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Decentralized Predictive Cruise Control For Energy Saving In REEV Using V2I Information For Multiple-vehicles ⋆

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Abstract: This paper proposes a Predictive Cruise Control for a Range Extended Electric Vehicle that uses the information of upcoming traffic lights to arrive at green or to reduce idling at red light. Simultaneously, it is decided in a predictive manner, which is the best energy management strategy to operate the vehicle's powertrain. The main goals are to reduce fuel consumption, to increase energy efficiency and to maintain a safety distance between vehicles. The control algorithm is formulated based on Model Predictive Control theory, which also allows the controller to operate in the absence of traffic light information as an Adaptive Cruise Control with predictive energy management. The controller tracks an optimal velocity trajectory computed based on current traffic light's timing and decides how much energy should be provided by the battery and by the generator. Multiple-vehicle simulations were carried out and the results showed a significant reduction in fuel and energy consumption.

Keywords: Predictive Control, Hybrid Vehicle, Energy Management Systems, Powertrain Control, Driver Assistance.

1. INTRODUCTION

The challenge to reduce greenhouse emissions and to decrease the dependency on crude oil and gas resources requires decisive changes in energy supply, conversion and storage technologies. For the transport sector, electrification of the drivetrain combined with telematics based predictive operating strategies seems to be a promising approach. This topic is addressed by the program, *Integrated Energy Supply Modules for Roadbound E-Mobility (mobilEM)*, at RWTH Aachen University. Its *Control and System Simulation Division* investigates Model Predictive Control (MPC) for optimized, predictive and energy-efficient operation of the complete system of Range Extended Electric Vehicles (REEV).

In this framework, the following study was conducted, which merges improvements in both urban infrastructure utilization and energy management in hybrid vehicles. On the one hand, the inefficient stop-and-go driving behavior in urban areas caused by the lack of information about the future state of traffic lights is addressed. This is based on the solution proposed by Asadi and Vahidi (2009), where a Predictive Cruise Control (PCC) based on MPC theory is designed to adapt the vehicle's velocity to arrive at green light or at least to minimize the waiting time at red lights, while also maintaining a safety distance between the vehicles. The reduction in acceleration and deceleration, achieved by smoothly following an optimal velocity for timely arrival at a green light, minimizes fuel consumption. On the other hand, a control strategy adopted for energy management is addressed. It is based on a contribution to handle this problem given by Bichi et al. (2010), where a MPC is designed to efficiently operate the powertrain of a REEV by deciding how much power should be provided by each energy source, namely the battery and the generator.

The aim is to develop a PCC for REEV based on the MPC theory, which uses in advance information about future states of the traffic lights along the route to adapt the vehicle's velocity and energy management to arrive at a green light. This will eliminate or reduce idling time, reduce fuel consumption and increase traffic fluency, while maintaining a safety distance between vehicles. Advantages of predictive control will be exploited to optimize the vehicle's energy management through an intelligent distribution of the power provided by each energy source. In addition, the controller can serve as an Adaptive Cruise Control (ACC) with predictive energy management for REEVs when the information about the upcoming traffic lights is unavailable, and also when lower fuel consumption and higher energy efficiency need to be achieved.

However, the success of the proposed controller depends strongly on the traffic conditions, i.e. other vehicles that prevent the vehicle from following the optimal velocity. Hence, the controller should consider real traffic to investigate the real improvement potential. Therefore, a multiple-vehicle scenario is designed, where a certain number of conventional vehicles travel along with the REEV on an

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urban road, which is chosen based on real traffic light data. Each vehicle will be equipped with a MPC utilizing information about upcoming traffic lights. It can operate either as an ACC or as a PCC, and only the last vehicle is a REEV with predictive energy management.

2. MODELING OF VEHICLES

2.1 Conventional vehicle

For a vehicle with a conventional powertrain, a simple model of the longitudinal dynamics is used. The longitudinal dynamics of a vehicle are generally modeled using Newton's Second Law, by setting the acceleration of a vehicle with mass m as a function of the forces applied to it, i.e., the effective traction force f_e, the braking force f_b, and the road resistances f_{road} as follows:

$$m\frac{d^2s(t)}{dt^2} = f_e - f_b - f_{road}. \tag{1}$$

The road resistance represents the summation of all the forces that hinder the vehicle's movement, i.e., aerodynamic drag, rolling resistance, and gravitational resistance as follows:

$$f_{road} = \frac{1}{2}\rho C_x A \frac{ds(t)}{dt}^2 + f_r mg\cos(\theta) + mg\sin(\theta), \tag{2}$$

where ρ is the density of air, C_x the drag coefficient, and A the frontal area of the vehicle. f_r is the rolling resistance coefficient of the tires, g the gravitational constant, and θ the slope angle of the track. By considering the road resistance as a disturbance, the model of a conventional vehicle can be expressed as follows:

$$\begin{bmatrix} s(k+1) \\ v(k+1) \end{bmatrix} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} s(k) \\ v(k) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{T_s}{m} & -\frac{T_s}{m} \end{bmatrix} \begin{bmatrix} f_e(k) \\ f_b(k) \end{bmatrix} + + \begin{bmatrix} 0 \\ -\frac{T_s}{m} \end{bmatrix} f_{road}(k), \tag{3}$$

where T_s is the sampling time.

2.2 REEV

The model of a REEV should consider the energy distribution in the powertrain, which is commonly expressed in terms of power. The requested power by the motor to propel the vehicle P_m should be supplied by the battery P_{el}, by the Range Extender (RE) through the generator P_{gen}, and by the conventional braking system P_{br}:

$$P_m(k) = P_{el}(k) + P_{gen}(k) - P_{br}(k). \tag{4}$$

The model used for the generator sets the power given by the generator as a function of the variation of the mechanical power provided, ΔP_{gen}, as follows:

$$P_{gen}(k) = P_{gen}(k-1) + \Delta P_{gen}(k). \tag{5}$$

The State of Charge (SoC) of the battery is determined by the amount of power demanded or given to it, P_{el}:

$$SoC(k+1) = SoC(k) - K\,T_s P_{el}(k), \tag{6}$$

where $SoC \in [0,1]$ and $SoC = 1$ corresponds to full charge, T_s is the sampling time, and K is a scalar parameter defined based on the capacity of the battery.

In order to merge longitudinal dynamics and energy management in one single model, (1) should be expressed in terms of power, i.e. the power supplied by the motor P_m and the power provided by the convectional friction brakes P_{br}, which can be performed by multiplying (1) by the vehicle's velocity $\frac{ds(t)}{dt}$:

$$\frac{ds(t)}{dt} m \frac{d^2s(t)}{dt^2} = P_m\eta\xi - P_{br} - \frac{ds(t)}{dt} f_{road}, \tag{7}$$

where η is the efficiency of the transmission, and ξ is its reduction, considering also the reduction of the differential. This modification leads to a non-linear model that has to be linearized at each operating point P_0 to meet the standard formulation in MPC. It is expressed as a state-space, discrete-time linear model, as follows:

$$\begin{bmatrix} s(k+1) \\ v(k+1) \\ SoC(k+1) \\ P_{gen}(k) \end{bmatrix} = A \begin{bmatrix} s(k) \\ v(k) \\ SoC(k) \\ P_{gen}(k-1) \end{bmatrix} + B \begin{bmatrix} P_m(k) \\ \Delta P_{gen}(k) \\ P_{br}(k) \end{bmatrix} + E, \tag{8}$$

$$[P_{el}(k)] = [0\ 0\ 0\ {-1}] \begin{bmatrix} s(k) \\ v(k) \\ SoC(k) \\ P_{gen}(k-1) \end{bmatrix} + + [1\ {-1}\ 1] \begin{bmatrix} P_m(k) \\ \Delta P_{gen}(k) \\ P_{br}(k) \end{bmatrix} \tag{9}$$

where

$$A = \begin{bmatrix} 1 & T_s & 0 & 0 \\ 0 & 1+a & 0 & 0 \\ 0 & 0 & 1 & K\,T_s \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$a = \frac{T_s}{m}\left[-\frac{1}{v(k)^2}\left(\eta\xi\, P_m(k) - P_{br}(k)\right) - \rho C_x A v(k) \right]\Bigg|_{P_0} \tag{10}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ \frac{T_s}{m}\frac{\eta\xi}{v(k)}\Big|_{P_0} & 0 & -\frac{T_s}{mv(k)}\Big|_{P_0} \\ -K\,T_s & K\,T_s & -K\,T_s \\ 0 & 1 & 0 \end{bmatrix} \tag{11}$$

$$E = \begin{bmatrix} 0 \\ e \\ 0 \\ 0 \end{bmatrix}$$

$$e = \frac{T_s}{m}\left[\frac{1}{2}\rho C_x A v(k) - f_r mg\cos(\theta) - mg\sin(\theta) - \frac{\eta\xi P_m(k)}{v(k)} - \frac{P_{br}(k)}{v(k)} \right]\Bigg|_{P_0}. \tag{12}$$

This formulation may add more complexities and computation cost, but helps in handling energy management and longitudinal dynamics in a single problem.

3. MODEL PREDICTIVE CONTROLLER DESIGN

Two main MPC formulations will be considered; a PCC for a conventional vehicle and a PCC for a REEV. Both controllers will have information about the upcoming traffic lights and the position of the preceding vehicle, but only the second will consider energy management issues. Hence, some principles will be common in both controllers. The main idea is: If the timing of the upcoming traffic lights is known, the velocity can be increased when there is