem becomes much more complex.

In the following, the eco-driving system proposed is divided into two sub-problems, namely the travel time minimization problem (TMP) and energy consumption minimization problem (EMP).

2.1 TMP formulation

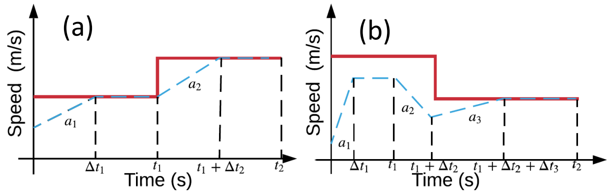

Fig 2 (a) Case 1, (b) Case 2

The TMP is solved by a receding horizon approach such that any updates on the traffic flows that affect the speed limits from V2I and V2V communications can be incorporated to get a more realistic speed profile. In particular, the predicting horizon is chosen to be two adjacent sections that have different speed limits. In TMP, the vehicle passes the two sections with maximum possible speed such that the travel time can be minimized.

There are two cases, as shown in Fig 2, in which the red solid line is the speed limit and the blue dashed line is one possible speed profile. In case 1, the speed limit of the second section is higher and the otherwise is true for case 2. For case 1, the vehicle can first accelerate to the lower speed limit if time allows, travel at the speed limit for the rest of section 1, and then accelerates again during the second section. The following optimization problem needs to be solved for case 1.

$$\min_{a_1,\Delta t_1,a_2,\Delta t_2} t_2 = \frac{d_1 + \frac{1}{2}a_1\Delta t_1^2}{v_0 + a_1\Delta t_1} + \frac{d_2 + \frac{1}{2}a_2\Delta t_2^2}{v_0 + a_1\Delta t_1 + a_2\Delta t_2}, \tag{1}$$

where a_1 and a_2 are accelerations, Δt_1 and Δt_2 are the acceleration time, and d_1 and d_2 are the distances of the first and second road sections, respectively. v_0 is the initial speed of the vehicle. Subject to the following constraints.

$$\underline{a} \le a_1, a_2 \le \bar{a}, \tag{2}$$

$$\underline{v}_1 \le v_0 + a_1\Delta t_1 \le \bar{v}_1, \tag{3}$$

$$\underline{v}_2 \le v_0 + a_1\Delta t_1 + a_2\Delta t_2 \le \bar{v}_2. \tag{4}$$

From here and onwards, subscripts 1 and 2 denotes the index of road sections.

The explicit solution of the TEM under such a case is given by **Algorithm 1**.

```
Algorithm 1: Case 1 solution
Input: $\bar{v}_1,\ \bar{v}_2, \bar{a},\ v_0$.
Set $k := 1$
while $k \le 2$ do
    Set $\bar{v} = \bar{v}_k,\ d = d_k,\ v_0 = v_{k-1}$
    if $\frac{\bar{v}^2 - v_0^2}{2\bar{a}} > d$ then
        the vehicle keeps accelerating to
          $v_x = \sqrt{2\bar{a}d + v_0^2}$ with $\Delta t_k = t_k = \frac{v_x - v_0}{\bar{a}}$
    else
        the vehicle accelerates to $\bar{v}$ then cruise at $\bar{v}$:
          $\Delta t_k = \frac{\bar{v} - v_0}{\bar{a}},\ t_k = \Delta t_k + \frac{d - \frac{\bar{v}^2 - v_0^2}{2\bar{a}}}{\bar{v}}$
    end
    $k = k + 1$
end
```

For the second case, the general time minimization problem can be formulated as

$$\min_{a_1,\Delta t_1,a_2,\Delta t_2,a_3,\Delta t_3} t_2 = \frac{d_2 + \frac{1}{2}a_3\Delta t_3^2}{v_0 + a_1\Delta t_1 + a_2\Delta t_2} + \frac{d_1 + \frac{1}{2}a_1\Delta t_1^2 - \frac{1}{2}a_2\Delta t_2^2 - a_1\Delta t_1\Delta t_2 - v_0\Delta t_2}{v_0 + a_1\Delta t_1} \tag{5}$$

Subject to constraints

$$\underline{a} \le a_1, a_2, a_3 \le \bar{a}, \tag{6}$$

$$\underline{v}_1 \le v_0 + a_1\Delta t_1 \le \bar{v}_1, \tag{7}$$

$$\underline{v}_2 \le v_0 + a_1\Delta t_1 + a_2\Delta t_2 \le \bar{v}_2, \tag{8}$$

$$\underline{v}_2 \le v_0 + a_1\Delta t_1 + a_2\Delta t_2 + a_3\Delta t_3 \le \overline{v}_2. \quad (9)$$

Analytic solution to the second case can be found following **Algorithm 2**.

Algorithm 2: Case 2 solution

```
Input: $\bar{v}_1,\ \bar{v}_2, \bar{a},\ \underline{a},\ v_0$.
Set $s_1 = \frac{\bar{v}_1^2 - v_0^2}{2\bar{a}}$, $s_2 = \frac{\bar{v}_2^2 - \bar{v}_1^2}{2\underline{a}}$, $s_3 = \frac{\bar{v}_2^2 - v_0^2}{2\bar{a}}$
if $s_1 + s_2 \le d_1$ then
    $\Delta t_1 = \frac{\bar{v}_1 - v_0}{\bar{a}}$, $\Delta t_2 = \frac{\bar{v}_2 - \bar{v}_1}{\underline{a}}$;
    $t_1 = \Delta t_1 + \frac{d_1 - s_1 - s_2}{\bar{v}_1} + \Delta t_2$;
    $t_2 = t_1 + \frac{d_2}{\bar{v}_2}$
else if $s_3 \ge d_1 + d_2$ then
    $t_1 = \frac{-v_0 + \sqrt{v_0^2 + 2\bar{a}d_1}}{\bar{a}}$, $v_1 = v_0 + \bar{a}t_1$;
    $t_2 = \frac{-v_1 + \sqrt{v_1^2 + 2\bar{a}d_2}}{\bar{a}}$
else if $d_1 \le s_3 < d_1 + d_2$ then
    $t_1 = \frac{-v_0 + \sqrt{v_0^2 + 2\bar{a}d_1}}{\bar{a}}$;
    $t_2 = \frac{d_1 + d_2 - s_3}{\bar{v}_2} + \frac{\bar{v}_2 - v_0}{\bar{a}}$
else
    The vehicle first accelerates to $v_x$ then decelerates
      to $\bar{v}_2$ over the first section.
    $v_x = \sqrt{\frac{2\bar{a} + v_0^2 + \bar{v}_2^2}{2}}$;
    $\Delta t_1 = \frac{v_x - v_0}{\bar{a}} \Delta t_2 = \frac{v_x - \bar{v}_2}{\underline{a}}$;
    $t_1 = \Delta t_1 + \Delta t_2$;
    $t_2 = \frac{d_2}{\bar{v}_2}$
end
```

With the help of the above formulations, the receding horizon travel time minimization problem is solved as shown in **Algorithm 3**.

Algorithm 3: Receding horizon travel time minimization

```
Set $k := 1$ and $\underline{t} = 0$
while $k \le$ number of road sections do
    if $\bar{v}_1 < \bar{v}_2$ then
        Solve the Case 1 TEM problem
        $\underline{t}_1 = t_1$
    else
        Solve the Case 2 TEM problem
        $\underline{t}_1 = t_1 + \Delta t_2$
    end
    $\underline{t} = \underline{t} + \underline{t}_1$
    $k = k + 1$
end
```

Notice that by following the receding horizon method, the updated road speed limits received by the vehicle through V2I and/or V2V communications can be readily incorporated, allowing an effective real-time implementation of the presented strategy. It is however noted that the above TMP formulated does not take into consideration of the passenger rid comfort because of two reasons. Firstly, the ride comfort can be accounted for by setting a relatively small max acceleration limit. Secondly, once the minimum travel time of a road segment is found, it is usually the case that the vehicle will not be able to pass the traffic light with this minimum time. The minimum pass time at the traffic signal obtained by (10) is therefore usually longer, allowing ride comfort to be considered by the MEP.

$$t_{pass} = \begin{cases} \underline{t}, \text{ if } \underline{t} \in [t_g, t_r); \\ t_g, \text{ if } \underline{t} \in [t_r, t_g); \end{cases} \quad (10)$$

where t_r and t_g are the time until the traffic light turns to red and green, respectively.

2.2 MEP formulation

Once the time to pass the traffic light ahead of the vehicle t_{pass} is determined, the MEP then optimizes the speed profile of the vehicle over $(0, t_{pass}]$ to minimize energy consumption by solving the following problem.

$$\begin{array}{ll} \underset{v}{min} & \int_0^{t_{pass}} f_t(t)v(t)dt \\ \text{s.t.} & \underline{a} \le a \le \overline{a} \\ & \underline{v} \le v \le \overline{v} \\ & \int_0^{t_{pass}} v(t)dt = D \end{array} \quad (11)$$

where

$$f_t = m\dot{a} + f_r + f_a$$

$$f_r = \mu mg\cos(\alpha) + mg\sin(\alpha)$$

$$f_a = \frac{1}{2}\rho_a C_d A_f v^2$$

are tractive force, resistance forces, and aerodynamic drag of the vehicle, respectively. *m* is the vehicle mass properly adjusted to account for rotational parts. μ is the rolling friction coefficient, α is the road slope, ρ_a is air density, C_d and A_f are air drag coefficient and the frontal cross area of the vehicle, respectively.

3. SIMULATION

The same traffic light configuration used in [4] is used here. All the traffic lights are represented by 40 s of green and 60 s of red periods. In terms of distance, they are away from the vehicle at $d_1 = 1500$ m, $d_2 = 3000$ m, $d_3 = 6850$ m and $d_4 = 10000$ m. Thus, the TEM is solved over a total distance of 10 km.

Parameter	Value
vehicle mass (kg)	1500
vehicle frontal area (m^2)	2.35
gravitational acceleration (m/s^2)	9.8
air density (kg/m^3)	1.02
air drag coefficient	0.3
rolling resistance coefficient	0.01

Table 1: Vehicle parameters

The parameters of the vehicle used in simulations are given in Table 1.

We first solve the TEM problem by **Algorithms 1 and 3** to find the minimum passing time of the vehicle at the four traffic lights ahead of it.

With an initial traveling speed of $v_0 = 50$ km/h, and the speed limits over the road given in Fig. 3, the minimum passing times t_{pass} of the vehicle at the four traffic lights are, respectively, 100 s, 220 s, 480 s, and 640s.

With these pass times determined, the MEP is then solved, which resulted in the speed profile of the vehicle over the simulated road shown in Fig. 3, in which the optimized speed profile by the method presented in this study and that obtained by a heuristic method presented in [4] are shown for a quick comparison.

It can be seen that the method presented in [4] and many similar research studies works very nicely if the speed limit over a road segment is constant. However, because [4] did not considered speed limit variation over a segment of the road, it can be seen in Fig. 3 that the resulting speed profile violates the speed limit over the section [3270, 5000] m of the road. The proposed method, on the hand, is able to find the optimal speed profile over the 10 km travel distance considered without violating any speed restrictions.

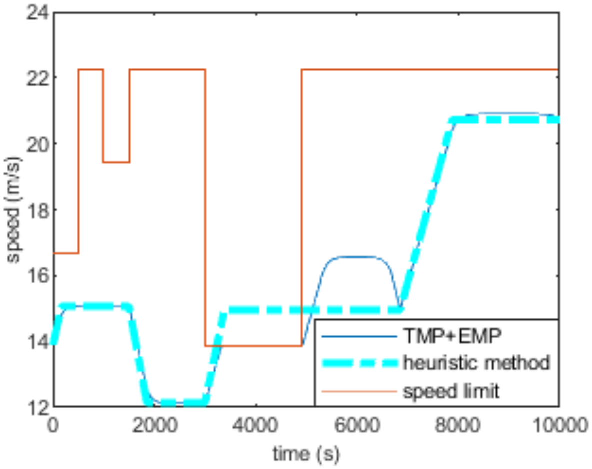

Fig. 3 Optimized speed profile

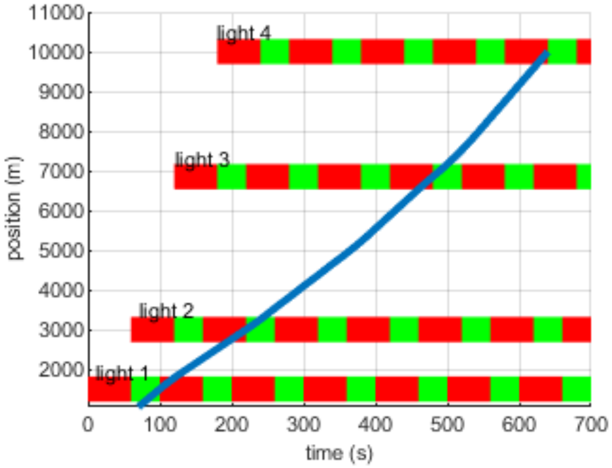

Fig. 4 Vehicle passing traffic lights

With the optimized speed profile shown in Fig. 3, Fig. 4 shows how the vehicle passed through all the traffic lights without stopping. In particular, the vehicle passes the first traffic light right before it turns to red, passes the second, third and fourth traffic lights right after the lights turn green.

ACKNOWLEDGEMENT

This work is supported financially by the National Research Foundation under grant number: 114141 and the research development fund of the University of Pretoria.

REFERENCE

[1] Dib W, Chasse A, Moulin P, Sciarretta A, Corde G. Optimal energy management for an electric vehicle in eco-driving applications. Control Engineering Practice 2014;29:299–307.

[2] Seredynski M, Dorronsoro B, Khadraoui D. Comparison of Green Light Optimal Speed Advisory approaches. Proceedings of the IEEE Conference on Intelligent Transportation Systems, ITSC 2013:2187–92.

[3] Xu Y, Li H, Liu H, Rodgers MO, Guensler RL. Eco-driving for transit: An effective strategy to conserve fuel and emissions. Applied Energy 2017;194:784–97.

[4] Zhang B, Guo G, Wang LY, Wang Q. Vehicle Speed Planning and Control for Fuel Consumption Optimization with Traffic Light State. Acta Automatica Sinica 2018;44:461.