Real Time Advisory System for Fuel Economy Improvement in a Hybrid Electric Vehicle*

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***Abstract* - In this paper, we present an improved version of the Advisory System for Fuel Economy Improvement in a Hybrid Electric Vehicle [11]. We address the competing requirements for improved fuel economy, while maintaining performance that is close to the current driving style and driver behavior. This is done by introducing a multiple-input, multiple-output rule base with a fuzzy reasoning mechanism that decomposes the space of the main factors that affect vehicle fuel economy and performance – instantaneous fuel consumption, acceleration, speed, and accelerator pedal position. This approach allows us to properly assign the boundaries of the desired accelerator pedal position that correspond to each of the specific areas, which are defined by the rules' antecedents. The system was developed and validated on the Ford (INSERT YEAR and make like SE) HEV Escape vehicle.**

I. INTRODUCTION

With the increased emphasis on improving fuel economy and reducing emissions, hybrid electric vehicles have emerged as a very strong candidate to achieve these goals. Fuel efficiency has become a top candidate towards achieving effective measures for sustainability and preserving the environment. As such, Ford Motor Company is continually developing and deploying various new advanced automotive technologies, such as hybrid electric vehicles (HEV), fuel cell hybrid vehicles (FCHV), and hydrogen vehicles. Significant efforts are focused on development of improved turbo-charged gasoline direct-injection engines, new more fuel efficient transmissions and lighter-weight vehicles. Another direction of research with substantial potential for creating environmental awareness is based on monitoring and analyzing the driving style, driver's behavior and preferences, and consequent adaptation of the vehicle systems with the final goal of providing means for maximal vehicle customization to the driver's expectations and requirements. This potential for improving fuel efficiency is estimated by different studies to be in the range of 20% to 40% [12]. Some of the work in this area is focused on providing feedback to the driver regarding the impact of his driving style on the instantaneous fuel efficiency of the vehicle. Visual indicators for fuel efficiency are already provided by a number of manufacturers (Ford Motor Company, Toyota, and Nissan have introduced visual warnings that notify the driver whether the vehicle is operated efficiently under current conditions). Although it is clear that the driver's behavior affects the fuel economy of a vehicle, it is often unclear how one should drive in order to maximize fuel economy [7]. Alternative driver advisory systems for fuel efficiency improvement have been described in [12] and [14]. These studies address the main driving factors than can affect the fuel efficiency - acceleration and deceleration patterns as dictated by the driver’s accelerator pedal and brake pedals. They clearly prove out that real-time feedback to drivers corresponding to their driving patterns can impact or improve their actions to maximize fuel economy without significantly affecting the drivability.

In [11], we proposed a novel advisory system called the “Fuzzy Rule-Based Driver Advisory System” for fuel economy improvement. This system monitors and identifies driving patterns and provides guidance for selecting the optimal driving strategy that results in maximizing fuel economy. This system includes two fuzzy logic controllers that determine the maximal driver demand (accelerator and brake pedal positions) corresponding to the desired fuel economy level, current engine operating conditions and vehicle speed. The output of the controller dynamically calculates the upper bound for the driver demand that can be continually conveyed to the driver through haptic or force feedback mechanisms. In this manner, the controller provides guidance to the driver that, if followed, can potentially maximize the fuel economy for given engine operating conditions and vehicle speed. The improvements result in the shaping and limiting of driver

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[*] Patents pending with the US patent office cover part of this work.

demands to improve overall fuel economy under normal driving conditions without reducing the vehicle's performance under heavy load or heavy acceleration.

This advisory system was developed and validated in a simulation environment using a Ford Escape Hybrid. Simulations demonstrated that the proposed driver advisory system could potentially improve overall fuel economy of a power-split HEV without significantly compromising the system's or vehicle's performance.

In this paper, we present an improved version of the algorithm for providing feedback to the driver through the accelerator pedal. We address the competing requirements for improved fuel economy, while maintaining performance that is close to the current driving style and driver behavior. We do this by introducing a multiple-input, multiple-output rule base with a fuzzy reasoning mechanism that decomposes the space of the main factors that affect vehicle fuel economy and performance – instantaneous fuel consumption, acceleration, speed, and accelerator pedal position. That approach allows us to properly assign the boundaries of the desired accelerator pedal position that correspond to each of the specific areas defined by the rules' antecedents. The system was developed and validated on the Ford Escape Hybrid.

II. THE TESTBED – FORD HEV ESCAPE

As a part of efforts to improve overall vehicle fuel efficiency and preserve the environment, Ford Motor Company developed a full hybrid electric vehicle (HEV), Escape Hybrid, with an e-CVT(Electronic Continuous Variable Transmission) or a power-split hybrid powertrain. HEVs are very attractive due to their low emissions and fuel economy improvements. Various type of hybrid systems exists [3],[4], including a series hybrid system, a parallel hybrid system, and a complex hybrid system. A power-split hybrid system, classified as a complex hybrid system, is used in the Escape Hybrid because it provides the characteristics of both a series and a parallel configuration. The power-split hybrid system uses planetary gear sets to connect an internal combustion engine, a generator, and a motor. This HEV powertrain has the ability for electric drive mode using the motor, where traction power is supplied through the high voltage (HV) battery only. It can also operate in hybrid drive mode using the proper reaction torque of the generator to control the engine speed together with the motor, where traction power is supplied through the engine as well as HV battery. In hybrid drive mode, the engine is operated in its most efficient region independent of the vehicle speed. Such e-CVT type flexibilities provide opportunity for improving fuel economy and emissions. HV battery is an energy storage that can also be used as additional power source device. The two electric machines, generator and motor, along with the engine in this power-split hybrid architecture use a coordinated vehicle control system. This coordination requires sophisticated control algorithms [5][6] to perform the balancing of torque, speed, and power from multiple power sources in this power-split hybrid configuration.

Figure 1 describes the power-split HEV configuration and its control system. The subsystems involved in controlling the power-split hybrid powertrain uses an engine controller (ECM), transaxle controller (TCM), high voltage battery controller (BCM), and a regenerative braking system (BSCM) to control engine, transaxle, HV battery and regenerative braking subsystems, respectively. In addition, the vehicle system controller (VSC) performs the overall vehicle system coordination and control by communicating with the subsystem controllers, as shown in Figure 1. It manages and coordinates the drivetrain functions to satisfy the driver's request and balance the energy flow to and from the multiple power units.

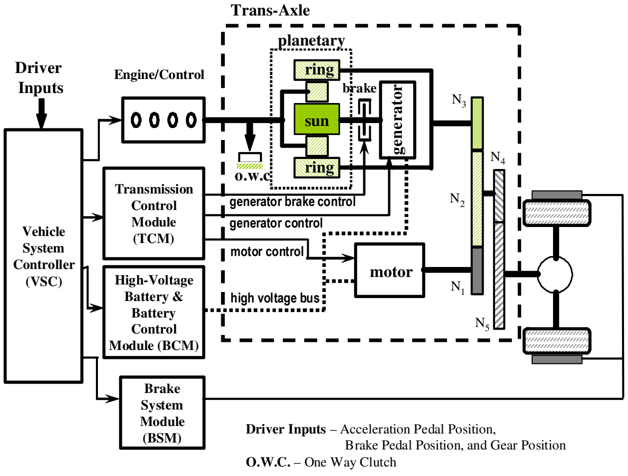


Fig. 1 Power-split hybrid architecture.

One of the main tasks that the VSC performs is optimally managing the energy flow through the planetary gear-set to provide the function for the unique hybrid operating modes, such as electric drive, regenerative braking, engine start-stop, hybrid drive, and HV battery power control and maintenance.

Ford Motor Company's Escape Hybrid, a power-split HEV using such a complex and efficient configuration ,provides the ability to maximize vehicle fuel economy and minimize vehicle exhaust emissions. Even with the availability of such efficient HEVs that are capable of achieving high fuel efficiencies, driver behavior plays a significant role in achieving these objectives. The main driver factors than can affect the fuel efficiency are the acceleration and deceleration patterns as dictated by the driver's accelerator pedal and brake pedal maneuvers. Although it is an obvious and known fact that the driving behavior affects the fuel economy of a vehicle, it is often unclear how one should drive in order to minimize fuel consumption [7]. Feedback to drivers on their driving patterns can impact or improve their actions to maximize vehicle's fuel economy without affecting the drivability. Currently, there do not exist tools that can provide direct advice to drivers regarding the optimal operation of accelerator pedal and brake pedal inputs, which can help them improve their fuel economy. Electronic devices on pedals using haptic or force feedback mechanisms can provide ways to convey such information to the driver [8].

III.THE FIRST GENERATION FUZZY ADVISORY CONTROL SYSTEM

As mentioned in Section I, driving behavior can affect the vehicle fuel economy. The driver traction request in a vehicle is conveyed through accelerator and brake pedals. During the operation of an HEV, the driver traction request level and profile or shape affects the fuel efficiency more than in comparison to a conventional vehicle. The reason for this greater impact on fuel economy in an HEV is that there is more than one energy source in an HEV, and based on the driver traction request, different operating modes of an HEV can be selected that may or may not be optimal for achieving optimal fuel efficiency. For example, during acceleration events, based on a higher traction force request, the vehicle system controller in an HEV may decide to enter into Hybrid mode of operation; whereas, if the driver traction request was slightly lower, it may have selected an electric mode of operation. Similarly, even in a hybrid mode of operation, based on a higher traction request, the vehicle system controller may opt to command the engine to an operating point that meets the driver's request, but results in less optimal fuel efficiency as compared to when driver traction request is lower.

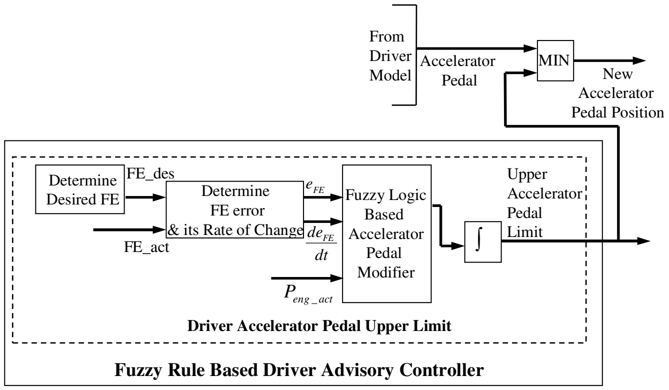


Fig. 2 The first generation fuzzy rule-based driver advisory control system for optimizing fuel efficiency in a HEV [11]

An intelligent advisory system that can determine the upper bound for the accelerator pedal was designed in [11]. The system conveys to the driver the optimal (with respect to fuel economy) accelerator pedal upper bound for a given vehicle driving condition. This controller was implemented as a fuzzy logic controller (FLC) (Figure 2).

The FLC that determines driver accelerator pedal upper bound uses desired fuel economy (*FE_des*) and actual or instantaneous fuel economy (*FE_act*) to determine the fuel economy error (e_{FE}) and rate of change of fuel economy error (de_{FE}/dt). A rule-base combined with a fuzzy reasoning then determined an accelerator pedal modifier based on fuel economy error, rate of change of fuel economy error and actual engine power (P_{eng_act}). Finally, the output (ΔA) of this fuzzy controller was integrated, and appropriate saturation limits were imposed to determine the upper limit for the accelerator pedal (A_{u_lim}). This recommended upper limit pedal position, if followed by the driver, provides the ability for the driver to improve fuel economy by modifying the actual accelerator pedal position. The driver advisory system improves overall vehicle fuel efficiency by providing a mechanism with which the driver can change his or her driving behavior.

Table 1 Fuzzy rules for accelerator pedal modifier

Rule No.	**If e_{FE} is**	**If de_{FE}/dt is**	**If P_{eng_act} is**	**Then ΔA_{u_lim} Is**
1	Don't care	Don’t care	Low	Zero
2	Negative	Negative	High	Positive low
3	Zero	Negative	High	Positive
4	Positive	Negative	High	Zero
5	Negative	Zero	High	Positive
6	Zero	Zero	High	Zero
7	Positive	Zero	High	Negative
8	Negative	Positive	High	Zero
9	Zero	Positive	High	Negative
10	Positive	Positive	High	Negative

Trapezoidal membership functions representing the negative, zero and positive states were chosen for the inputs and output of the fuzzy accelerator pedal modifier controller. The fuzzy rules for the first generation controller are described in Table 1. The rules in Table 1 exemplify different HEV acceleration/deceleration conditions that are defined by the rule antecedents and the corresponding recommended changes of the upper limits of the accelerator pedal as consequents.

A validated simulation environment [5][6][9] consisting of the vehicle model together with the subsystem models of the various hybrid specific systems was used for the development and testing of this fuzzy rule-based driver advisory controller. Simulations were performed for FTP-72 drive cycle to study the effectiveness of this controller. The simulations showed that this first generation fuzzy rule-based driver advisory system with a small rule set can provide feedback mechanisms that had substantial affect on improving fuel economy of a HEV, with improvements of up to 3.5% even for a very soft, informed and conscious driver.

IV. THE SECOND GENERATION FUZZY ADVISORY CONTROL SYSTEM

In order to evaluate the effectiveness of the first generation fuzzy rule-based driver advisory system, described in section III, in the real world environment, it was implemented in an HEV, Ford Escape Hybird, and tested/evaluated at Ford test tracks by measuring the critical powertrain and vehicle variables of interest. Test results demonstrated that while the simulation environment outcome showed improvement in fuel economy, the performance and drivability feel were unacceptable. Moreover, the virtual upper limit on the advised pedal position often resulted in recommendations (through a haptic device) that were perceived as intrusive to the driver. Hence, this controller required further improvement to take acceptable drivability criteria into account.

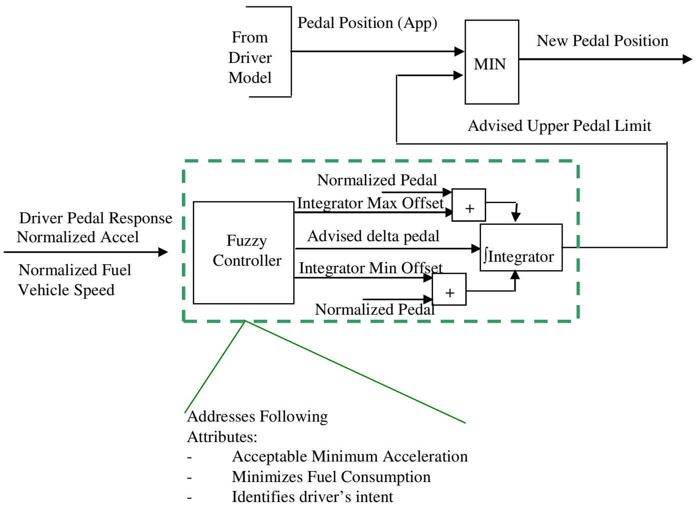
To design an effective fuzzy rule-based driver advisory controller, input variables, output variables, and the associated fuzzy sets had to be redefined. We first examine the inputs of the old fuzzy advisory controller shown in Figure 2. It can be noticed from Figure 2 that two of the inputs used in the first generation design were fuel economy error and rate of change of fuel economy error. In addition to these inputs, the third input was engine power. Note that these inputs only convey the effect on overall fuel economy in an HEV [1] without taking into account drivability and intrusiveness to the driver. Also, these inputs only provided a way of designing a nonlinear fuzzy logic based controller that was completely feedback based and could not take predictability or look for opportunities to improve fuel economy without affecting the drivability.

To take drivability into account, the essence of prediction and taking advantage of opportunistic states is very important; hence, input signals to the fuzzy controller needs to be modified. One of the inputs used in the first generation controller was fuel economy, which is calculated as a fraction of vehicle speed to fuel consumption. Since vehicle speed is a good indicator of vehicle driving state (city type or highway driving), it is more relevant to use fuel consumption and vehicle speed as inputs instead (of what?). Hence, the two the new inputs that were chosen to achieve improved fuel economy and drivability were the normalized fuel consumption (fc_n) and vehicle speed (vs). The normalized fuel consumption is the ratio between the instantaneous or actual fuel consumption and the maximum fuel consumption during a given driving condition.

To address the criteria for acceptable drivability or performance, the vehicle shall be able to achieve minimum acceptable acceleration at all the times. Hence, one of the other inputs that is needed is the normalized vehicle acceleration (a_n), the ratio between the instantaneous or actual vehicle acceleration and the maximum possible vehicle acceleration during a given driving condition.

To predict for driver behavior and make use of opportunistic states of the driving behavior, the driver pedal response ($\zeta_{\Delta A}$), which is the difference between the actual pedal position and filtered pedal position, was selected as an input.

Similar to the first generation fuzzy advisory controller, one of the outputs of this newly improved controller is the advised change (delta) of the accelerator pedal position (ΔA_{u_lim}) together with two other outputs, the maximum integrator offset (I_{oft_max}) and the minimum integrator offset (I_{oft_min}). This advised change of accelerator pedal position is fed into an integrator whose lower and upper bounds are calculated based on actual pedal position and minimum integral offset and actual pedal position and maximum integral offset, as shown in Figure 3. This controller utilizes the human control knowledge and experience from the usage and testing of the first generation fuzzy advisory controller to intuitively construct a more sophisticated intelligent controller so that the resulting controller will emulate the desired control behavior, to a certain extent [10], [13]. Figure 3 shows the newly improved fuzzy advisory controller.



Addresses Following Attributes:
- Acceptable Minimum Acceleration
- Minimizes Fuel Consumption
- Identifies driver's intent

Figure 3. Fuzzy Advisory Controller

In summary, the design of the newly improved fuzzy rule-based driver advisory controller is as follows: 1) The input variables consist of driver accelerator pedal response, vehicle speed, normalized vehicle acceleration, and normalized fuel consumption; 2) The output variables consist of advised change of the pedal position, minimum integrator offset, and maximum integrator offset; 3) The input fuzzy sets or membership functions are chosen to be low and high trapezoidal functions; and 4) The three output fuzzy sets are of singleton type for the advised change of accelerator pedal position, maximum integrator offset, and minimum integrator offset. The output fuzzy sets for maximum integrator offset is of singleton type representing high, low and zero values. Similarly, the output fuzzy sets for minimum integrator offset are of singleton type representing negative high (-High), negative low (-Low) and zero values. Finally, the output fuzzy sets for advised change of accelerator pedal position is of singleton type representing high, low, negative low (-Low) and negative high (-High) values. The fuzzy rules for this controller are described in Table 2. The rules in Table 2 exemplify different HEV conditions, such as steady state and transient together with completely feedback-based corrective, opportunistic and predictive conditions. These conditions are defined by the rule antecedents and the corresponding recommended changes of the upper limit of the accelerator pedal as consequents. These rules are laid out in a manner that they describe and address various different driving conditions where fuel efficiency can be improved and acceptable vehicle performance can be achieved.

Table 2. Rule-base of the second generation Fuzzy Advisory Controller

Rule No.	**If** $\zeta_{\Delta A}$ **is**	**If** vs **is**	**If** a_n **is**	**If** fc_n **is**	**Then** ΔA_{u_lim} **is**	**Then** I_{oft_max} **is**	**Then** I_{oft_min} **is**
1	Low	Low	Low	Low	High	High	Zero
2	Low	Low	Low	High	Low	Low	Zero
3	Low	Low	High	Low	Low	High	Zero
4	Low	Low	High	High	− Low	Zero	− Low
5	Low	High	Low	Low	High	High	Zero
6	Low	High	Low	High	Low	Low	Zero
7	Low	High	High	Low	Low	High	Zero
8	Low	High	High	High	− High	Zero	− High
9	High	Low	Low	Low	− Low	high	Zero
10	High	Low	Low	High	− Low	Low	Zero
11	High	Low	High	Low	High	Low	Zero
12	High	Low	High	High	− High	Low	Zero
13	High	High	Low	Low	− Low	Low	Zero
14	High	High	Low	High	− High	Low	Zero
15	High	High	High	Low	Low	Low	Zero
16	High	High	High	High	− Low	Zero	− Low

Some of these rules perform pure feedback based functions, whereas some of the other rules perform predictive functions and opportunistic functions where they set the appropriate delta accelerator position, integrator maximum offset and integrator minimum offset to anticipate for deteriorating fuel efficiency. Several iterations of experiments using Ford Escape Hybrid, a power-split HEV, were performed under different driving conditions to appropriately and manually calibrate antecedent and consequent membership functions of the fuzzy rules sets. Once the calibration of antecedent and consequent membership functions were complete, experiments were performed for a particular drive cycle or pattern to study the effectiveness of the newly designed proposed controller.

V. EXPERIMENTAL TESTS

To study the behavior of the newly designed controller, experimental tests using Ford Escape HEV, were performed to validate the fuel economy improvements. To quantify the improvement in fuel economy together with acceptable performance and drivability, a specific driving route was selected at Ford test tracks. This test was comprised of both city type and highway type driving along with stop and go regions. In this test, the experiments were performed with and without the use the proposed controller to determine the fuel economy improvement while ensuring acceptable performance or drivability was achieved. Figure 4 shows results from such a test, where the fuzzy advisory controller was not used. This figure shows the actual accelerator pedal position and the vehicle speed. Figure 4 also shows the advised accelerator pedal position if the fuzzy advisory controller were to be used. It can be noticed from Figure 4 that there are regions where the advised accelerator pedal position upper limit is below the accelerator pedal position. These are regions where potential fuel economy can be improved without adversely compromising the vehicle performance or drivability. If the vehicle speed in Figure 4 is integrated over time, we can accurately estimate the distance traveled during this test. The total distance travelled during this test is 3.2547 mi.

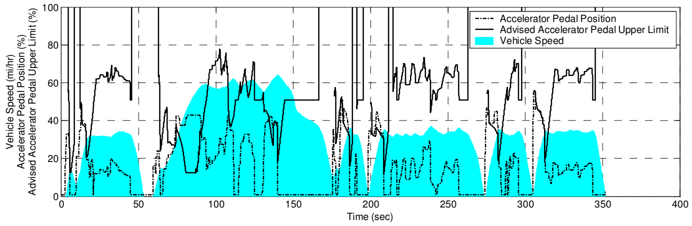


Figure 4. Vehicle speed and accelerator pedal position without using Fuzzy Advisory Controller.

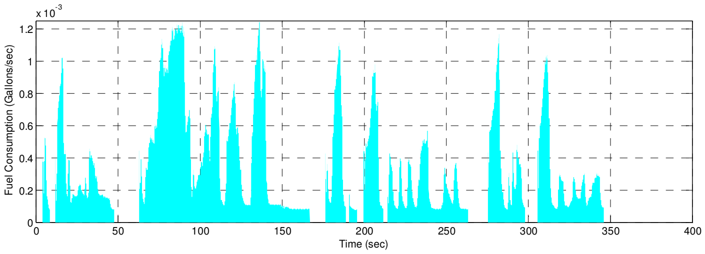


Figure 5. Fuel consumption without using Fuzzy Advisory Controller.

Figure 5 shows the fuel consumption during the same test. By integrating the fuel consumption over time, the total fuel consumed during the test is 0.1052 gal, resulting in a total fuel economy of 30.94 mpg when the fuzzy advisory controller is not used.

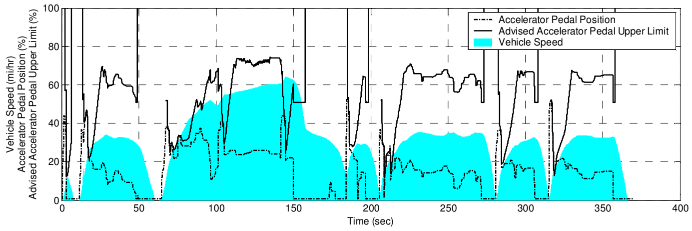


Figure 6. Vehicle speed and accelerator pedal position using the second generation Fuzzy Advisory Controller.

Again, the same test is performed where the fuzzy advisory controller is used and the driver followed the advised accelerator pedal position upper limit. Figure 9 shows the results from such a test. It is clear from Figure 9 that the driver followed the advised accelerator pedal position, which resulted in a smoother vehicle speed profile. By integrating the vehicle speed, it is clear that the total distance travelled is 3.2524 mi, which is very close to the distance traveled when no fuzzy advisory controller was used.

Figure 7 shows the fuel consumption during the same test where fuzzy advisory controller is used. Again, by integrating the fuel consumption over time, the total fuel consumed during the test is 0.0957 gal, resulting in a total fuel economy of 33.98 mpg when the fuzzy advisory controller is not used. It is clear that the use of fuzzy advisory controller resulted in a fuel economy improvement of 9.83% in this real world test while driving this drive cycle with the fuzzy advisory controller only took extra 10secs or 2.9% more time.

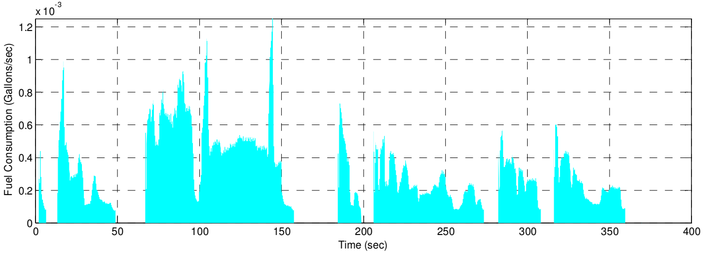


Figure 7. Fuel consumption using Fuzzy Advisory Controller.

IV. CONCLUSION

A fuzzy rule-based driver advisory control system to provide feedback to the driver for improving fuel efficiency without significantly affecting the drivability in HEV has been presented in this paper.

This controller improves on previous work that only improved fuel economy, but failed to address the acceptable drivability criteria. However, the use of the presented fuzzy rule-based driver advisory control system can guide a driver to further improve the fuel economy of the vehicle while maintaining acceptable drivability.

The experimental results comprising both city and highway type driving conditions clearly demonstrated that the fuzzy rule-based driver advisory system with the designed rule sets can provide feedback mechanisms that have substantial affects on improving fuel economy of an HEV. The improvement in the experimental real world driving test was around 10% even when acceptable drivability criteria are met. Hence, this approach provides a very cost effective way of improving the fuel economy of an HEV.

This proposed fuzzy rule-based driver advisory controller provided a method for improving the fuel efficiency in a power-split HEV, which can also be used in conventional vehicles as well. Further research needs to be performed to determine the improvement in fuel economy utilizing such techniques for various types of driver behaviors and driving conditions.

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