



Intelligent Look-ahead Energy Management System Design for an Intercity bus using a fuzzy gain scheduling algorithm

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ABSTRACT

Reducing the fuel consumption and energy use in transportation systems are the active research areas in recent years. This paper considers the repetitive mission of the intercity passenger buses as a case for fuel reduction. A look-ahead energy management system is proposed which uses the information about the geometry and speed limits of the road ahead. This data can be extracted using road slope and speed limits database in combination with a GPS unit. A fuzzy gain scheduling algorithm is proposed to improve the performance of the look-ahead control. The road slope and speed limit specifications called road pattern can define some two dimensional regions. The main parameters of the proposed fuzzy look-ahead controller are optimized in each region using the genetic algorithm. The final output of the proposed controller is the desired speed that regularly is fed to the conventional cruise controller with new set points. The simulation results of the proposed energy management system show that the fuel consumption is significantly reduced.

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1. Introduction

Considering the increasing growth of energy consumption and its resulting costs, all industries strive to reduce energy consumption and increase efficiency [1]. In this regard, transportation industry is important as one of the industries with the maximum fuel consumption [2]. Many efforts have been made to reduce fuel consumption in the transportation industry which are as follows: optimizing the existing transmission components (for example, direct injection (DI) technology for combustion engines, supercharging and size reduction of components, variable compression ratio, and variable valve timing) [3], total weight reduction, developing new transmission components (such as fuel cell technology, flywheels, super-capacitors, and continuously variable transmission (CVT), and infinite variable transmission (IVT) [4], optimizing energy demand for operating auxiliary systems (42 v electric system, integrated start/generator), and low-energy lighting [5], reducing energy loss such as aerodynamic drag, friction resistance, and brake loss considering vehicle inertia, integrating existing transmission systems for producing advanced transmission technologies, using alternative fuel (CNG) and developing some new control algorithms.

A new approach for improving fuel consumption of road and rail vehicles is look-ahead control [6]. The main logic of this approach is to use ahead path information (including road slope, its twisting and bending, traffic information, etc.) in control decision-making for acceleration and braking. In look-ahead control approach, a part of ahead path distance is selected as "look-ahead window" and average of the characteristics of the path inside this window is calculated. These average values represent the characteristics of ahead path. The start of the look-ahead window is placed at a determined distance from the current location of the vehicle, which is known as the application range of previous control commands. In fact, one look-ahead part extracts the information of the ahead path and sends it to the control part. The control part can use this information to operate various control theories.

Look-ahead method has been used as an effective tool for reducing fuel consumption of trucks by Hellström, who used dynamic programming for solving the optimization problem [7]. In this paper, a look-ahead window with the length of 1500 m was used which began right from the instantaneous location of the vehicle. Ganji et al. employed fuzzy look-ahead method as a fast method for optimizing energy consumption in hybrid cars [8]. In their paper, a look-ahead window with the length of 10 m was considered within 200 m of the instantaneous location of the vehicle. Khayyam et al. used this approach to optimize ventilation system of vehicles [9] and the results showed considerable efficiency of using this method in road transportation industry. Look-ahead system was also used as a combination with the car cruise system [10]. In these two studies, a look-ahead window with the length of 200 m was used at 300 m distance of the instantaneous location. This look-ahead method was also applied in the railway transportation [11]. In this paper, a look-ahead window with the length of 100 m located at 100 m distance from the instantaneous location of train was applied.

In the reviewed studies which have used look-ahead control approach, considering the desired problem, specifications of look-ahead window including window length and its distance from the instantaneous location are considered constant, while these parameters should be selected under the influence of the factors such as instantaneous speed of vehicle, etc. and change dynamically. Since look-ahead control studies are at their early stages, they have not discussed the internal structure of look-ahead part and its effective parameters.

Considering the major share of intercity buses in passenger transportation and the importance of reducing fuel consumption in this area, this paper proposed an approach for implementing a look-ahead control algorithm which used a simulation model for an intercity bus. A dynamic model of the bus motion is presented. Then, the algorithm structure, the proposed fuzzy gain scheduling approach was explained. Finally, improved performance of look-ahead algorithm was demonstrated by applying the proposed approach and according to the simulation results.

2. Modeling of the bus power transmission system

In order to achieve an efficient model, one needs to know how accurate the model is and what level of accuracy is acceptable for the intended use. In this paper, different components of the power transmission system are first formulated, then a mathematical description is provided. This model should establish a good compromise between accuracy and computational time. This goals are not achieved only by engineering knowledge but also need experience and intuition.

2.1. Quasi-static modeling for an internal combustion engine (ICE)

If the power available in fuel in each time moment is shown by P_{ch} , the following equation can be written:

$$P_{ice,e} = \omega_{ice} T_{ice,e} = \eta(\cdot) P_{ch} = \eta(\cdot) \dot{m}_f Q_{LHV} \quad (1)$$

where $P_{ice,e}$ is the effective power of combustion engine, ω_{ice} is the engine angular velocity, $T_{ice,e}$ is the engine Effective torque, $\eta(\cdot)$ is the engine efficiency, \dot{m}_f is mass flow rate of the fuel, and Q_{LHV} (J/g) is the fuel chemical energy which is defined as: "The heat of reaction at constant pressure or at constant volume at standard temperature (always 25°C or 77°F) for complete combustion of a unit mass of fuel". Normally For gasoline $Q_{LHV} = 42.5$ MJ/kg.

Engine efficiency can be achieved by a linear equation between torque and fuel mass in a cycle and approximated as below:

$$T_{ice,e} = e_{ice} T_{ice,a} - T_{ice,loss} = \frac{\dot{m}_f Q_{LHV}}{\omega_{ice}} - T_{ice,loss} \quad (2)$$

Where $T_{ice,a}$ is the available torque regarding to complete conversion of chemical energy into mechanical energy, $T_{ice,loss}$ is the dissipated torque by friction and other losses, e_{ice} is the efficiency of internal combustion process.

Traditionally, internal combustion engines were known by torque, speed and fuel

consumption maps. To prevent the size effects, speed and torque variables are replaced by their corresponding normal variables, including average speed of the piston $c_{ice,m}$ and average effective pressure $P_{ice,m}$ as follows:

$$c_{ice,m} = \frac{S}{\pi} \omega_{ice} \quad (3)$$

$$P_{ice,ma} = \frac{4\pi Q_{LHV} \dot{m}_f}{V_d \omega_{ice}} \quad (4)$$

$$P_{ice,me} = \frac{4\pi}{V_d} T_{ice,e} \quad (5)$$

where S is the engine stroke (m), V_d is the engine displacement in m^3 and $P_{ice,ma}$ is the average effective pressure of the engine which is theoretically available. The efficiency of internal Combustion engine η can be defined as a non-dimensional definition as the following:

$$\eta = \frac{P_{ice,me}}{P_{ice,ma}} \quad (6)$$

Input-output equation can be written as:

$$P_{ice,me} = e_{ice} P_{ice,ma} - P_{ice,loss} \quad (7)$$

Then, the dissipated average effective pressure can be defined as

$$P_{ice,loss} = \frac{4\pi}{V_d} T_{ice,loss} \quad (8)$$

Two parameters, e_{ice} and $P_{ice,loss}$ are functions of engine speed and pressure. The following equations has been confirmed experimentally on various engines.

$$P_{ice,me} = e_{ice}(c_{ice,m}) P_{ice,ma} - P_{ice,loss}(c_{ice,m}) \quad (9)$$

$$e_{ice}(c_{ice,m}) = e_{ice,0} + e_{ice,1} c_{ice,m} + e_{ice,2} c_{ice,m}^2 \quad (10)$$

$$P_{ice,loss}(c_{ice,m}) = P_{ice,loss0} + P_{ice,loss2} c_{ice,m}^2 \quad (11)$$

The average effective pressure $P_{ice,max}$ while the throttle is wide open, can be obtained from the following equation

$$P_{ice,max} = \sum_{i=0}^3 P_{ice,maxi} c_{ice,m}^i \quad (12)$$

The unknown coefficients $e_{ice,i}$, $P_{ice,lossi}$ and $P_{ice,maxi}$ are obtained from the engine

experimental data. Most engines used in the automobile applications are spark ignition (SI) vehicles with gasoline fuel or compression ignition (CI) with diesel fuel. A set of coefficients for each type of these engines can be obtained and stored via interpolation curve for comparison means. In scaling method, average speed of piston is calculated based on the dimensional parameters of the scaled engine. Then, for each engine speed, efficiency and frictional losses are calculated using the stored scaling coefficients for the same type of gasoline or diesel engine. This method called "Willans scaling line" can be used for proportional models of fuel consumption, emissions models and efficiency diagrams. This method is fairly accurate and can be used as a presentation for fuel consumption and efficiency graphs of the internal combustion engine.

A conceptual View of the internal combustion engine model is shown in Figure 1. It is a quasi-static model which means that the dynamics of the crankshaft and the torque variations are neglected.

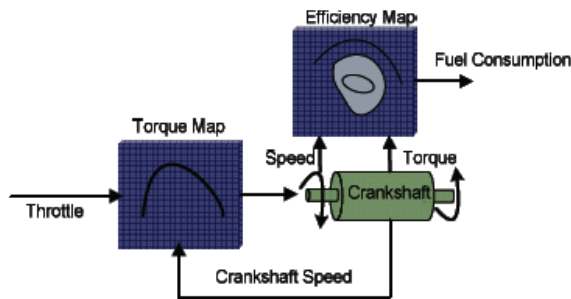


Figure 1. The quasi-static model for internal combustion engine

2.2. Gearbox model

Gearbox is considered as an intermediate between the engine and the differential. The main parameter of the gearbox is the gear number or gear ratio. Gear shifting Strategy in gearbox is as follows: if desired speed is achievable in the current gear number by increasing or decreasing

fuel rate and consequently the engine speed and torque, then the gear number does not change. The governing equations in gearbox include:

$$r_{gb} = \frac{\omega_{ice}}{\omega_{gb,out}} \quad (13)$$

$$T_{gb,out} = \eta_{gb} r_{gb} T_{ice,e} \quad (14)$$

where r_{gb} is the speed ratio of the gearbox, $\omega_{gb,out}$ is the angular velocity of the gearbox output, $T_{gb,out}$ is the gearbox output torque and η_{gb} is the gearbox efficiency which is a function of its operating conditions. Power loss in gearbox is usually a positive value that can be calculated as follows:

$$P_{loss} = \omega_{gb,out} T_{gb,out} (1 - \eta_{gb}) \quad (15)$$

2.3. Differential (Final Drive) model

The differential is a gear system with mechanical parts and no control system. A simple model of final drive considers only speed, torque ratios and efficiency. Efficiency considers the losses due to friction. A simple expression of a differential presents a constant value for the efficiency. Therefore, the mathematical equations are

$$r_{diff} = \frac{\omega_{gb,out}}{\omega_{ds}} \quad (16)$$

$$T_{diff} = \eta_{diff} r_{diff} T_{gb,out} \quad (17)$$

Where r_{diff} is the speed ratio in the differential, ω_{ds} is shaft speed, T_{diff} is the differential torque and η_{diff} is the differential efficiency. A more accurate model of the final drive can be obtained by consideration of efficiency as a function of operating conditions, for example, the efficiency curve in terms of speed and load. Similar to power loss in gearbox, power dissipation in the final drive is normally a positive value and can be calculated as follows:

$$P_{loss} = \omega_{gb,out} T_{gb,out} (1 - \eta_{diff}) \quad (18)$$

2.4. Wheel and tire model

Wheels are the connection between the external environment and the powertrain. Wheel

model should include the wheel rotation, the effect of forces between the tire and the road surface, and the braking effect. The conceptual model of wheel is shown in Figure 2.

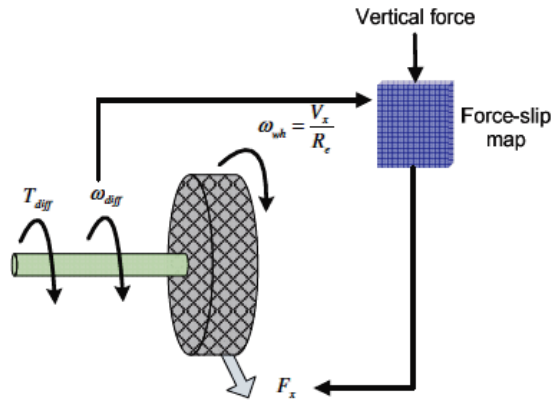


Figure 2. Wheel and tire model based on load-slip curve.

Brake acts as an additional torque that decreases the net torque on the tire. Brake torque is proportional to the pressure exerted on the brake pedal. Thus, the total torque acts on the wheels can also be written:

$$T_{tr} = T_{diff} - T_{brake} - T_{wh,loss} \quad (19)$$

$$T_{brake} = \rho T_{b,max} \quad (20)$$

where T_{tr} is the traction torque at the wheels. $T_{wh,loss}$ is the amount of loss torque in the wheel that is a function of the weight on the drive shaft. T_{brake} is the braking torque, ρ is the braking signal which is a variable between 0 and 1. $T_{b,max}$ is the maximum available braking torque.

Slip coefficient S indicates the difference between wheel linear speed $R_e \times \omega_{wh}$ and vehicle linear speed V_x .

$$S = \frac{R_{wh} \times \omega_{wh} - V_x}{V_x} \quad (21)$$

Slip coefficient is modeled as a function of the ratio between traction force F_x and the effective weight on the driving wheel W_{rear_axle} .

$$S = S\left(\frac{F_x}{W_{rear_axle}}\right) \quad (22)$$

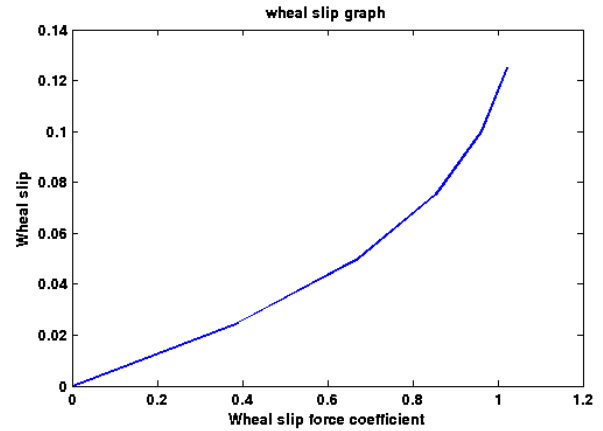


Figure 3. Wheel slip graph

2.5. Vehicle dynamics

Vehicle dynamics can be expressed by the longitudinal motion of vehicle. Newton's second law is used to formulate the vehicle motion. Longitudinal forces in vehicle motion are shown in Figure 4.

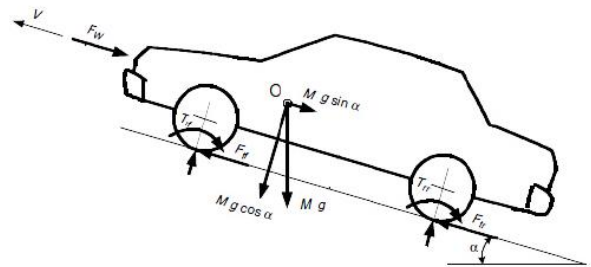


Figure 4. Longitudinal forces on a vehicle

The force needed to overcome the friction force $F_{rolling}$ is calculated as

$$F_{rolling} = M g \cos\theta (\mu_1 + \mu_2 V_x) \quad (23)$$

where M is the vehicle mass, g is the acceleration due to gravity, θ is the angle of road slope, μ_1 is the primary friction coefficient, μ_2 is the secondary friction coefficient and V_x is the vehicle speed. The required Climbing force F_{grade} is stated as

$$F_{grade} = M g \sin\theta \quad (24)$$

The aerodynamic drag F_{air} can be calculated by the following equation

$$F_{air} = \frac{1}{2} \rho_a C_D V_x^2 \quad (25)$$

Where ρ_a is the air density and C_D is the drag coefficient.

The force responsible for the speed changing or accelerating force F_{acc} is defined as

$$F_{acc} = M \dot{V}_x \quad (26)$$

Where \dot{V}_x is the vehicle acceleration. Therefore, considering the vehicle as a rigid body, the net traction force will be sum of longitudinal forces

$$F_x = F_{rolling} + F_{grade} + F_{air} + F_{acc} \quad (27)$$

2.6. Speed Controller

In actual driving, the driver follows the desired speed by some control means (including brake, throttle pedal and gear ratio). The speed controller tries to simulate the behavior of a cruise control system.

If the vehicle speed is beyond the the desired speed, the controller primarily closes the throttle and uses the brakes if needed. If the vehicle speed is less than desired speed, controller will opens the throttle. In the meantime, the controller will make gear shifts under the terms of the engine working conditions. To review the conditions of gear shifting, maximum engine torque $T_{ice,max}$ in each engine speed should be calculated.

The load on the engine $load_{ice}$ is defined as the ratio of the engine torque to the maximum engine torque $T_{ice,max}$.

$$load_{ice} = \frac{T_{ice,e}}{T_{ice,max}} \quad (28)$$

The load on the engine is an index for gear shifting. In other words, two curves presenting the bounds for increasing and decreasing the gear number are defined in the engine work space in terms of engine speed and engine torque. If the engine operating point exits the space between the border lines, the gear will be changed. Border curves for increasing and

decreasing the gear number are shown in Figure 5.

In fact, gear shifting boundaries can slightly prevent that the engine working points to enter the low efficiency areas. But, they can not necessarily move the engine working point to a high efficiency area. The engine working point depends on vehicle speed and road gradient. After determining the gear number, one can calculate the engine working point and the fuel consumption rate (which is a function of engine working point).

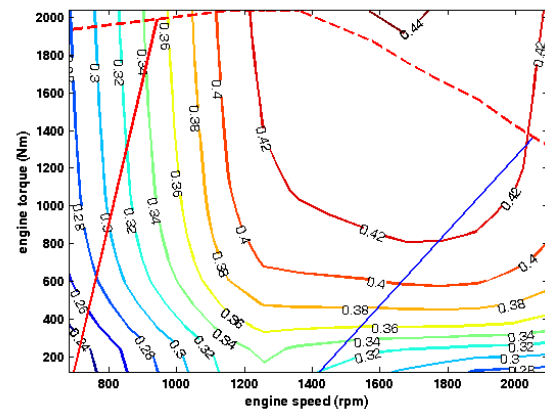


Figure 5. Gear shifting boundaries on the engine efficiency map

2.7. Validation of the bus simulation model

To validate the proposed simulation model for the intercity bus and demonstrate the performance of speed controller, the bus motion is simulated and compared to the real trip results.

The bus model Scania Maral 4212 manufactured by Oghab-Afshan company has the engine model Scania DC 13107 constructed by Scania company. This six-cylinder engine has a displacement of 12.7 liters which has been designed for use in heavy duty vehicles. This engine has a maximum power of 294 kW at 1900 rpm. The net weight of the engine is 920 kg. Maximum torque of the engine is 2000 Nm at 1000-1350 rpm.

The simulation path was 120 kilometers from Nain-Isfahan road. The path is shown on the

map in Figure 6 and the simulation results is also shown in Figure 7.



Figure 6. Simulation path (Nain-Isfahan road)

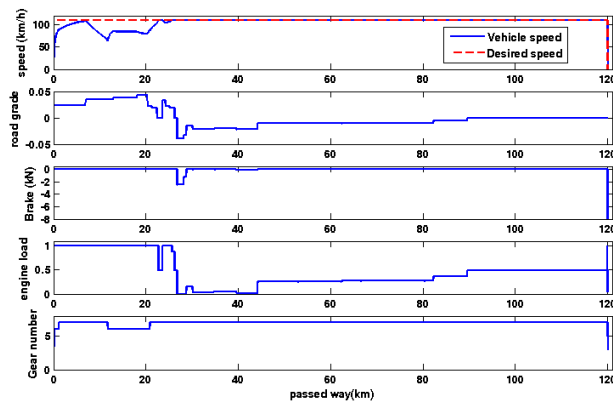


Figure 7. Simulation results of bus motion on Nain-Isfahan road

According to speed profiles in Figure 7, speed controller should track a constant speed of 110km/h. The desired speed was tracked well except the first 30 km. In the first 30 km, the road slope is positive and the path is uphill. Therefore, the bus speed drops and speed controller has attempted to reduce the gear number from 7 to 6. In km 20-22 down the path, the bus enters the downhill. Thus, speed controller should reduce the speed and prevent the speed increment beyond 110 km/h. Speed decrease is done by reducing the engine load without using the brakes. But, around km 30 down the path, due to the downhill slope increase, reducing the engine load is not sufficient only and the controller used the brake.

The real test was performed on actual path and the results comparison are shown in Table 1. According to the results presented in Table 1, fuel consumption error in simulation model compared with the real test is about 1.6%. This error may be due to environmental conditions such as wind speed or error in estimating the weight of passengers and cargo.

Table 1. Results comparison of simulation and actual test

Simulation / test	Fuel consumption (l)	Travel time (s)
Simulation Model	36.39	4133
Real test	37	4200

3. Performance analysis of the look-ahead control using engine efficiency map

To study the philosophy of the look-ahead control and to achieve a logical framework to design some optimum fuzzy rules, different road conditions are discussed in this section. It is considered that the bus is moving in a two-way road that its legal speed limit is 95 km/h. The first comparison option is the cruise control system that aims to track a constant speed of 85 km/h and the second option is the look-ahead control system that modifies the optimum speed between 75km/h to 95km/h. the average speed of both options should be close, so that the travel time difference be little.

3.1. Engine efficiency as a function of road slope and vehicle speed

The main factors in determining the efficiency and fuel consumption of a diesel engine includes the engine rotational speed and torque. Engine rotational speed is a function of the vehicle linear velocity and in the other hand, engine torque is a function of road slope. Therefore, the impact of speed increase on engine efficiency in a constant slope road can be studied. Engine working points at a constant slope of 0% and speed range of 75 to 95 km/h are shown in Figure 8. Gear number in this speed range of

vehicle is 8. By increasing the road slope, the torque of working points will increase. Engine working points at a constant slope of 2% and speed range of 75 to 95km/h are shown in Figure 9. The gear number corresponding to speeds 75 to 86 km/h is 7.

According to figures 8 and 9, it can be stated that in a road with a constant slope, vehicle speed increase leads to increasing the engine speed. In the other hand, due to increase of aerodynamic resistant force, engine torque is also slightly increased. Therefore, the engine working point is shifted upward and to the right which leads to displacement of the working point to a higher efficiency region. If the speed increase lead to gear shifting to a higher gear number, then the engine efficiency is reduced. But, in the new gear number this is also true that the speed increase can lead to engine efficiency increase.

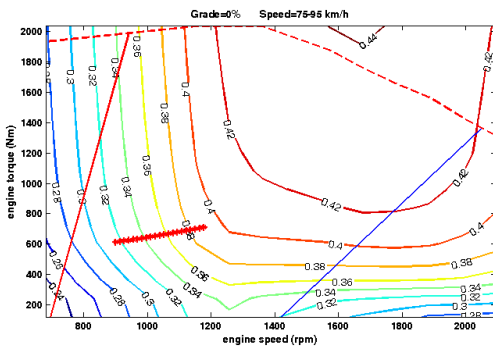


Figure 8. Engine working points at a constant slope of 0% and speed range of 75 to 95 km/h

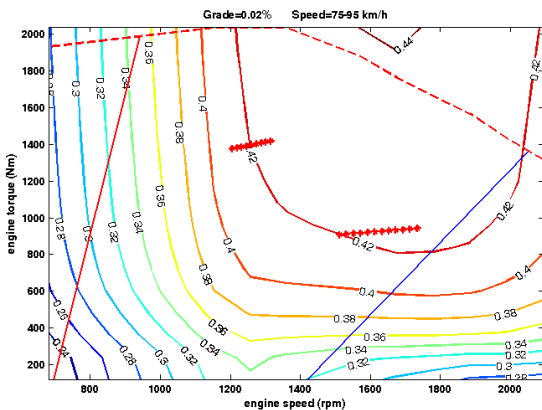


Figure 9. Engine working points at a constant slope of 2% and speed range of 75 to 95 km/h

Additional requirement for studying the performance of the look-ahead control is constant power curves of diesel engine as shown in Figure 10. Realization of these curves is important to explain the displacement of engine working point when the road slope is suddenly increased. In other words, when the cruise control system is reached the desired speed on a road section, it keeps the engine power constant. If the road slope is increased in the next road section, vehicle speed will slightly decreased in a short time. Then, the cruise control system tries to increase the engine power to compensate the speed decrease. Thus, according to constant power graphs in Figure 10 when the road slope is increased, the engine speed will decreased.

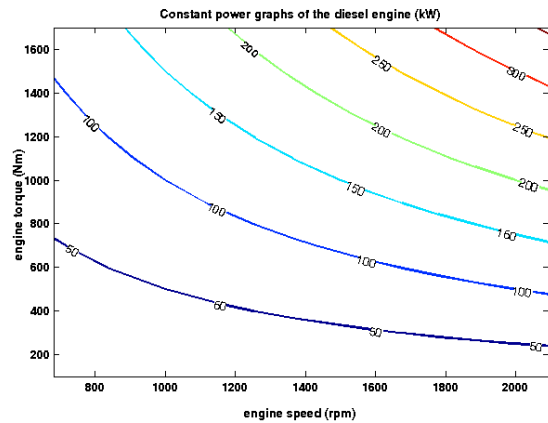


Figure 10. The curve of constant power operating points in the diesel engine

3.2. Effect of speed increase before crossing the uphill

To examine the effects of speed increase before an uphill, displacement of the engine working point in two modes (keeping a constant speed and a slight increase in speed) are compared and their results are shown in Figure 11. In this study, the vehicle is passed from a road section with 0% slope to a 3% slope section. In the case of cruise control, a constant k speed of

85km/h is tracked. Due to increasing road gradient, vehicle speed drops and the desired speed is reached again by decreasing the gear number. But if the desired speed is increased to 95 km/h in 500 meters before uphill, engine working points will moved to a higher efficiency region as shown in Figure 12. Fuel consumption rate is higher in the look-ahead approach, but due to high request of kinetic energy in the uphill section, more efficient energy conversion is done in this approach. It should be noted that the decreasing the gear number occurred later in look-ahead approach. In addition, look-ahead control might pass some uphill sections without decreasing the gear number.

The path ABCD in Figure 12 is the Path of engine working points in cruise control approach and the path corresponding to look-ahead control is A'B'C'D. The AB path is due to road slope increase and maintaining the constant power by cruise control system according to constant power curves in Figure 10. Because of engine speed reduction and reaching the gear shift border, speed controller has decreased the gear number and the engine working point is displaced to point C. In lower gear, engine speed decreases first and then has increased with increasing fuel rate and the engine working point is displaced to point D. In general, by comparing the two paths of ABCD and A'B'C'D, it can be seen that the engine efficiency is increased by using the look-ahead approach.

The results of look-ahead approach on passing the uphill is reviewed in Table 2 which shows a reduction in fuel consumption and travel time by using the look-ahead approach.

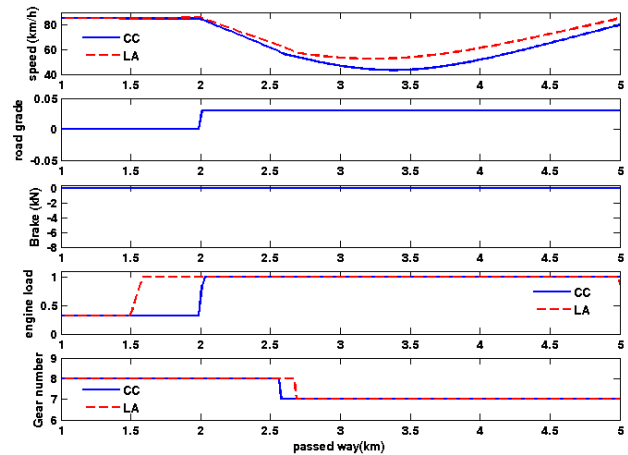


Figure 11. Results of speed increase before an uphill (from 0% slope to 3% slope)

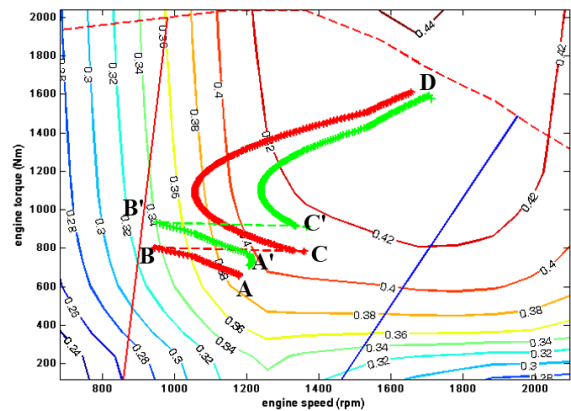


Figure 12. The path of engine working points by increasing the speed before an uphill (from 0% slope to 3% slope)

Table 2. Results comparison of two control approach in passing an uphill (from 0% slope to 3% slope)

Control approach	Fuel consumption (l)	Travel time (s)
Cruise control	4.65	295
look-ahead control	4.58	272

3.3. Speed limit existence in uphill

To investigate the effect of speed limit existence on uphill, the intercity bus motion on a road from 0% slope with speed limit of 95 km/h to a 3% slope uphill with speed limit of 75 km/h was simulated. The results of this simulation are shown in Figure 13 and the locus of engine working points is shown in Figure 14. As a result of reducing the speed limit, speed controller tried to reduce the engine load first and then applying the brake force. Two different levels of speed increase in look-ahead approach are considered in this study. In the first case, speed increased 10 km/h and in the second case 5 km/h. Results in Table 3 show that 5 km/h speed increase led to less fuel consumption. This result can be interpreted that additional fuel consumed for speed increase of 10 km/h, resulted in higher kinetic energy of the vehicle. But, due to the reduced speed limit, this redundant energy is necessarily wasted in the brake. Consequently, it is a logical rule that if there is a reduced speed limit in uphill sections; for example in a curved uphill, look-ahead speed increase should be less than a similar uphill with no speed limit reduction.

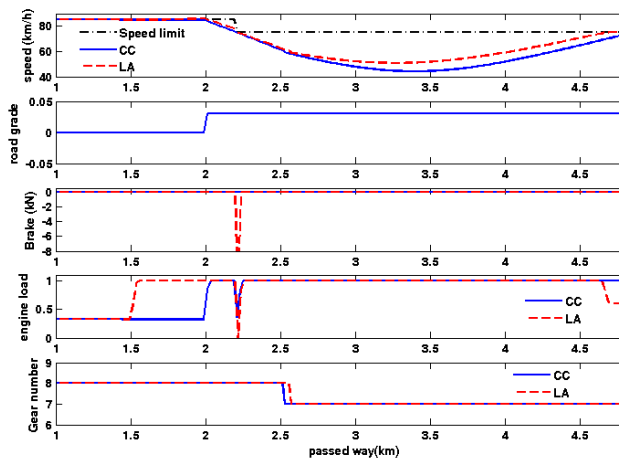


Figure 13. Results of speed increase before an uphill with speed limit reduction (from 0% slope to 3% slope)

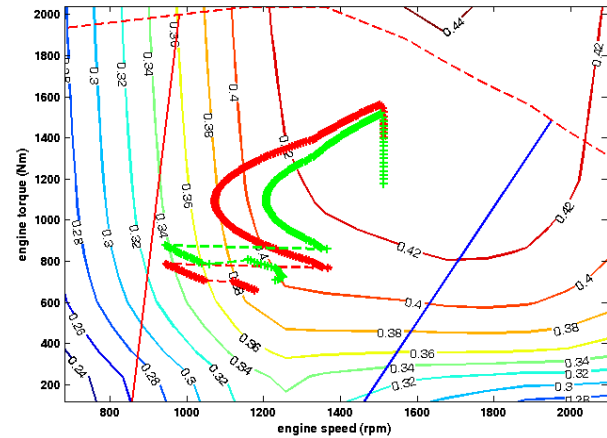


Figure 14. The path of engine working points by increasing the speed before an uphill with speed limit reduction (from 0% slope to 3% slope)

Table 3. Results comparison of two control approach in passing an uphill with speed limit reduction (from 0% slope to 3% slope)

Control approach	Fuel consumption (l)	Travel time (s)
Cruise control	4.51	294
look-ahead speed increase (10 km/h)	4.46	278
look-ahead speed increase (5 km/h)	4.4	278

3.4. The effect of engine speed on the look-ahead control approach

The cruise control system is the main speed control loop in the vehicle and the look-ahead control system modifies the desired set point for the cruise control system. Therefore, if the look-ahead controller have no information about engine working point, then speed increase may not improve the engine efficiency only but also it may reduce it. An example of this situation is simulated in which the vehicle moves in a road from 2% slope to 4% slope. The simulation results are shown in Figure 15 and 16. The engine working point corresponding to vehicle speed of 85km/h and road slope of 2% is near the gear

shifting border. Therefore, look-ahead speed increase led to increasing the gear number. This new gear number is not proper for the road slope of 4 % and the speed controller forced to reduce the gear number.

Results in Table 4 show that in the conditions of studied example, look-ahead speed increase has led to increased fuel consumption and also an increase in travel time. The best accessible variable that make it possible for the look-ahead controller to have information about the working conditions of cruise control is the rotational speed of the diesel engine. Therefore, if three fuzzy regions is considered for the engine speed including low, medium and high; then another logical law that should be included in the fuzzy rules base is this: "if the engine speed is high, then desired speed changes should be zero".

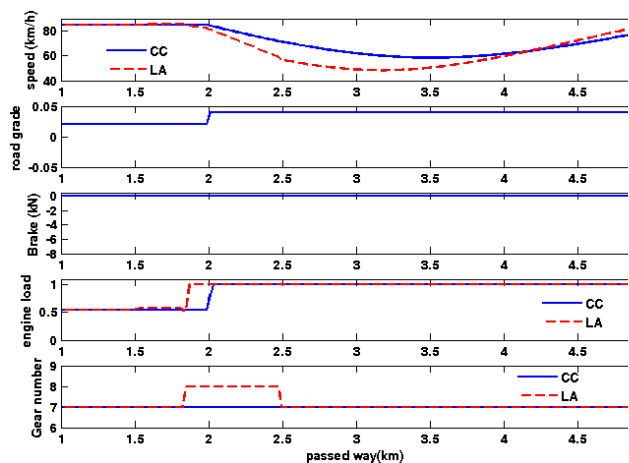


Figure 15. Results of speed increase before an uphill (from 2% slope to 4% slope)

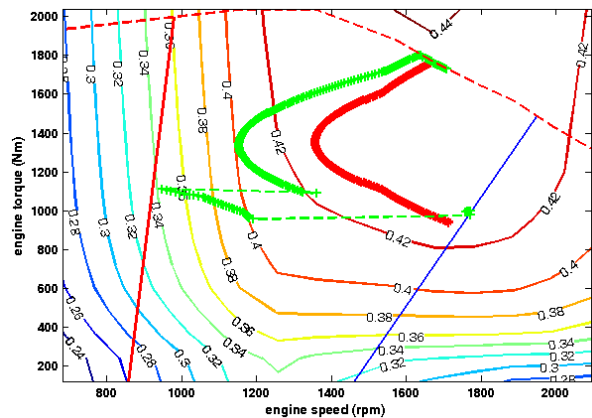


Figure 16. The path of engine working points by increasing the speed before an uphill (from 2% slope to 4% slope)

Table 4. Results comparison of two control approach in passing an uphill (from 2% slope to 4% slope)

Control approach	Fuel consumption (l)	Travel time (s)
Cruise control	4.91	269
look-ahead speed increase	5.08	287

3.5. Effect of decreasing the vehicle speed before reaching a speed limit

When the vehicle reaches a speed limit, the vehicle brakes and redundant kinetic energy of the vehicle compared to allowable kinetic energy (according to speed limit) is converted into heat and dissipated. However, look-ahead speed decrease can reduce the output power of diesel engine and decrease the dissipated energy. If the look-ahead information about ahead speed limit be accessible, then it is possible to reduce the engine load instead of using the brake. Decreasing the engine load will move the engine working point to the working region of lower power and lower efficiency. Noting the dependency between the engine working point and wheel speed, reduction in engine efficiency is inevitable. But, the look-ahead speed decrease is reasonable because the vehicle does not need to higher power even with more efficiency.

4. Fuzzy look-ahead controller

The proposed look-ahead control in this paper is a predictive control scheme that modifies the desired speed for the cruise controller accounting for changes of slope and speed limit in the ahead road and also it examines the engine speed. Internal structure of look-ahead control is shown in Figure 17. The look-ahead controller can be divided to three units includes look-ahead unit, fuzzy controller and change rate limiter.

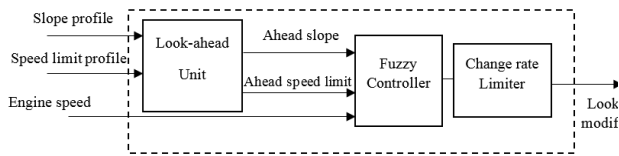


Figure 17. Internal structure of the look-ahead controller

4.1. look-ahead unit

The look-ahead unit calculates the ahead slope and speed limit. According to Figure 18, a look-ahead window is considered for this calculation.

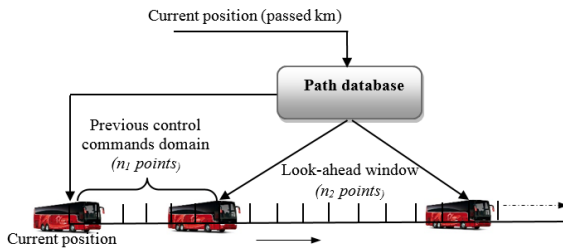


Figure 18. Look-ahead window

Given the current location, a distance is considered for the effect of previous control commands and a distance considered as a look-ahead window. The road path is considered as a set of discrete points that their information (slope and speed limit) are available in the road database. If the distance of discrete points (dx) be smaller, then the accuracy will be higher with heavier computational effort and time. Discretization distance must be small sufficiently such as the curved sections of the road can be

estimated by a series of connecting lines between the discrete points. The ahead slope and speed limit are the average values of the discrete points inside the look-ahead window. If the length of previous control commands interval be n_1 points and the length of look-ahead window be n_2 points, then the ahead slope and speed limit can be calculated as:

$$\text{Ahead slope} = \frac{\sum_{k=n_1}^{n_1+n_2} (\text{slope of window inside point})}{n_2} \quad (29)$$

$$\text{Ahead speed limit} = \frac{\sum_{k=n_1}^{n_1+n_2} (\text{speed limit of window inside point})}{n_2} \quad (30)$$

4.2. Fuzzy controller

The second unit of fuzzy look-ahead control algorithm is the fuzzy controller. This unit plays the role of decision maker in the control algorithm. Data obtained about the ahead slope and speed limit are entered into the fuzzy controller in which the decisions for desired speed modifications are made using the fuzzy rules based on experience and logic. For example, if the ahead slope is increasing and there is no reduction in speed limit, then the desired speed should be increased so the vehicle could pass the uphill easier without decreasing the gear number which may lead to additional fuel consumption. The engine speed plays a role here so that if in the mentioned example, the engine speed is high, then the desired speed should not be increased because it may leads to an inefficient increase in the gear number.

The designed fuzzy controller has three inputs including engine speed, changes of ahead slope and speed limit compared to current situation. The output variable of fuzzy controller is desired speed modifications. As shown in Figure 19, scaling factor method is used to optimize the fuzzy rules base. In this method, fuzzy membership functions are distributed uniformly between -1 and 1 and the inputs are weighted so that they would be placed in the

range of -1 to 1. The engine speed variable has a clear range and its membership functions are considered in their actual range and its scaling factor assumed as 1.

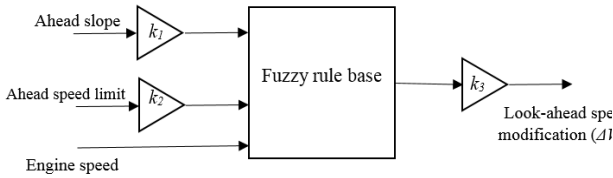


Figure 19. Scaling factors in the fuzzy control

The variables of ahead slope, speed limit and look-ahead speed modification have five triangular membership function includes: Big Negative (BN), Medium Negative (MN), zero (Z), Medium Positive (MP) and Big Positive (BP). Distribution of these membership functions and distribution of engine speed membership functions are shown in Figure 20 and 21. The fuzzy rule base has 125 rules and the corresponding control surfaces are shown in Figure 22 to 24.

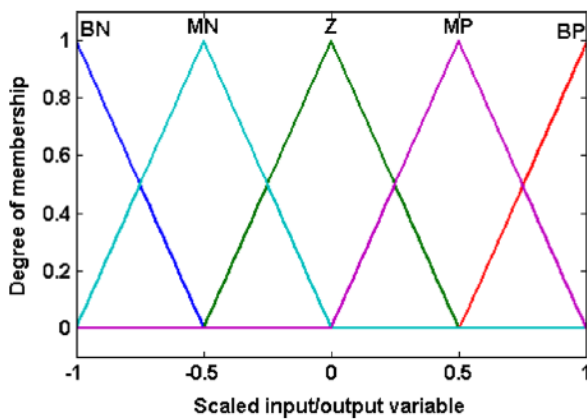


Figure 20. Membership functions of ahead slope, ahead speed limit and look-ahead speed modification

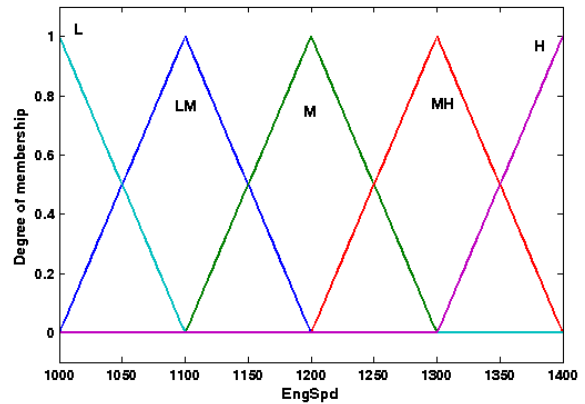


Figure 21. Membership functions of engine speed

4.3. Change rate limiter

Change rate of the look-ahead control command is a function of road slope and speed limit profiles. The look-ahead window moves in front of the vehicle and scans the ahead path gradually. Therefore, any changes in the road slope is detected gradually. For example, if the vehicle moves on a flat road, the whole points of the look-ahead window has a zero slope and thus the window has an average slope of zero. When the window touches the start point of an uphill (while the vehicle is still in the flat section), the number of inside window points with a positive slope increases gradually. The ahead slope would be the uphill slope when the whole window placed in the uphill section. Therefore, the ahead slope increased gradually and corresponding speed modifications are made gradually. Hence, it can be stated that if vehicle speed is higher, the look-ahead window moves faster and the change rate of desired speed commands will be greater. But, if the change rate of speed command be great, then following the speed command may be impossible for the speed controller and in the other hand, great change rate of desired speed may lead to increased fuel consumption.

To limit the change rate of control commands of the look-ahead control system, a

first-order filter with a transfer function of $G_f(s)$ is used:

$$G_f(s) = \frac{1}{\tau s + 1} \tag{31}$$

where τ is the filter time constant and s is the Laplace variable.

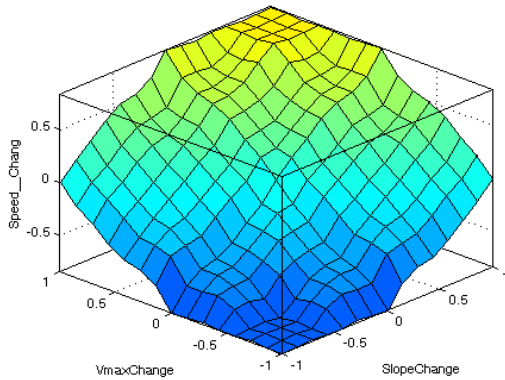


Figure 22. Fuzzy control surface based on ahead slope and ahead speed limit

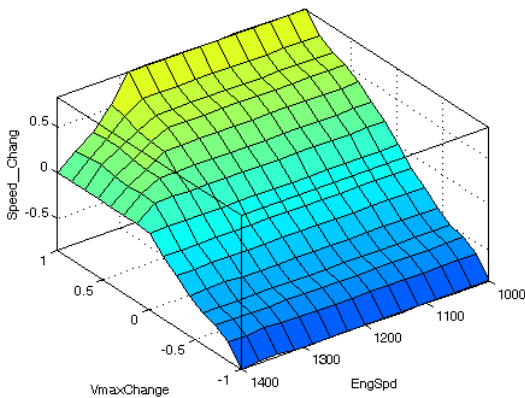


Figure 23. Fuzzy control surface based on engine speed and ahead speed limit

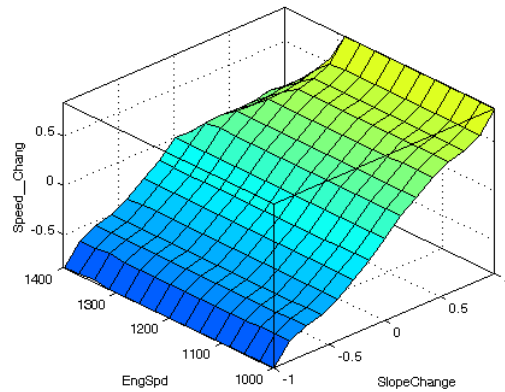


Figure24. Fuzzy control surface based on ahead slope and engine speed

4.4. Optimization of look-ahead control using fuzzy gain scheduling approach

The proposed look-ahead Control has several tuning parameters that must be optimized for achieving the optimized performance of this controller. Parameters n_1 and n_2 in the look-ahead unit are a function of the vehicle speed and data variance of look-ahead window. In the other words, if the vehicle speed increased, the look-ahead window should be placed in further distance (greater n_1). If the data variance of look-ahead window increased, the length of look-ahead window should be smaller (smaller n_2) to have a more uniform window. The scaling factors K_1 , K_2 and K_3 in the fuzzy controller must be tuned too. K_1 and K_2 are scaling the ahead slope and speed limit to the range of -1 to 1. K_3 specifies the effective bandwidth of the look-ahead controller. The change rate of desired speed must be tuned in the change rate limiter unit by tuning the parameter τ . The tuning parameters of the look-ahead fuzzy controller are listed in Table 5.

Table 5. Tuning parameters of the look-ahead fuzzy controller

controller unit	parameter	corresponding variable
look-ahead unit	Length of the look-ahead window	and distance of the n_1, n_2

Fuzzy Controller	scaling factors	K_1, K_2, K_3
change limiter	rate time constant of the first-order filter	τ

Tuning of these parameters requires to check the road slope and speed limit profiles and classify the road sections in several working areas that in each working area, optimizations of the tuning parameters is possible. The proposed index in this paper that aimed for this classification called "road pattern". An intercity bus can encounter different road patterns in terms of road slope and speed limit. For example, a desert pattern (with low or high curve numbers) or a mountain pattern (with low or high curve numbers). Road pattern determination should be done in a greater distance than the look-ahead window called "road pattern window". Simple comparison of the road pattern window and the look-ahead window is shown in Figure 25.

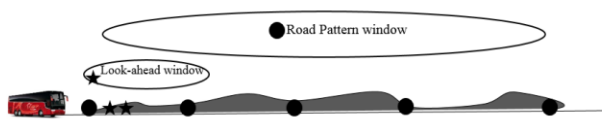


Figure 25. Comparison of length and calculation rate between road pattern window and look-ahead window

The length of road pattern window is ten times the length of look-ahead window approximately. In this study, the length of road pattern window is considered as 5km. On the other hand, calculations of look-ahead window are almost continuous, but calculation rate of the road pattern is slower and almost one time in each kilometer of the path.

Another important point in the conceptual distinction between the look-ahead window and road pattern window is the difference in the concluding logic for ahead slope discussion. In the concept of look-ahead window, the average value of window inside points is calculated. But, this averaging method in the road pattern

detection of 5 km ahead road with the calculation rate of one time per each kilometer can cause severe error in the algorithm. For example, if the road slope in the ahead 5 km has a value of 3% in the first half and -3% in the second half, then the average slope of the window is zero that represents a flat road pattern. In the proposed approach, in addition to the average slope, the maximum slope is also checked. If the maximum slope has at least ten percent of the window length, then the road slope pattern is determined based on the window maximum slope. In studying the speed limit profiles, minimum speed limit and its relative length has checked and considered in determining the road speed limit pattern. The block diagram of fuzzy pattern recognition and membership functions of fuzzy variables are shown in Figure 26 to 30.

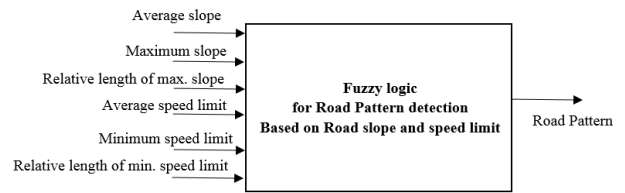


Figure 26. Block diagram of fuzzy pattern recognition

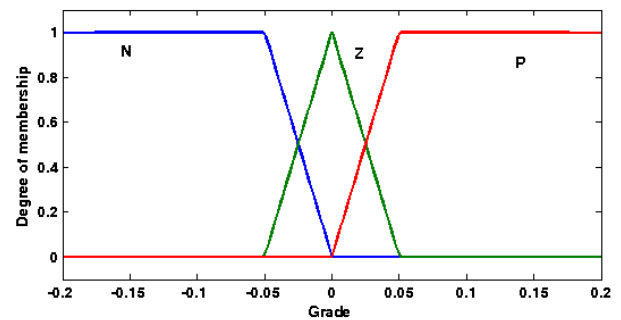


Figure 27. Membership functions of the average and maximum slope of the road pattern window

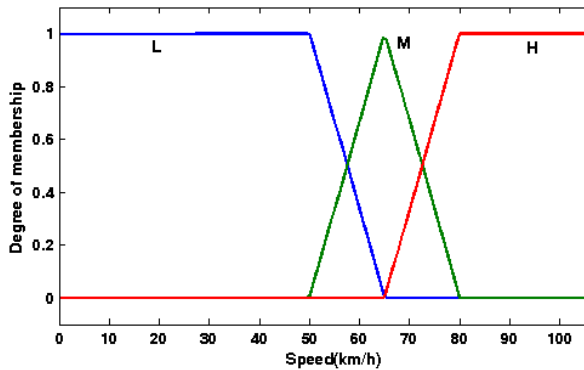


Figure 28. Membership functions of the average and minimum speed limit of road pattern window

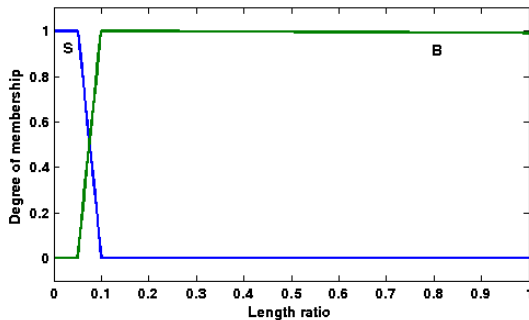


Figure 29. membership functions of the relative length of the maximum slope and minimum speed limit of road pattern window

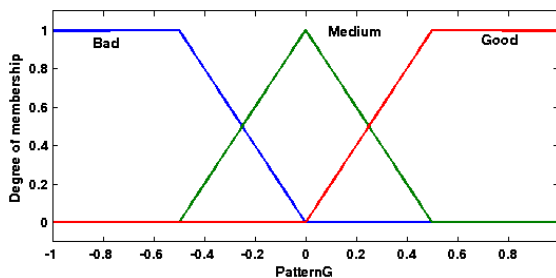


Figure 30. Membership functions of road slope pattern and road speed limit pattern of road pattern window

In the proposed approach, slope and speed limit Profiles of the road pattern window are checked separately to determine the road slope pattern and road speed limit pattern that

they are blended fuzzily to determine the road pattern. Both road pattern dimensions (slope and speed limit) considered to have three fuzzy situation include good, medium and bad. Fuzzy blending of these two road pattern dimensions create 9 fuzzy regions in two-dimensional space that are shown in Figure 31.

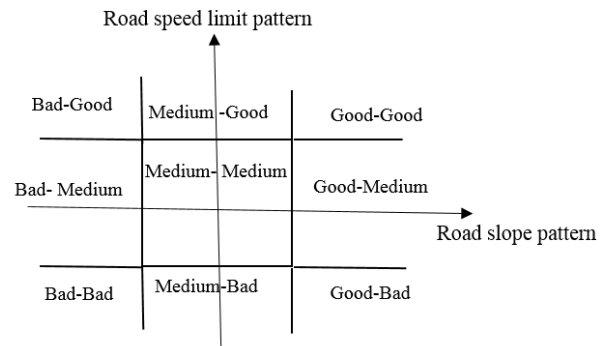


Figure 31. Road pattern based on road slope pattern and road speed limit pattern

According to Figure 31, road conditions are defined in 9 separate regions that make it possible to use a fuzzy gain scheduling approach to fine tune the proposed look-ahead control. It means that optimal parameters of the look-ahead controller can be calculated by fuzzy blending of local optimal parameters of the road pattern regions which can be achieved using genetic algorithm. Fuzzy blending of the local optimal parameters using the average centroid method is in such a way that final parameter can be written as

$$Gain = \sum_{i=1}^9 \theta_i Gain_i \quad (32)$$

where $Gain$ is the final parameter and $Gain_i$ is local optimal parameter in the i^{th} region of the road pattern and θ_i is the share of i^{th} road pattern region in construction of the actual road pattern. It is important to note that

$$\theta_i > 0, \sum_{i=1}^9 \theta_i = 1 \quad (33)$$

If in the i^{th} region of the road pattern, the road slope pattern is μ_{gi} and the road speed limit pattern is μ_{si} , then

$$w_i = \mu_{gi} \mu_{si} , \theta_i = \frac{w_i}{\sum_{i=1}^9 w_i} \quad (34)$$

4.5. Final structure of the proposed fuzzy look-ahead controller

The final structure of the proposed fuzzy look-ahead controller that designed to reduce the fuel consumption of buses on intercity roads is shown in Figure 32. The first control loop is the cruise control system that follows the desired speed command. Control tools available for the cruise control includes the gear number, the gas and the brake pedals. The desired speed command is provided by the second control loop in which the initial desired speed is modified by the look-ahead controller. The fuzzy look-ahead control approach is fine-tuned by fuzzy gain scheduling approach using the proposed concept called road pattern.

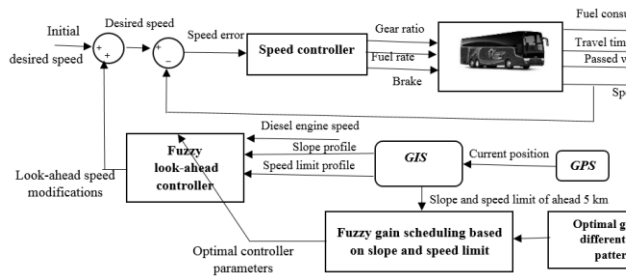


Figure 32. Final structure of intelligent look-ahead control strategy

5. Simulation of the intelligent fuzzy look-ahead control algorithm

To evaluate the performance of the proposed intelligent fuzzy look-ahead control, the intercity bus motion on a 100 kilometers in a two-way road simulated and the proposed algorithm was implemented. Road slope Profile is shown in Figure 33. Profiles of some factors that can reduce the speed limit and their resultant speed limit profile are shown in Figure 34 and 35. Theses speed limit reducing factors include road curvature, road width, road surface quality, road vision quality, traffic quality.

The speed limit profile in Figure 35 is the legal speed limit in a two-way road (95 km/h) which is decreased at various points of the road due to a reduction factor.

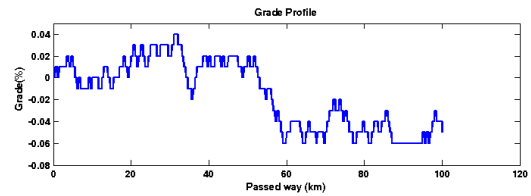


Figure 33. Road slope profile

The fuzzy logic of road pattern recognition is performed in each kilometer of the road and the resultant road patterns along the road are shown in Figure 36. The distribution of points in Figure 36 shows that the most road slope patterns are medium and a low number of them are good. However, the road speed limit pattern has all three situations of good, Medium and bad.

Then, the optimal values for the tuning parameters of the fuzzy look-ahead controller is obtained in each road pattern region using the genetic algorithm and they are shown in Table 8.

Reviewing the values of k_3 in Table 8 shows that whatever the road pattern is better, intervene and modification range of the desired speed by the fuzzy look-ahead controller can be higher. On the other hand, having better road pattern, it is possible to consider a larger look-ahead window (larger values of n_2) in a further distance (larger values of n_1) from the current vehicle location. Reviewing the time constant values also show that in a road with worse pattern, the change rate of speed command must be lower to avoid sever braking. Increasing and decreasing trends of k_1 and k_2 can be interpreted knowing that they must map the slope and speed limit values to the range of -1 to 1.

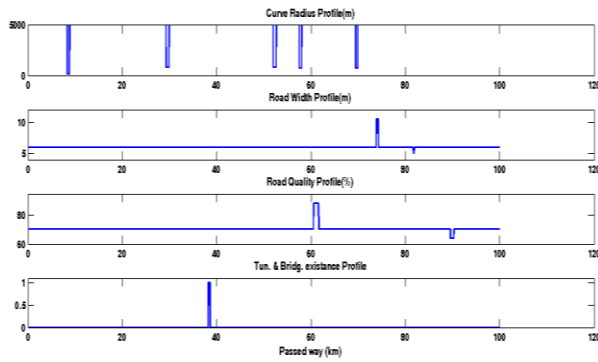


Figure34. Profiles of road curvature, road width, road surface quality and tunnel or bridge existence

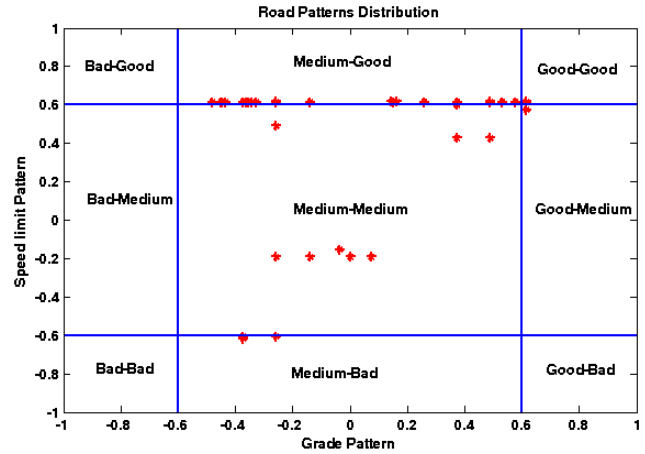


Figure 36. Road pattern profile

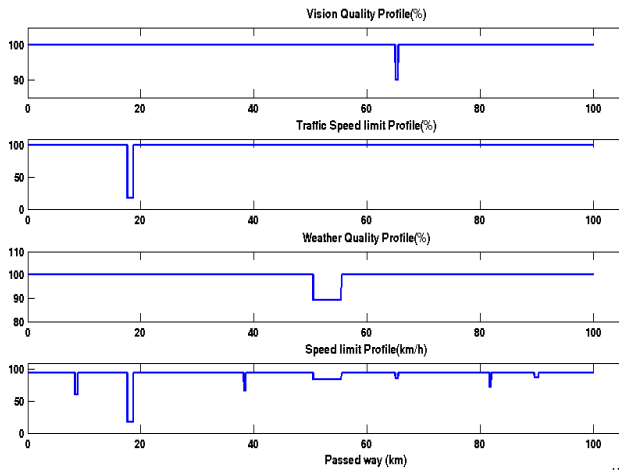


Figure35. Profiles of road vision quality, traffic quality, weather quality and the resultant speed limit profile

Table 8. Results of the offline optimization of tuning parameters of the look-ahead controller using genetic algorithm in each road pattern region.

Road pattern	τ	n_2	n_1	k_3	k_2	k_1
Good-Good	0.5	13.82	21.84	9.66	0.01	66.96
ood -Medium	0.56	8.87	21.13	8.03	0.03	66.80
Good- Bad	0.8	8.57	18.68	7.57	0.07	49.71
edium - Good	0.8	8.48	12.25	7.18	0.01	22.54
dium - Medium	0.8	6.22	11.17	6.68	0.04	21.98
ivMedium - Bad	1.5	6	8.8	43.6	0.07	7.18
Bad- Good	1.6	5.98	8.77	23/6	0.02	7
Bad - Medium	1.74	5	5	5.5	0.04	6.25
Bad - Bad	1.86	5	5	2.5	0.07	6

In the next step, the intercity bus motion on the mentioned road simulated using the cruise control approach and its results are shown in Figure 37. In this approach, the speed controller should pass the whole path with the initial desired speed which is about 10 km/h below the speed limit profile. Reviewing the speed profiles in Figure 37 shows that the desired speed profile tracked carefully in final 60 km of the path in which the path is downhill. But, in the first 60 km of the path, the effect of slope increasing on the vehicle speed decrease is quite evident and it

takes some time for the cruise controller to compensate the vehicle speed drop by increasing the engine load and fuel consumption rate.

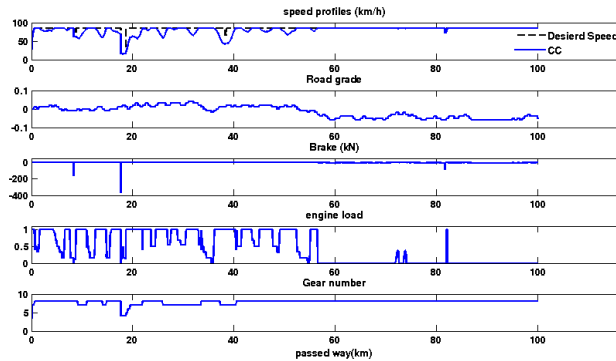


Figure 37. Results of the intercity bus simulation with the cruise control approach

Then, the intercity bus motion on the same road and using the intelligent look-ahead control approach was simulated and its results are shown in Figure 38.

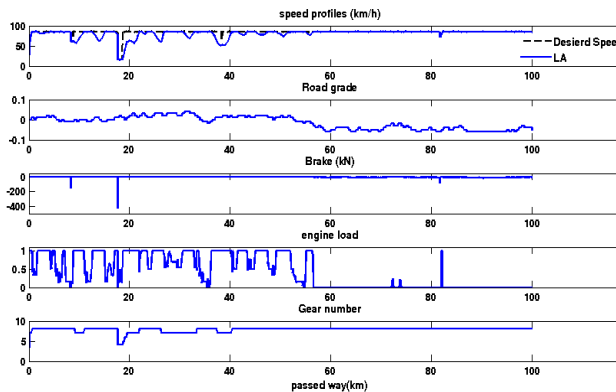


Figure 38. Results of the intercity bus simulation with the intelligent look-ahead control approach

Comparison of the gear shifting Profiles in Figures 37 and 38 shows that near km 15 down the path that the look-ahead controller could pass the uphill by applying the look-ahead speed increase without increasing the gear number. The effect of look-ahead control approach in increasing the diesel engine efficiency in 5km section of the road (between km 36 and 41) with more detail is shown in Figure 39.

The operation of diesel engine through the 5km distance in Figure 39 is similar to crossing the uphill in section 3.2. Engine efficiency profile in Figure 39 shows that the engine efficiency increased 2% initially. The efficiency difference of two approaches reaches even 5% because of gear number decrease in the cruise control approach.

The results of fuel consumption and travel time corresponding to three control approaches are compared in Table 9. According to these results, it can be said that the proposed look-ahead approach without tuning algorithm can reduce the fuel consumption and travel time about 2.5% and 0.6% respectively. Using fuzzy gain scheduling approach to fine tuning the look-ahead controller parameters can improve the reduction in fuel consumption and travel time to 5.3% and 1.5% respectively. On the other hand, the intelligent fuzzy look-ahead approach could increase the engine efficiency about 2.1% and also decrease the dissipated brake power about 0.02%.

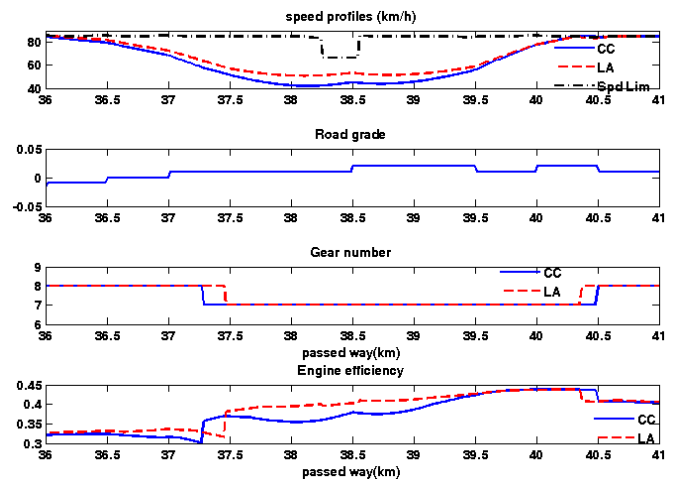


Figure 39. Comparison of the speed profiles, gear shifting and engine efficiency profiles in cruise control and intelligent fuzzy look-head control approaches

Table 9. Comparison of fuel consumption and travel time of three control approaches.

Control approach	Fuel consumption (liters)	Travel time (seconds)	Engine average efficiency (%)	Brake Energy Dissipation (Mega Joule)
Cruise control	40.54	4784	33.48	235.9
look-ahead control without optimization algorithm	39.53	4753	34.33	235.87
look-ahead control with fuzzy gain scheduling	38.4	4713	35.92	235.85

6. Conclusion

In this paper the repetitive mission of the intercity passenger buses is considered as a case for fuel reduction. A look-ahead energy management system is proposed which uses information of ahead road conditions and engine speed to modify the desired speed command. Fuzzy rules are discussed through corresponding examples. A fuzzy gain scheduling algorithm is proposed to improve the performance of the look-ahead control. The road slope and speed limit specifications called road pattern used to define some 2 dimensional fuzzy regions. The main parameters of the proposed fuzzy look-ahead controller are optimized in each region using the genetic algorithm. The simulation results of the proposed energy management system show that using fuzzy gain scheduling approach to fine tuning the look-ahead controller parameters can improve the reduction in fuel consumption and travel time to 5.3% and 1.5% respectively. On the other hand, the intelligent fuzzy look-ahead approach could increase the engine efficiency about 2.1% and also decrease the dissipated brake power about 0.02%.

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