Energy-efficient powertrain control of hybrid vehicles through traffic jams

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Abstract

Energy consumption of a vehicle is highly dependent on the number of acceleration and deceleration instances during a drive cycle. Out of all the driving scenarios traffic jam results in the maximum number of acceleration and deceleration instances. Reducing these acceleration and deceleration instance or their magnitude during the traffic jam will result in a reduced energy consumption.

The project aims to reduce energy consumption of heavy-duty hybrid vehicles during a traffic jam by designing an optimal control strategy for a 2-vehicle system (lead vehicle and follower vehicle). The optimal control strategy optimizes the energy consumption of the follower vehicle. The relative distance between the lead vehicle and the follower vehicle is kept in between a window which allows the follower to have reduced acceleration and deceleration instances as compared to the lead vehicle.

The optimization problem is divided into 2 sub parts. A) Vehicle Energy optimization of follower vehicle, B) Implementation of ECMS for the follower vehicle.

The optimization was done using the fmincon solver in MATLAB, results show that the follower vehicle has approximately 7% reduced energy consumption as compared to the lead vehicle for a traffic jam situation.

Github Link: https://github.com/singhvi1811/Design-Optimization-Project-.git

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1. Design Problem Statement -Akshay Singhvi and Harsh Lal

The objective of the project is to reduce energy consumption of heavy-duty hybrid vehicles during a traffic jam by designing an optimal control strategy for a 2-vehicle system (lead vehicle and follower vehicle).

1.1 Vehicle Energy Optimization

The optimal control strategy should optimize the energy consumption of the follower vehicle. The relative distance between the lead vehicle and the follower vehicle is kept in between a window which allows the follower to have reduced acceleration and deceleration instances as compared to the lead vehicle. The figure below explains the constraint.

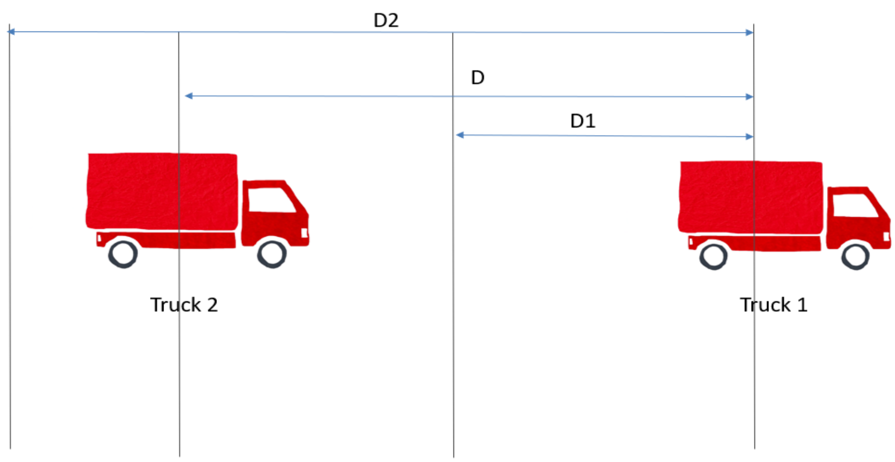


Figure 1 Relative Distance Constraint

$D1 < D < D2$

where,

$D1$: Minimum distance that should be maintained between the 2 vehicles

$D2$: Maximum distance that should be maintained between the 2 vehicles

D: The actual distance between the 2 vehicles

1.2 ECMS

Design a control strategy which decides on the distribution of power demand from the ICE and the electric motor.

The Cost function is defined as:

$$f = E_{Engine} + \alpha E_{Motor}$$

where,

E_{Engine}: Energy consumption due to combustion in ICE (Fuel Energy)

E_{Motor}: Energy consumption by motor

α: Equivalence factor for comparing electrical energy with fuel energy (ECMS).

Constraints:

SOC of battery >Threshold value

2. Nomenclature

f: $Objective\ function$
P_{veh}: $Total\ Vehicle\ Power$
F_{total}: $Total\ force\ available\ after\ driveline$
$V = Current\ vehicle\ velocity$
F_{tr}: $Traction\ force$
F_{gr}: $Gradient\ resistance\ force$
F_{rr}: $Rolling\ resistance\ force$
F_{aero}: $Aerodynamic\ drag$
$m = mass\ of\ the\ vehicle$
a_1: $acceleration\ of\ truck\ 1$
a_2: $acceleration\ of\ truck\ 2$
g: $acceleration\ due\ to\ gravity$
θ: $Road\ Grade$
C_r: $Coefficient\ of\ rolling\ resistance$
ρ: $Air\ density$
C_d: $Drag\ coefficient$
A: $Frontal\ area\ of\ the\ truck$
D_1: $Minimum\ allowable\ distance\ between\ vehicle1\ and\ vehicle2$
D_2: $Maximum\ allowable\ distance\ between\ vehicle1\ and\ vehicle2$
D: $Relative\ distance\ between\ vehicle1\ and\ vehicle2$
Pos_1: $Position\ of\ truck\ 1$
Pos_2: $Postion\ of\ truck\ 2$

3. Mathematical Models

3.1 Longitudinal vehicle dynamics – Akshay Singhvi

The following forces act longitudinally on a vehicle

i) Traction force (F_{tr}): force available on the wheels.

ii) Grade Force (F_{gr}): Gradient force

iii) Tire Rolling resistance (F_{rr})

iv) Aerodynamic drag (F_{aero})

$$F_{total} = F_{tr} + F_{gr} + F_{rr} + F_{aero}$$
$$F_{tr} = ma_2$$
$$F_{gr} = mgsin\theta$$
$$F_{rr} = mg * C_r$$
$$F_{aero} = 0.5\rho V^2 c_d A$$

$$a = \frac{F_{tr}}{m}$$
$$V = \int a \, \partial t$$
$$Pos = \int V \, \partial t$$

3.2 Objective Function (Vehicle Energy) – Akshay Singhvi

As we are trying to optimize the vehicle energy the consumption the objective function derived using the longitudinal vehicle dynamics. The derivation of the objective function is given below

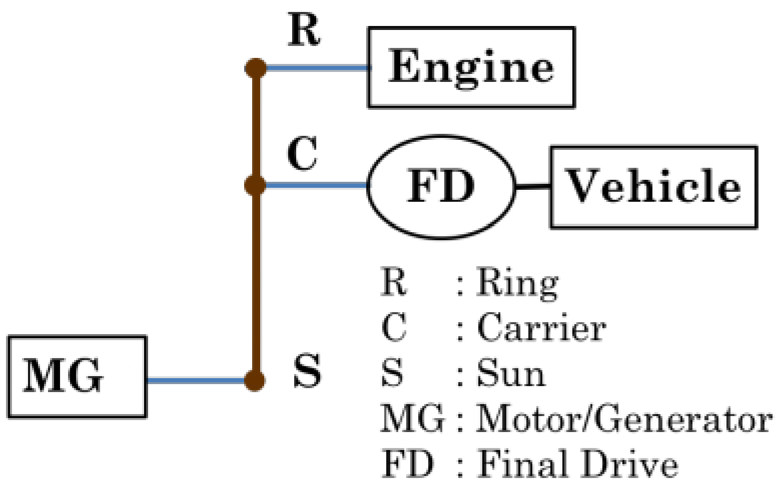
$$f = \int_0^T P_{Veh} * dt$$
$$f = \int_0^T F_{total} * V * dt$$
$$f = \int_0^T (F_{tr} + F_{gr} + F_{rr} + F_{aero}) * V * dt$$
$$f = \int_0^T (ma_2 + mgsin\theta + mg * C_r + 0.5\rho V^2 c_d A) * V * dt$$

we want to minimize f with respect to acceleration a_2. such that it satisfies the following constraint:

$$D_1 < D < D_2$$
$$D = Pos_1 - Pos_2$$
$$D = \int v_1 - \int v_2$$

3.3 ECMS Model – Harsh Lal

We use a Power-split architecture between the motor and the engine for our ECMS implementation [1].



Based on the drive cycle of the vehicle, we obtain the required Torque and RPM values at the axle given by T_{shft} and W_{shft} respectively.
Engine Torque and RPM (T_{eng} and W_{eng}) are predefined based on the specifications of the engine.
Depending on these parameters we compute the motor Torque and RPM (T_{MG} and W_{MG}) corresponding to the optimized fuel consumption value.

The other parameters are defined below:

rho: $Planetary\ gear\ ratio\ between\ ring\ gear\ (R) and\ sun\ gear\ (S)$.
FR: $Final\ Drive\ Ratio\ of\ the\ vehicle$.

We obtain the following relations for our power-split model:

$$W_{MG} = -rho * W_{eng} + (1 + rho) * W_{shft} * FR$$

$$T_{MG} = \frac{1}{(1 + rho)} * \frac{Tshft}{FR}$$

4. Model Analysis and Methodology

4.1 Vehicle Energy Model – Akshay Singhvi

The Vehicle Energy model considers all the longitudinal forces. Due to the limitation of data availability we have made some assumption in the vehicle energy model which are as follows:

i) The Road grade is assumed to be zero.
ii) The Aerodynamic drag force is assumed to be zero
iii) The static friction taken equal to the dynamic friction

This results in the following vehicle energy model:

$$f = \int_0^T (ma_2 + mg * C_r) * V * dt$$

The following energy function is treated as the sum kinetic energy of the vehicle and the energy due to friction.

Using the kinetic energy as $0.5 * m * V^2$ converts the objective function into a single variable function. The design variable is velocity.

4.1.1 Constraints

The following constraints are taken into consideration while forming the optimization problem

i) Relative distance (D)

The relative distance is calculated by taking the difference between absolute position of vehicle 1 and absolute position of vehicle 2. The upper limit for relative distance is taken as 20 meters and lower limit is taken as 70 meters.

$$D_1 < D < D_2$$
$$D = Pos_1 - Pos_2$$
$$D = \int v_1 - \int v_2$$

ii) Acceleration Constraint:

In order to avoid sudden acceleration peaks, we are also providing a physical constraint on the acceleration. The acceleration values are limited to 1 m/s2.

4.1.2 Optimization methodology – Akshay Singhvi and Harsh Lal

The Optimization problem is solved using Model Predictive control algorithm. The fmincon solver in Matlab with Sequential Quadratic Programming is used for optimization.

Keeping the design variable as the velocity of vehicle 2 and the constraint as the relative distance we apply model predictive control to solve the optimization problem.

The optimization problem is solved by taking different time steps in the MPC algorithm. The time steps are varied from 50 seconds to 600 to analyze the effect of time steps on the optimization results.

4.2 ECMS model – Harsh Lal

The optimized drive cycles obtained from the energy optimization are used for getting the optimized fuel consumption and mileage of the hybrid vehicle.

We have considered a planetary gear ratio (rho) as 4 and a final drive ratio of 3.9 for all the drive cycles.

5. Results

5.1 Vehicle Energy Optimization

With the constraint limit on relative distance between Vehicle 1 and Vehicle 2 as:
Minimum relative distance: 20 meters
Maximum relative distance: 70 meters
We Observed the following Energy consumption improvement for various drive followed by the lead vehicle.

S.no	Drive Cycle	Time (secs)	% Energy Savings
1	UDDS	597	7.78%
2	US06	597	2.14%
3	SC03	597	8.60%
4	HWFET	597	1.04%

Table 1 Energy Saving on various drive cycles

The results show that highway drive cycles (US06 and HWFET) have a lower energy saving as compared to non-highway drive cycles (UDDS and US06). This is mostly because of the velocity variation on non-highway.

The Following graphs are for the **SC03 Drive cycle** followed by the lead vehicle:

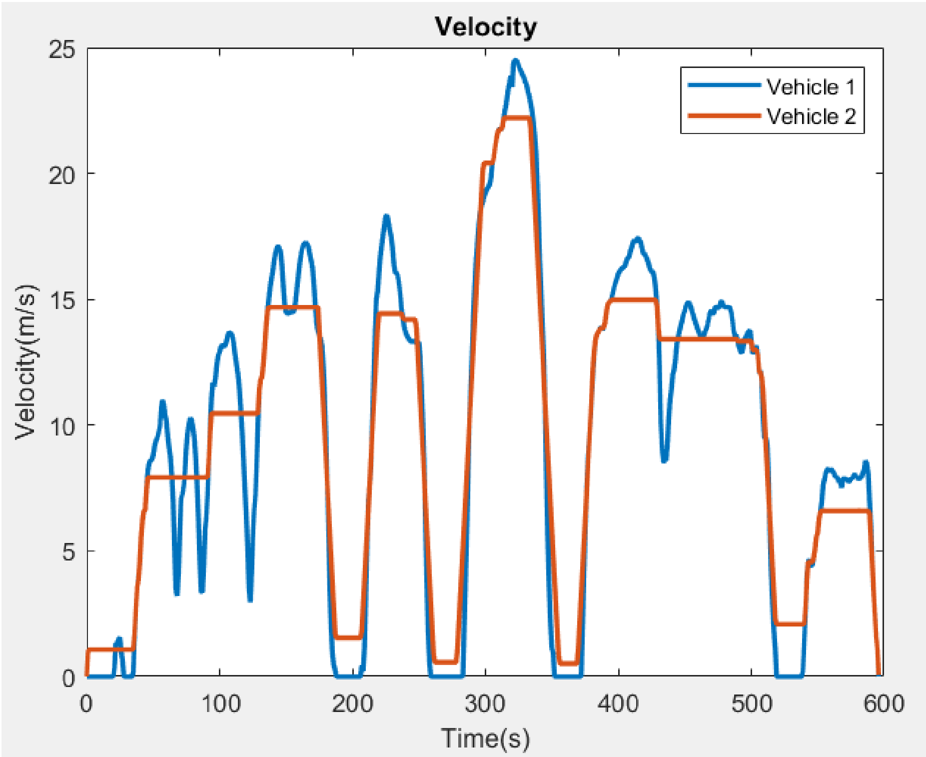


Figure 2Velocity profile of lead vehicle (1) and follower vehicle (2)

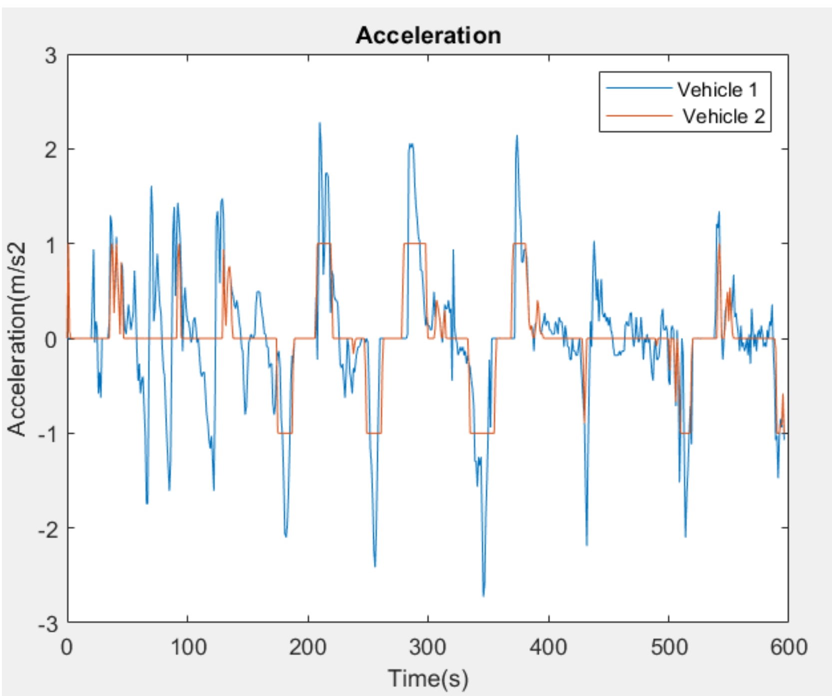


Figure 3Accleration profile for lead vehicle (1) and follower vehicle (2)

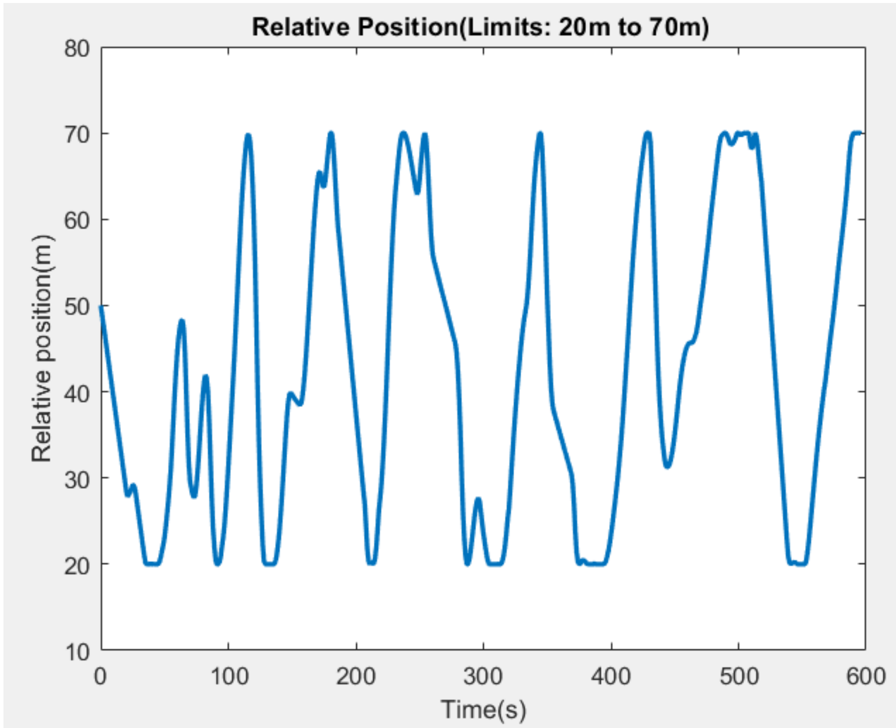


Figure 4 Relative Position between Lead vehicle and Follower vehicle

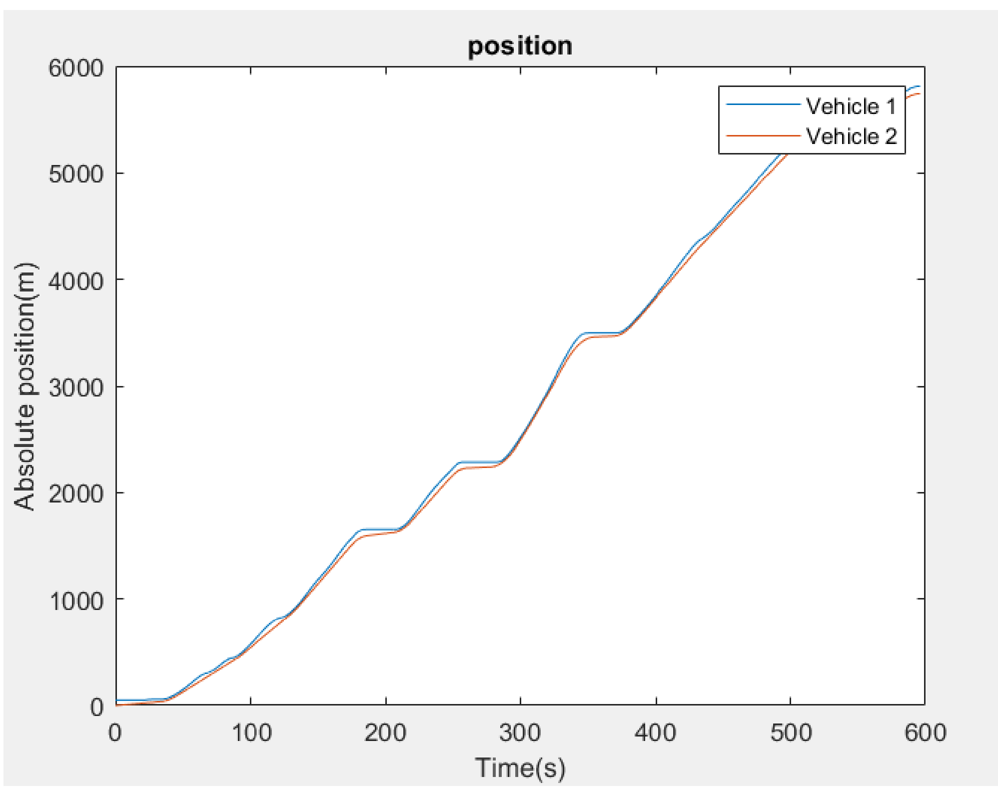


Figure 5 Absolute Position of Lead vehicle (1) and Follower vehicle (2)

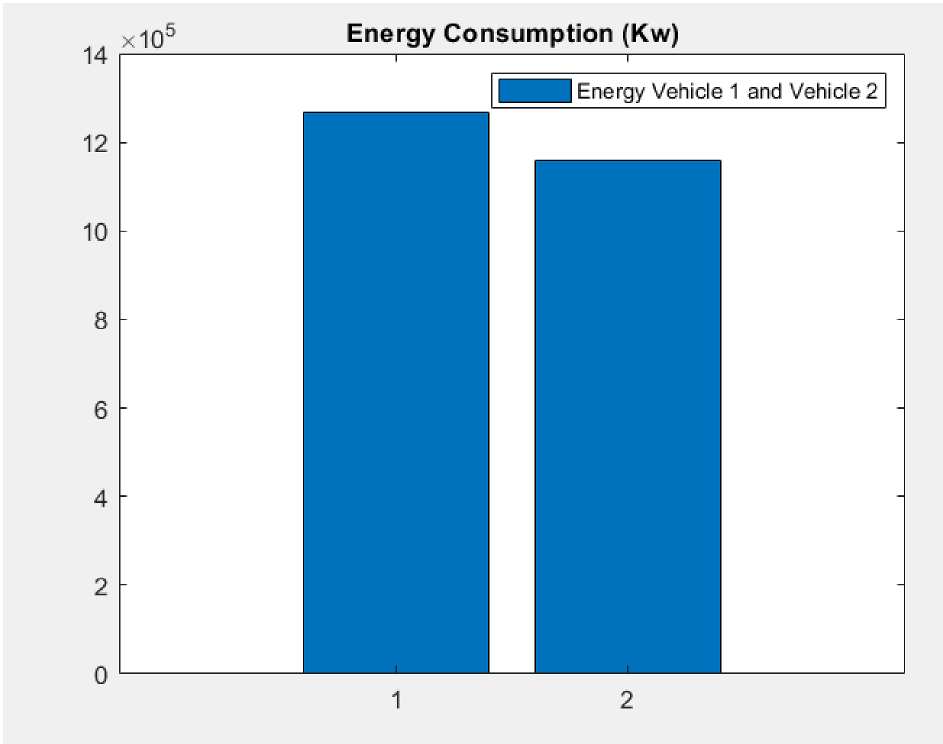


Figure 6 Energy Consumption for Lead vehicle (1) and Follower Vehicle (2)

5.1.1 Velocity comparison for different drive cycles

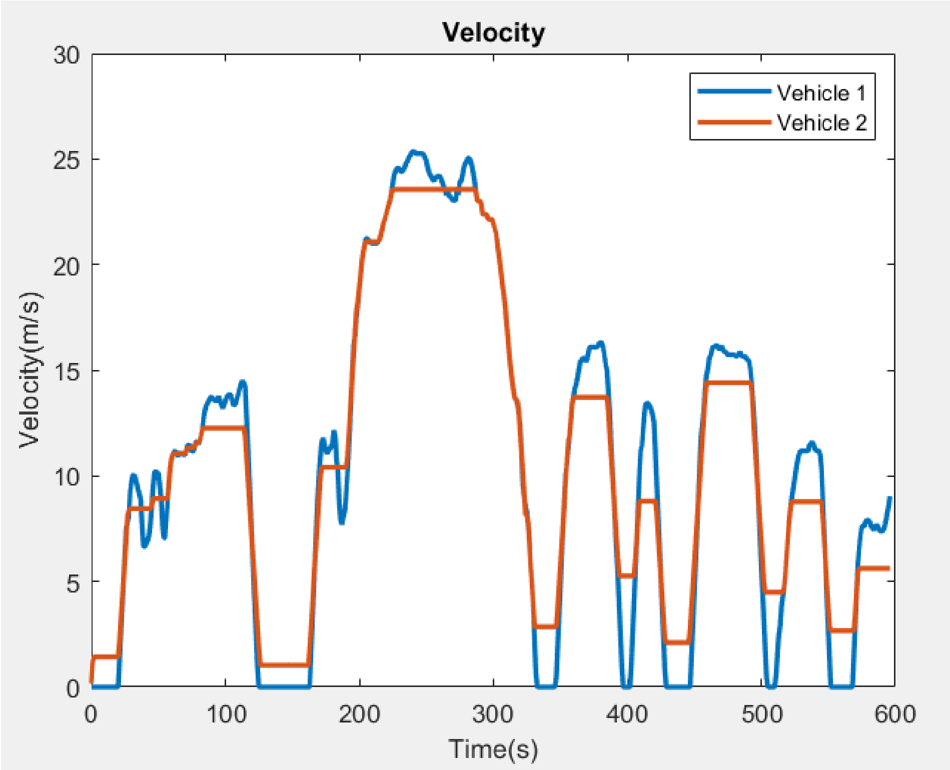


Figure 7 Velocity profile for UDDS drive cycle

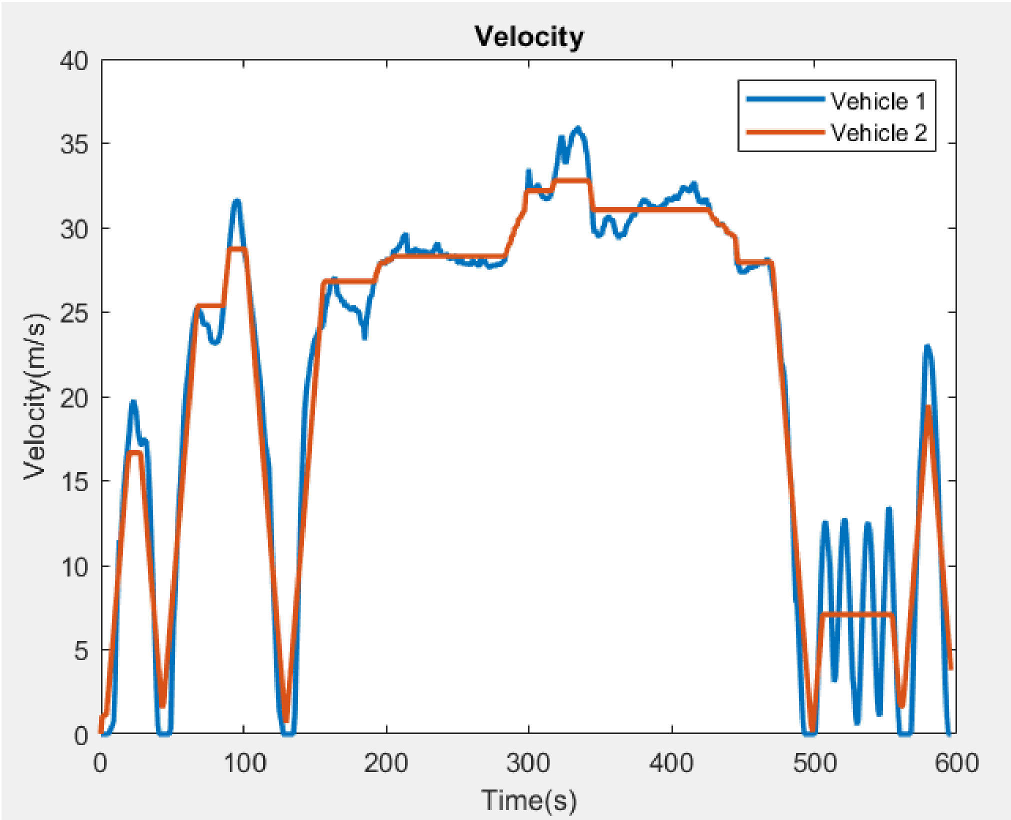


Figure 8 Velocity Profile for US06 drive cycle

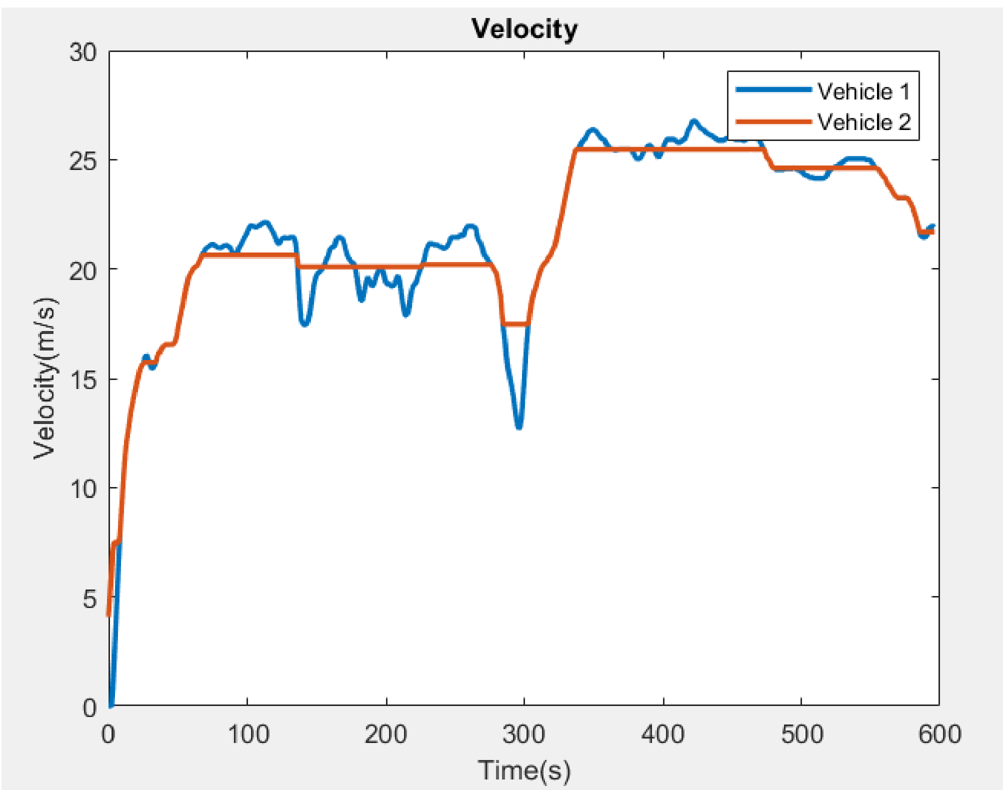


Figure 9 Velocity Profile for HWFET drive cycle

5.1.2 MPC time step size vs Energy savings

The Reduction vehicle energy consumption is also dependent on the Future time step taken in the MPC. The following table summarizes the variation in results with respect to time steps:

S. No	Drive Cycle	Time Step (Sec)	%Energy Savings
1	SC03	50	4.26%
2	SC03	150	6.84%
3	SC03	300	7.52%
4	SC03	597	8.60%

Table 2Energy saving variation with time step size

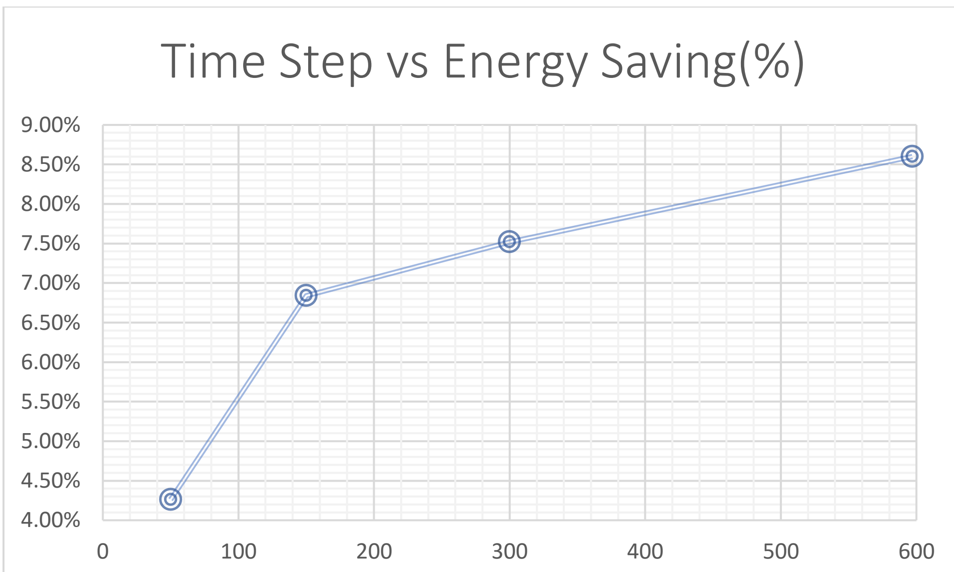


Figure 10 MPC Time step size vs Energy Saving (%)

5.2 Fuel Consumption Optimization (ECMS results)

The following graphs represent the optimized motor Torque and RPM obtained.

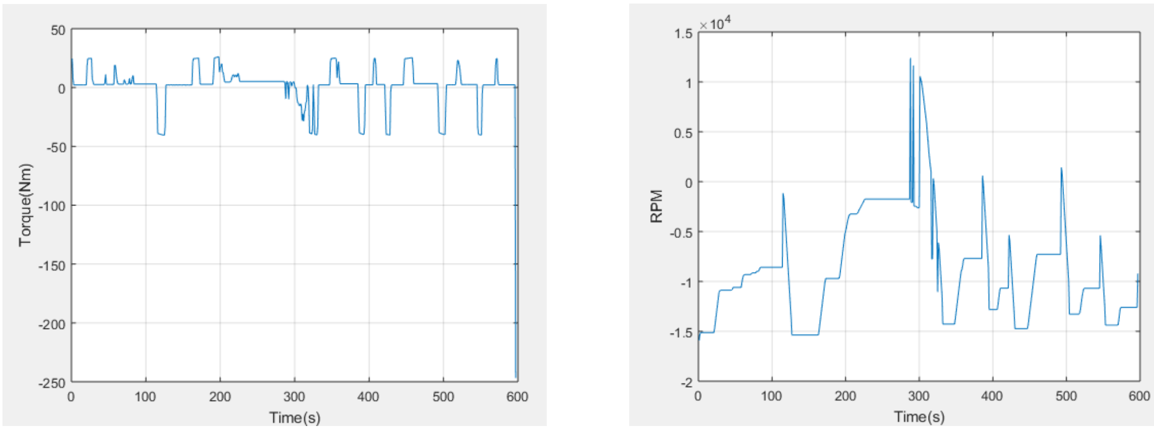


Figure 11 Motor Torque and RPM for UDDS profile.

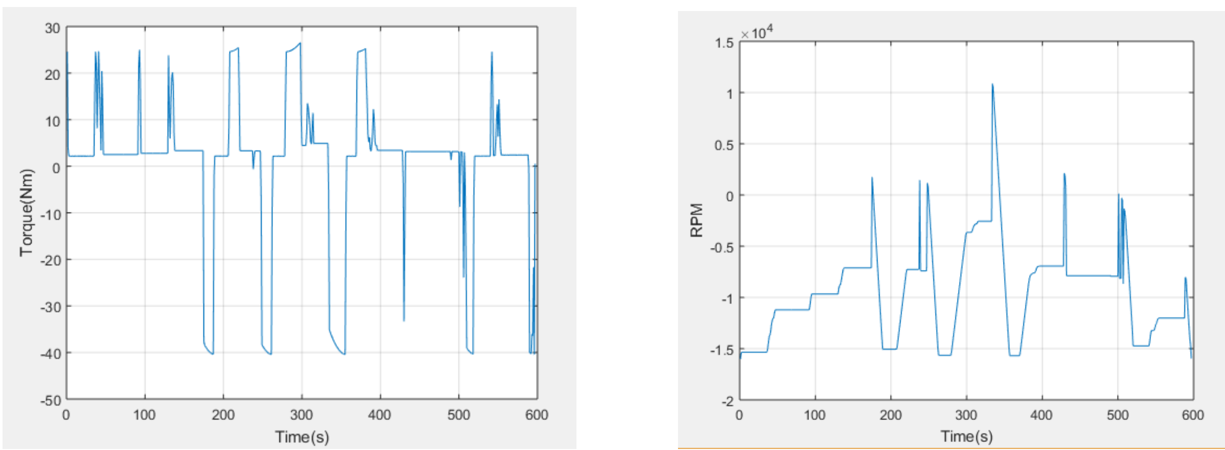


Figure 12 Motor Torque and RPM for SC03 profile.

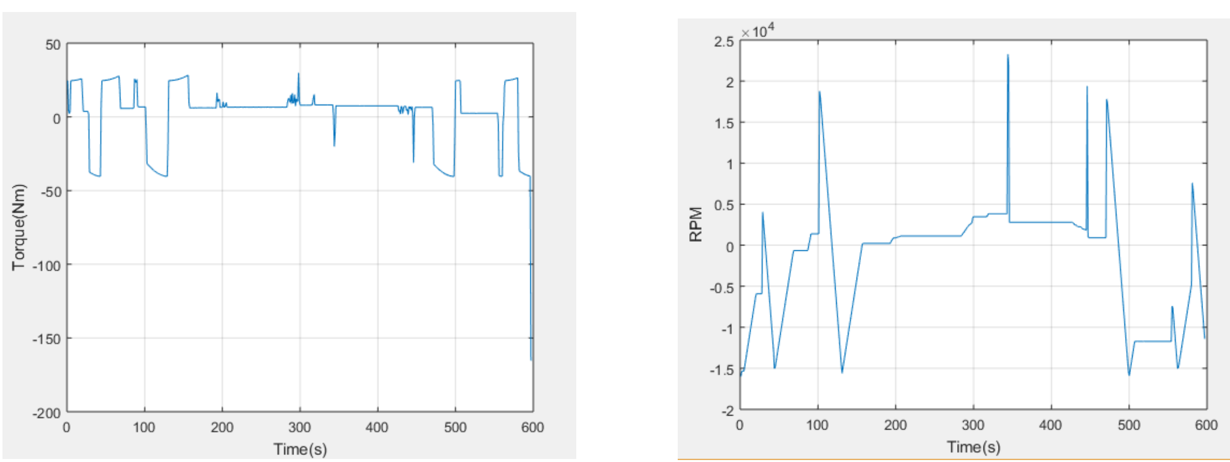
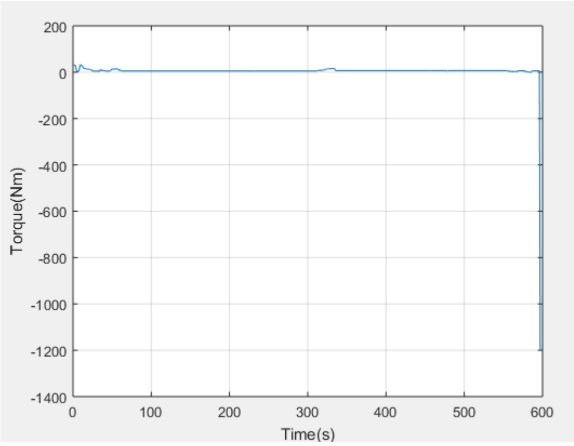


Figure 13 Motor Torque and RPM for US06 profile.



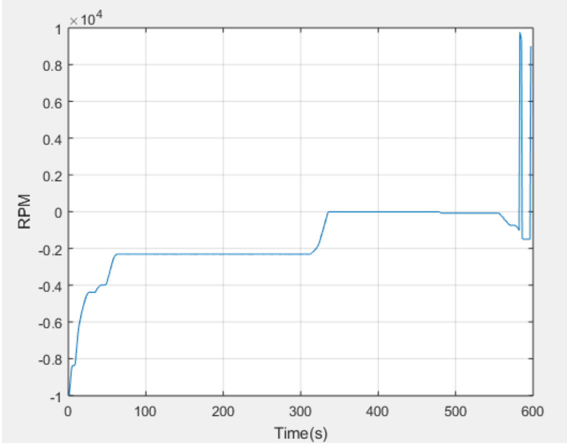


Figure 14 Motor Torque and RPM for HWFET profile.

The following table compares the optimized fuel consumption and mileage for the corresponding drive cycles.

Drive Cycle	**MPG**	**Fuel Consumption (g)**
UDDS	35.2292	353.64
SC03	32.0783	354.14
US06	72.7881	350.64
HWFET	71.4948	354.44

Table 3 Fuel Consumption and mileage for various drive cycles

6. Conclusion and Future Work

The Current optimization results reveals that if we adopt lead-follower vehicle topology we can minimize the energy consumption of a follower vehicle during a traffic jam situation by substantial amount without losing time.

For future work the Vehicle energy optimization model can be combined with ECMS model to find out the most practical solution to the problem.

7. References

[1] Alparslan Emrah Bayrak, Yi Ren, Panos Y. Papalambros. Topology Generation for Hybrid Electric Vehicle Architecture Design.