

# Predictive algorithm to detect uphill or downhill road ahead of vehicle and simulation analysis of impact on fuel economy and drivability

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**Abstract** - We present an analysis of impact of road slope or gradient on a vehicle's fuel consumption and driving comfort. From classical mechanics and vehicle dynamics it is known that while driving on a relatively flat surface, when a vehicle encounters an uphill, there is an increase in resistance to driving torque generated by engine and if driving conditions are unchanged such as no gear change done or gas pedal not pressed by driver, the engine RPM (rotation per minute) will come down.

On the other hand when vehicle encounters a downhill, the inertia of the vehicle and gravity component contributes to the engine generated driving torque and an increase in engine RPM is observed provided driving conditions are unchanged. When vehicle runs on a slope (up or downhill), the torque requirement changes. Driver has to respond to this change continuously.

Here we are proposing an algorithm to detect uphill or downhill road by measuring engine RPM gradient and controlling pulse width of fuel injector in such a way that drivability could be improved in case of uphill and fuel economy could be improved in case of downhill.

By controlling the pulse width of fuel injector, we basically try to control the drive torque generated by engine as a result of combustion of fuel inside the cylinders of engine.

Important point to note is, the amount of pulse width correction is very small because our purpose is not to do away with gear change and acceleration by pressing gas pedal. Driver still should control driving condition of the vehicle such as proper gear ratio selection and throttle control in diverse road situation, but we aim to control small uphill and downhill correction in a typical city traffic where it is not necessary for driver to change gear or accelerator pedal continuously and thus improving driving experience.

**Index Terms**- Road gradient, fuel economy, fuel injector, vehicle dynamics, engine RPM, fuzzy logic

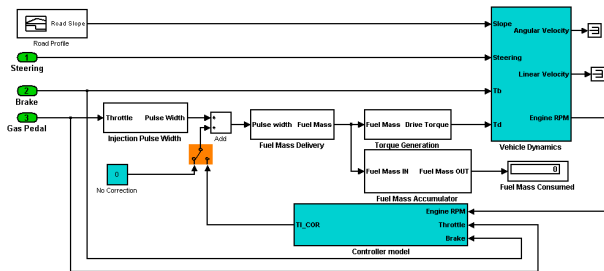
## 1. Introduction

Entire analysis in this paper is done by simulation of classical plant-controller approach where vehicle dynamics is modelled as plant and our fuzzy algorithm is modelled as controller.

Vehicle dynamics is representation or approximation of behaviour of a vehicle under influence of acceleration, brake and steering applied by a driver. The output of a typical vehicle model is vehicle speed, angular velocity and engine RPM. A controller can use any one or all of these parameters to design a control algorithm.

An overview or architecture of the plant-controller model is shown in Figure 1 below.

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**Figure 1: Overview of Plant-Controller architecture**

The most important parameter in this study is engine RPM which is input to our controller model and the algorithm implemented in controller model provide a correction pulse (in ms) to add (or subtract) with main injection pulse (in ms) .

Additionally we have provision to accept or discard this correction by a switch in simulation for a comparative study i.e. performance analysis with and without deploying controller. We have implemented a sub-system '**Fuel Mass Accumulator**' which indicates amount of fuel consumed (in mg) during complete simulation time and we can analyse the fuel mass consumption with and without injection correction time applied to plant model.

In the Figure 1, it can also be seen that amount of gas pedal pressed by driver (0 to 100 %) is translated into pulse width generated by fuel injector in subsystem '**Injection Pulse Width**'. Subsequently, it is known that injector pulse width is the time for which fuel injector is opened so that the fuel (Gasoline for example) is delivered inside the combustion chamber of an Internal Combustion (IC) engine. As a result of combustion of fuel, piston of IC engine moves and a drive torque is generated, which drives the vehicle and this is implemented in subsystem '**Torque Generation**'.

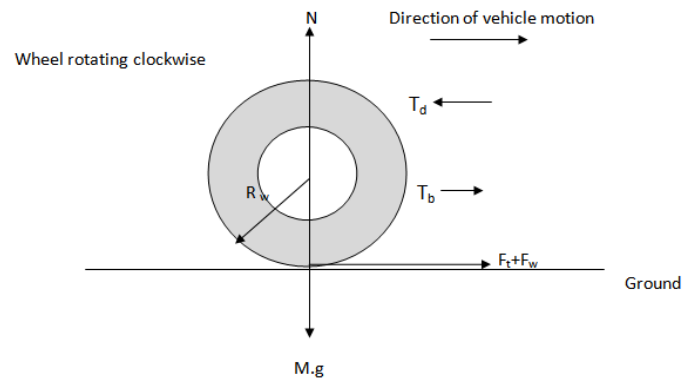
## 2. Vehicle Dynamics Model

To validate our controller algorithm we need a close representation of vehicle's behaviour on road. For simplicity we have analysed the forces acting on each wheel and derived angular velocity of wheels which is proportional to engine RPM in a particular gear ratio.

The basic forces acting on vehicle are: drive torque as a response to gas pedal pressed and brake torque and steering

applied by driver .combination of these three forces give direction and movement to the vehicle.

Consider a wheel resting and rotating in contact with ground surface as shown in Figure 2.



**Figure 2: Wheel dynamics and various forces acting on it**

Angular velocity is calculated as<sup>[1]</sup>:

$$\frac{d\omega}{dt} = \left[ \frac{T_d - T_b - R_w \cdot F_t - R_w \cdot F_w}{J_w} \right] \dots\dots\dots \text{equation (1)}$$

$$\text{Or } \omega = \int \left[ \frac{T_d - T_b - R_w \cdot F_t - R_w \cdot F_w}{J_w} \right] dt \dots\dots\dots \text{equation(2)}$$

Where,

$\omega$  is angular velocity,  $T_d$  is torque generated by engine(in Nm),  $T_b$  is torque produced by pressing brake pedal(in Nm),  $R_w$  is radius of wheel(in m),  $F_t$  is traction force(in N) , $F_w$  is wheel viscous friction(in N).

The, traction force is given by<sup>[1]</sup>,

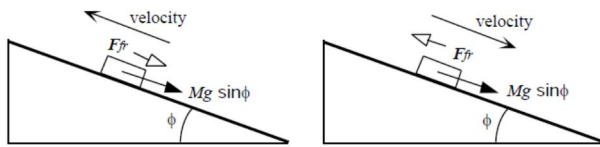
$$F_t = \mu \cdot N = \mu \cdot M \cdot g \dots\dots\dots \text{equation (3)}$$

Where,  $\mu$  is coefficient of friction between tyre and road surface,  $M$  is the mass component of the vehicle acting on a wheel and theoretically it is quarter of total mass of the vehicle.

## 3. Impact of Road Slope

Assuming the vehicle to be a point mass moving on a slope of angle  $\phi$ , the gravity component plays a very crucial role in determining the total forces acting on vehicle.

The direction of various forces acting on vehicle in case of uphill and downhill movement is shown in Figure 3.



**Figure 3: Direction of forces acting in uphill or downhill movement of vehicle**

$F_{fr}$  is the friction force and adds to gravity component ( $M.g.\sin\phi$ ) in uphill and subtracts in downhill movement [2].

Resultant force on uphill travel of vehicle is given by [2]:

$$F_{up} = Mg \sin\phi + F_{fr} \dots\dots\dots \text{equation (4)}$$

Resultant force on downhill travel of vehicle is given by [2]:

$$F_{down} = Mg \sin\phi - F_{fr} \dots\dots\dots \text{equation (5)}$$

#### 4. Validation of Plant Model

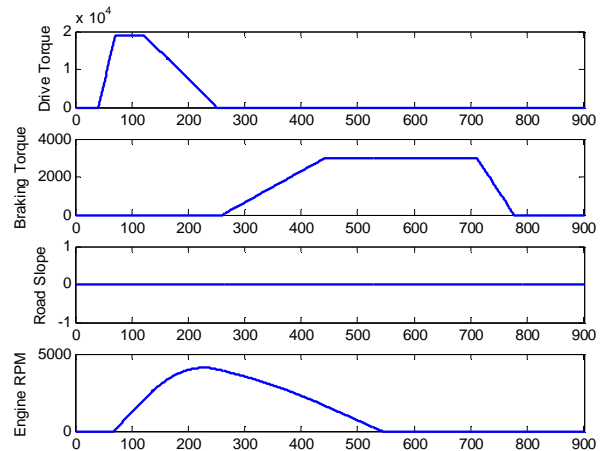
Using the equation (1) to equation (5) described above, the plant model is validated before designing the controller model. A well designed and validated plant model is the key for error-free controller algorithm development. Two driving scenarios are created: Without road slope and with road slope. An attempt is made to recreate a typical driving behaviour of a driver.

##### Case I: Driving the vehicle on flat surface

Figure 4 showing the increase in engine RPM in response to throttle pedal pressed (which in turn produces drive torque, shown in subplot 1). Drive torque gives momentum to the vehicle. Then throttle is kept constant for a while and then pulled back to initial position. After this time brake is applied in a ramp and after keeping it constant for sometime it is also pulled back to original position and brake torque generation is shown in subplot 2.

Due to inertia and friction between road surface and tyre, engine RPM gradually increases and as a result of applying brake, it becomes zero as shown in subplot 4.

Subplots 3 representing slope in road surface and in this case, there is no slope.

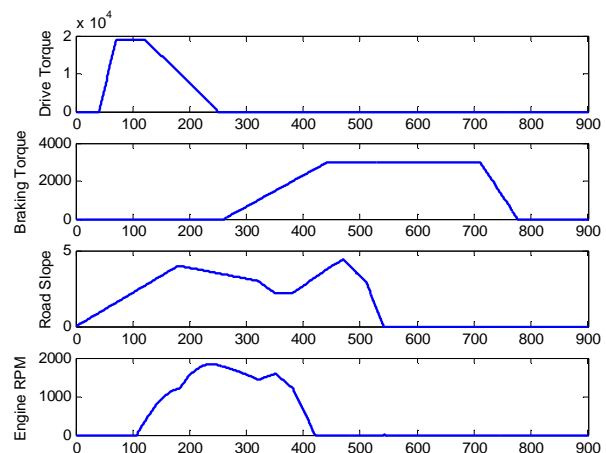


**Figure 4: Driving in no slope (Flat Road) condition**

##### Case II: Driving the vehicle on an inclined surface

In this case, all other driving parameters are same as described in **Case I**; except a slope in road is introduced. Behaviour of vehicle is shown in Figure 5 which is obtained from plant model.

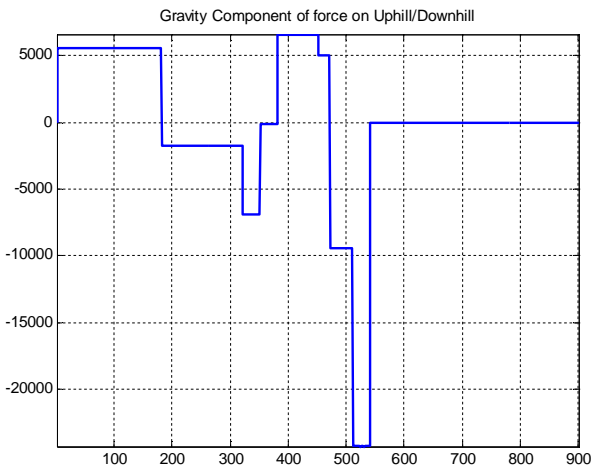
Due to uphill and downhill road, contribution of gravity factor explained as in Figure 3, is clearly seen in terms of variation of engine RPM. Additionally, due to opposition offered by uphill, the net drive torque is reduced, thus vehicle stopped earlier in this case.



**Figure 5: Driving in inclined road condition**

The fluctuation in engine RPM in **Case II** compared to **Case I**, is due to the influence of gravity component(refer equation 4 and 5) and is shown in Figure 6. This force component(in Nm) either contributes or resists to net force acting on wheels.

So, we can conclude with these results that, vehicle's plant model is very close replica of a real vehicle running on a road.



**Figure 6: Force component acting on a vehicle due to surface inclination**

## 5. Development of Controller Model

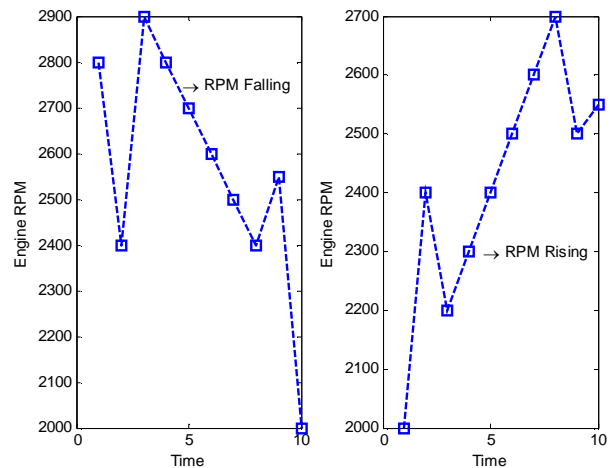
The fundamental input for the controller model is engine RPM with gear position, gas pedal and brake pedal signals.

An algorithm is developed to detect gradient in engine RPM. By analysing gradient we try to predict whether vehicle is travelling in uphill or downhill. Merely by measuring rpm gradient it will be impossible and incorrect to say if the vehicle is travelling on a slope; so to make this prediction robust we additionally analyse gear position, gas pedal and brake pedal signal variation.

A sudden increase in RPM could be due to acceleration requested by driver and similarly a sudden drop in RPM could be due to application of brake. So it is very important to clearly differentiate the RPM rise or fall due to road slope with that of due to driver applied gas or brake pedal.

## 6. Engine RPM gradient detection algorithm

RPM is measured at every 100 ms(for ex) and measured RPM is compared with last observed value and if we see 10(for ex) values continuously falling or increasing we consider this as gradient. Confirmation of slope after 10 values or recurrence of 100ms is indicative for analysis purpose in this simulation and could be any reasonable number which can be calibrated for a particular vehicle. Just a gradient in RPM is not enough but by observing it continuously for some predefined time to predict trend is important because this will ensure correct prediction of road slope ahead of vehicle .If prediction of upcoming slope is accurate then only the torque correction can be achieved correctly. An example of monitoring the trend in RPM gradient is explained in Figure 7.



**Figure 7: Determination of fall or rise in engine RPM**

RPM fluctuation is discarded because it could be due to irregularity in road surface or vibration in vehicle or noise in vehicle's ECU (Electronic Control Unit) or sensors, so only continuous falling or rising values are considered to determine if engine is slowing down or ramping up.

Predictive analysis is a statistical method where by analysing the existing available dataset, future trend is computed. In our case we are using the measured RPM and then compute rate of change of RPM. Using these two parameters, and under some boundary conditions we try to predict whether vehicle is running on uphill or downhill.

## 7. Road Slope (Uphill or Downhill) prediction and torque correction algorithm

Every 100ms ,gas pedal ,gear position and brake pedal signal is acquired and if brake not applied and gear not changed and additionally gas pedal is not released(because RPM may fall because of pedal released) for say in last 10 measurement; then we can confirm that fall in RPM is due to vehicle travelling on uphill.

So, we have to apply positive correction to injection pulse width to maintain constant torque. This correction can improve driving experience or drivability because driver needs not to apply gas pedal to meet increased torque requirement in uphill.

Similarly, if gas pedal is not pressed (because RPM may rise because of gas pedal pressed) for say in last 10 measurement; then we can confirm that rise in RPM is due to vehicle travelling on downhill.

So, in this case we can trim the injection pulse by applying negative correction so that a constant torque is maintained. This correction may improve the fuel economy because consumption was reduced by trimming injection pulse. This algorithm is summarised in the form of a flow chart in Figure 8.

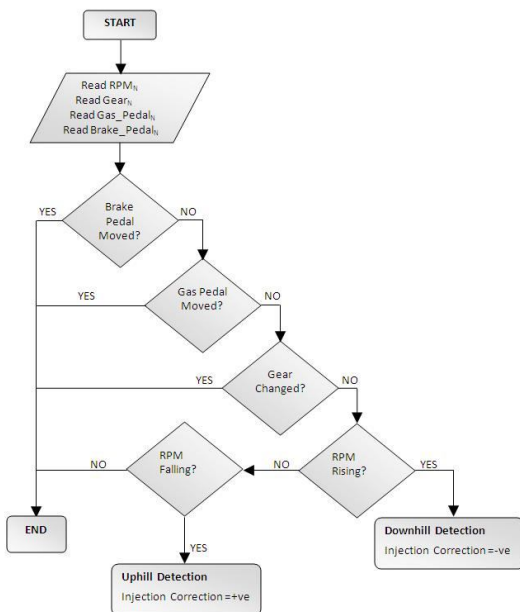


Figure 8: Flow chart representation of Road slope detection algorithm

## 8. About Fuel injector

A fuel injector is an electronic device mounted on intake manifold of the engine and is used to deliver the fuel inside the combustion chamber. An ignition coil ignites the fuel inside the chamber and the thermal energy produced in the process pushes the piston and thus rotating the shaft. Wheels of the vehicle are coupled to the shaft and vehicle gets the motion. Working principle of an Internal Combustion Engine is simplified because a detail description is beyond the scope of this paper.

The amount of opening of Injector is proportional to the throttle pedal pressed by driver. By pressing the gas pedal, driver request the engine to generate a drive torque. To meet this torque requirement, throttle valve allows air to flow inside intake manifold and injector is opened so that air-fuel mixture can be formed suitable for combustion.

## 9. Injection Time Correction

In response to the gas pedal pressed by driver, injector is opened to deliver the fuel inside of combustion chamber of IC engine. When an electrical stimulus is provided to injector, a needle is lifted to allow the fuel maintained at high pressure to flow in intake manifold, then it is held for some time and after electrical stimulus is not present, injector needle comes back to its originally closed position to block further flow of fuel(Gasoline for ex) .

This process is explained in Figure 9. A to B is the time for which needle is lifted, B to C is the time for which needle is kept in fully open position and when electrical stimulus is off, the needle goes back to its original position following path C to D. TI (in ms) is the pulse width of injector.

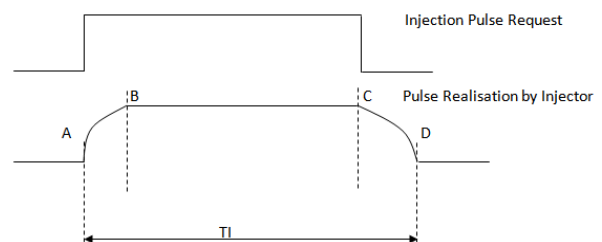


Figure 9: Operation of a fuel injector

Typically, injection pulse widths depend upon many factors such as battery voltage etc but most important is the fuel mass request. In practical situation, the TI is a complex function as shown in equation (6)

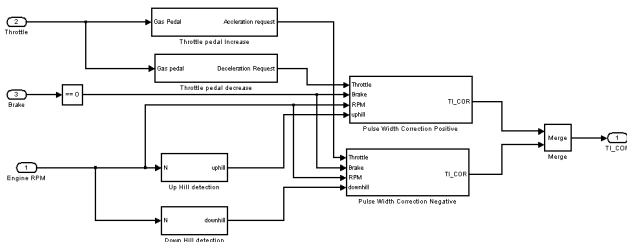
$$TI(\text{in ms}) = f(\text{fuel mass, battery voltage, fuel temperature, fuel rail pressure}) \dots\dots\dots\text{equation (6)}$$

Appropriate correction factor is applied on injection time because there are various sensors in a vehicle to measure battery voltage, temperature, pressure etc.

In this paper we are proposing an additional time correction factor into main injection pulse as below:

$$TI = f(\text{fuel mass, battery voltage, fuel temperature, fuel rail pressure}) \pm TI\_COR \dots\dots\dots\text{equation (7)}$$

Calculation of TI\_COR (in ms) is based on Uphill and Downhill prediction algorithm described above and is shown in a simple form in Figure 10.



**Figure 10: Overview of algorithm to calculate additional correction factor due to road slope**

The amount of positive or negative correction will depend on two parameters: Engine RPM and gradient in Engine RPM. Gradient in RPM is very important because this indicates how fast or slow the RPM is falling or increasing so that appropriate amount of correction can be applied.

If current RPM is  $R_N$  and previous RPM was  $R_{N-1}$ , then the gradient is determined as:

$$RPM_{grad} = \frac{|R_N - R_{N-1}|}{\Delta t} \dots\dots\dots\text{equation (8)}$$

Where,  $\Delta t$  is the rate at which data is acquired.

A fuzzy algorithm is implemented as shown below in Table 1:

		Engine RPM		
RPM Gradient		S	B	V
	S	L <sub>1</sub>	L <sub>4</sub>	L <sub>7</sub>
	B	L <sub>2</sub>	L <sub>5</sub>	L <sub>8</sub>
	V	L <sub>3</sub>	L <sub>6</sub>	L <sub>9</sub>

**Table 1: Correction factors determination by fuzzy algorithm**

S, B and V are levels representing small, big and very big respectively; and L<sub>1</sub> through L<sub>9</sub> are various levels or amount of injection time correction in millisecond which could be positive or negative.

In context of Engine RPM (represented by  $R_N$ ) the S, B and V could be defined by various ranges assuming 7200 as maximum RPM as below:

$$S: 0 \leq R_N \leq 2500$$

$$B: 2501 \leq R_N \leq 5000$$

$$V: 5001 \leq R_N \leq 7200$$

Similarly, in context of RPM gradient ( $RPM_{grad}$ ) the S, B and V could be defined by various ranges assuming 100 as maximum possible gradient in RPM as below:

$$S: 0 \leq RPM_{grad} \leq 25$$

$$B: 26 \leq RPM_{grad} \leq 50$$

$$V: 51 \leq RPM_{grad} \leq 100$$

By independently analysing the levels of both parameters: Engine RPM and rate of rise or fall of RPM, the appropriate correction is applied.

The fuzzy algorithm described in Table 1 is used for positive correction(in case of uphill) and negative correction (in case of downhill)by a simple mapping of all 9 levels with separate 9 positive or negative levels as shown below in Table 2:

	L <sub>1</sub>	L <sub>2</sub>	L <sub>3</sub>	L <sub>4</sub>	L <sub>5</sub>	L <sub>6</sub>	L <sub>7</sub>	L <sub>8</sub>	L <sub>9</sub>
+ ve Correction	P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	P <sub>7</sub>	P <sub>8</sub>	P <sub>9</sub>
-ve Correction	N <sub>1</sub>	N <sub>2</sub>	N <sub>3</sub>	N <sub>4</sub>	N <sub>5</sub>	N <sub>6</sub>	N <sub>7</sub>	N <sub>8</sub>	N <sub>9</sub>

**Table 2: Mapping of positive or negative injection pulse width correction into fuzzy levels.**

So, the final Uphill and downhill injection correction factors which is either added or subtracted with main injection pulse looks as shown in Table 3 and table 4.

		Engine RPM		
RPM Gradient		S	B	V
	S	P <sub>1</sub>	P <sub>4</sub>	P <sub>7</sub>
	B	P <sub>2</sub>	P <sub>5</sub>	P <sub>8</sub>
	V	P <sub>3</sub>	P <sub>6</sub>	P <sub>9</sub>

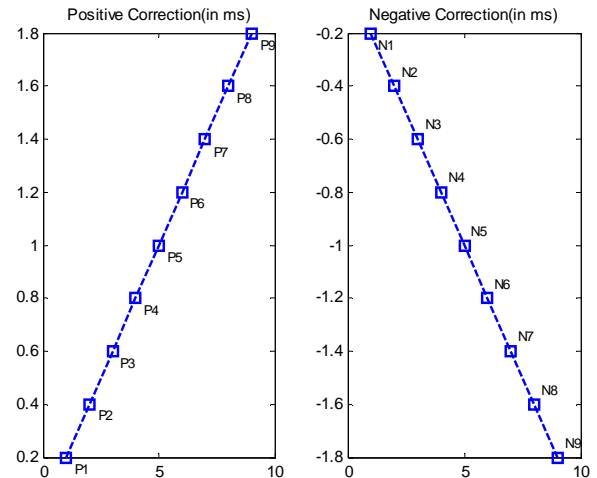
**Table 3: Positive correction in Uphill driving case**

		Engine RPM		
RPM Gradient		S	B	V
	S	N <sub>1</sub>	N <sub>4</sub>	N <sub>7</sub>
	B	N <sub>2</sub>	N <sub>5</sub>	N <sub>8</sub>
	V	N <sub>3</sub>	N <sub>6</sub>	N <sub>9</sub>

**Table 4: Negative correction in Downhill driving case**

The amount of positive or negative correction to main injection pulse width should be small enough so that driver still should change gear or apply gas pedal to maintain desired torque but at the same time the correction should be sufficient enough so that due to relatively smaller uphill or downhill, driver should not feel the need to change the gear or press the gas pedal.

The range of P<sub>1</sub> to P<sub>9</sub> and N<sub>1</sub> to N<sub>9</sub> should be chosen very carefully and typical values could be as shown in Figure 11.

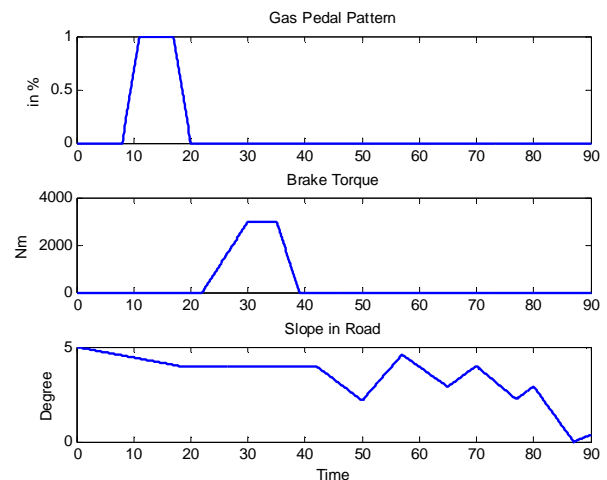


**Figure 11: The amount of injection time correction in ms**

## 10. Conclusion and Analysis

A practical driving scenario is simulated taking plant and controller models together in account, with small uphill and downhill road as shown in Figure 12.

### Scenario I: Road with random uphill and downhill

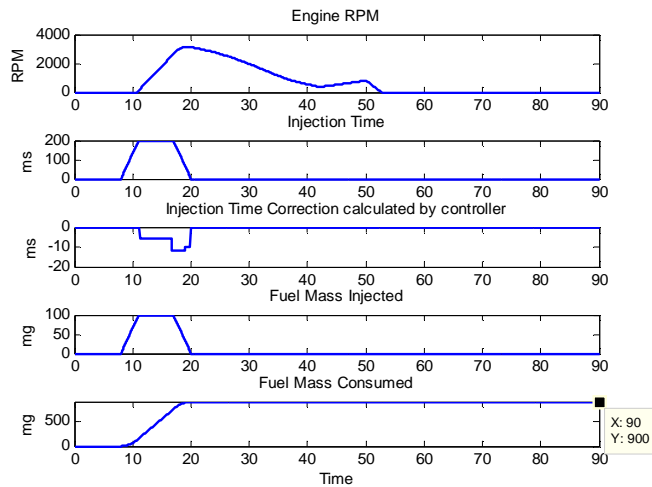


**Figure 12: A practical driving scenario with variation of gas and brake pedal and road slope**

In response to the driving scenario described in Figure 12, the engine RPM, injection opening time in ms, injection time correction in ms, fuel mass injected in mg and total fuel mass consumed is shown in Figure 13 without applying the injection time correction factor.

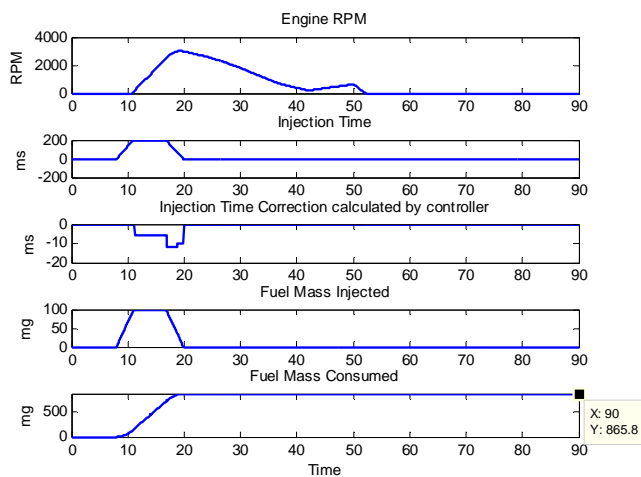


Simulation indicates 900 mg of total fuel consumed. This data is our reference for further analysis.



**Figure 13: Without controller, the total fuel mass consumption and other engine parameters**

Now, if the correction computed by fuzzy controller algorithm is applied; we get the response shown in Figure 14.



**Figure 14: With controller, the total fuel mass consumption and other engine parameters**

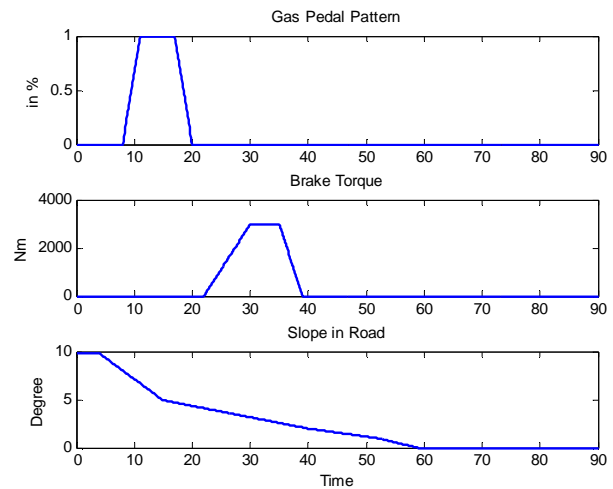
We can see that the total fuel mass consumption with controller is 865.8 mg and without controller is 900 mg.

Although, in this case we saw reduction in fuel consumption but it cannot be simply concluded that we will always get improvement in fuel economy by our controller strategy. This

will heavily depend on the pattern of applying gas and brake pedal, position and amount of road slope etc.

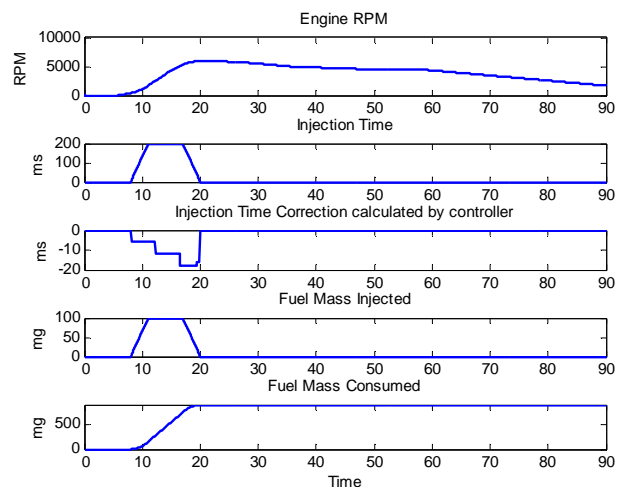
## Scenario II: Down Hill Road only

Now, let us consider a case where during its travel, the vehicle only encounter downhill. The used driving scenario is shown in Figure 15.



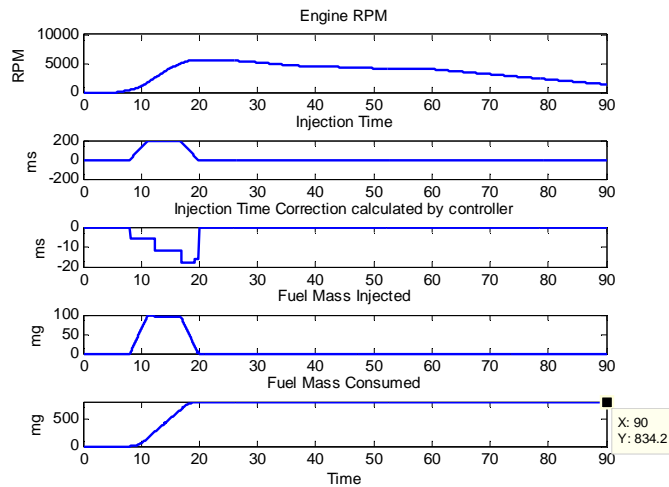
**Figure 15: Driving under downhill, the acceleration, brake and road slope**

Without applying controller algorithm, the engine parameter such as injection time and fuel mass consumption etc is shown in Figure 16 and the same with using our proposed fuzzy controller algorithm is shown in Figure 17.





**Figure 16: Engine parameters in response to downhill road condition (without controller)**

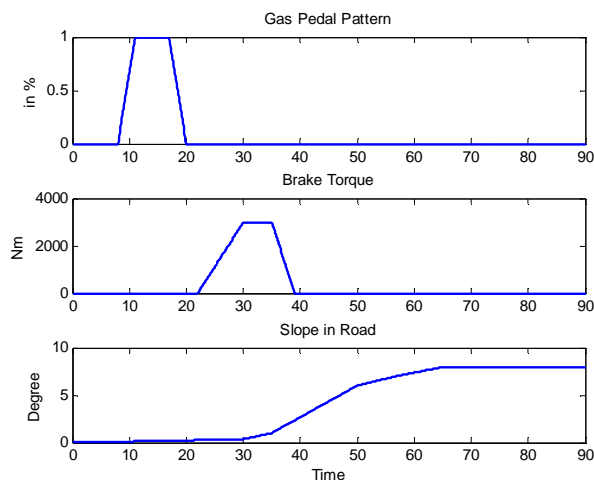


**Figure 17: Engine parameters in response to downhill road condition (with controller)**

It can be seen clearly that due to downhill road, the gravity component contributed positively to the drive torque and thus reducing the total fuel consumption to 834.2 mg without altering any other parameter.

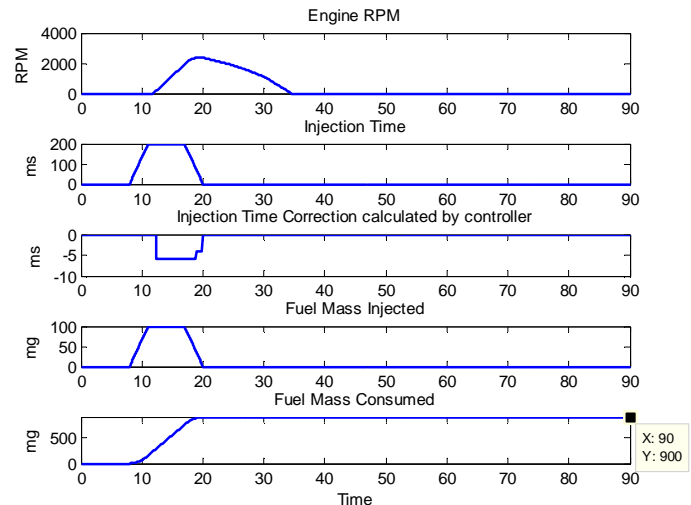
### Scenario III: Uphill Road only

Now, with same driving condition used in Scenario II, only the road condition is changed to continuous uphill. The used driving scenario is shown in Figure 18.

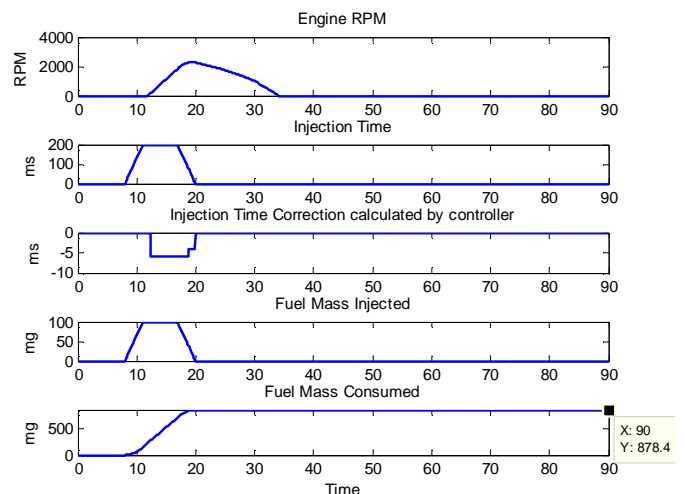


**Figure 18: Driving under uphill, the acceleration, brake and road slope**

Again similar to Scenario II, without applying controller algorithm, the engine parameter such as injection time and fuel mass consumption etc is shown in Figure 19 and the same with using fuzzy controller algorithm is shown in Figure 20.



**Figure 19: Engine parameters in response to uphill road condition (without controller)**



**Figure 20: Engine parameters in response to uphill road condition (with controller)**

Due to uphill road, the gravity component contributed negatively to the drive torque and thus increasing the total fuel consumption to 878.4 mg (in case of downhill it was 834.2 mg) without altering any other parameter.

## 11. Summary

There are two major impacts of this control strategy: Drivability and fuel economy. Drivability is an experience and cannot be quantified whereas the increase or decrease of fuel consumption can play a very important role in using the algorithm commercially. It is also possible that fuel saving achieved during downhill is compensated by additional fuel consumption in uphill.

A more detail study using a real vehicle on various road conditions might help to improve the algorithm.

## Acknowledgements

We are very thankful to our esteemed organisation 'Continental Automotive GmbH' for providing encouragement and a conducive atmosphere for research. The tools used are MATLAB, SIMULINK and STATEFLOW.

## Reference

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