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Development and validation of a model to detect active gear via OBD data for a Through-The-Road Hybrid Electric Vehicle

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Abstract: Recently, the possibility of upgrading conventional vehicles to Hybrid Electric Vehicles (HEV's) is gaining interest. Among the different options for hybridization, researchers are focusing on electrification of rear wheels in front-driven vehicles, transforming the vehicle in a Through-The-Road (TTR) parallel HEV. This paper deals with the research work on the development of a kit for converting a conventional vehicle into a TTR Hybrid Solar Vehicle (HSV). In order to develop an effective and safe control strategy for wheel-motors, a precise real-time knowledge of the Driver Intention is required. In particular, the detection of the active gear is needed. In this paper, a mathematical model for the real-time identification of the active gear, using only data measured by the On Board Diagnostics (OBD) port, is presented and validated over on road experimental data.

Keywords: Hybrid and alternative drive vehicles; Automotive sensors and actuators.

1. INTRODUCTION

Despite increasing alarms on fossil fuel depletion and global warming, today the majority of the personal transportation energy comes from petroleum, which is used either in form of gasoline or diesel in conventional vehicles powered by internal combustion engines. Road transport contributes about one-fifth of the EU total emissions of carbon dioxide (CO_2), the main greenhouse gas. CO_2 emissions from road transport increased by nearly 23% between 1990 and 2010, and without the economic downturn growth could have been even bigger. In last decade, Hybrid Electric Vehicles (HEV) have emerged as one of the most effective and feasible alternatives to engine-driven vehicles, allowing significant reductions in fuel consumption and emissions (Sciarretta and Guzzella, 2007).

Furthermore, an increasing attention is being paid to the integration of Hybrid Electric Vehicles (HEV) and Photo-Voltaic (PV) sources (Letendre et al., 2003; Rizzo, 2010), as confirmed by the recent launch of an HEV mounting solar panels by a major automotive company. Hybrid Solar Vehicles (HSV) can give substantial benefits to fuel economy and reduction of emissions, especially in the case of intermittent use in urban driving (Marano et al., 2013). Moreover, their economic feasibility may be achieved in a near future, also thanks to the decreasing cost and to the increasing efficiency of photovoltaic panels (REN21, 2012). The adoption of tracking solar roofs to maximize solar contribution during parking phases, by keeping roof surface orthogonal to solar rays, is also under study (Rizzo et al., 2013).

But, despite the launch of new electric vehicles (EV) and the recent commercial success of HEV's, their market share is still insufficient to produce a significant impact on energy consumption on a global basis. The comparison between expected and actual sales for some recently proposed vehicles is explanatory (Figure 1).

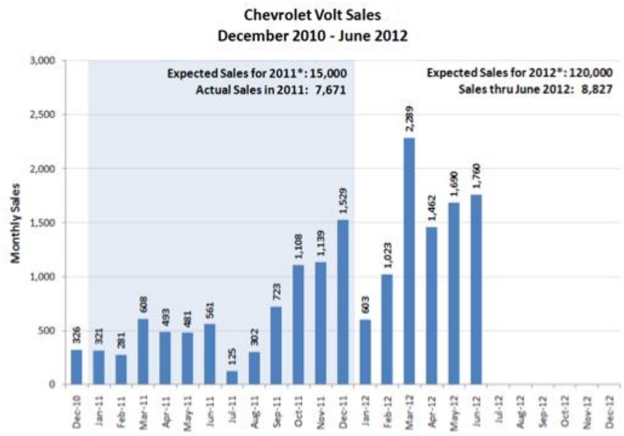

Figure 1 - Chevrolet Volt Sales Vs Expected Sales

Moreover, considering the current economic crisis in most of Western countries, it is unlikely that, in next few years, EV's and HEV's will substitute for a substantial number of conventional vehicles, since relevant investments on production plants would be needed. This fact could of course impair the global impact of these innovations on fuel consumption and CO_2 emissions, at least in a short term scenario.

Therefore, the possibility of upgrading conventional vehicles to hybrid vehicles, possibly PV assisted, is gaining increasing interest. Such a proposal has been recently formulated and patented at the University of Salerno (www.hysolarkit.com). Preliminary studies performed by simulation analysis have shown that the solar hybridized vehicle can achieve significant reduction of fuel consumption, up to 20% in typical urban driving (Rizzo G. et al, 2013). A prototype has been installed on a FIAT Punto (Figure 2, Figure 3).

In last few years, some tools for the hybridization of conventional cars have been proposed, as after-market kits (i.e. Poulsen Hybrid, Landi Renzo). These solutions, including the one presented in this paper, make the vehicle behaving as Through-The-Road (TTR) Hybrid Electric Vehicle. Most of them are based on the use of wheel motors (Yang Y.-P. et al, 2007), considered as a "disruptive technology" for the automotive industry (Murata S., 2012).

In the following chapters, the structure of the hybridized vehicle is presented and the main issues related to vehicle control and to the interactions between the driver and the vehicle are discussed. In particular, a model able to detect active gear using data measured only by the OBD port is developed and validated over experimental results.

2. THE KIT FOR SOLAR HYBRIDIZATION

The hybridizing equipment, installed on a FIAT Grande Punto, consists of:

- in-wheel motors;
- auxiliary Lithium-ion battery pack;
- flexible photovoltaic panels installed on vehicle roof and hood;
- additional control system that interacts with existing vehicle components and optimizes energy flows.

Figure 2 - HySolarKit installed on a FIAT Grande Punto and some wiring details.

Thus, a mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with in-wheel motors. The vehicle is also equipped with an OBD gate (On Board Diagnostics protocol), which allows accessing data such as pedal position, vehicle speed, engine speed, manifold pressure and other variables. In this way, the vehicle can operate in pure electric mode (when ICE is switched off or disconnected by the front wheels) or in hybrid mode (when the ICE drives the front wheels and the rear in-wheel motors operate in traction mode or in generation mode, corresponding to a positive or negative torque).

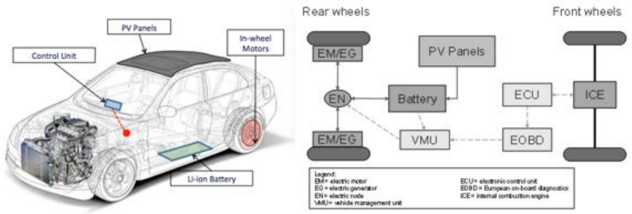

Figure 3 - Hybridization kit and vehicle integration – system schematics.

The Vehicle Management Unit (VMU) implements control logics compatible with typical drive styles of conventional-car users, receives the data from OBD gate, from battery (SOC estimation) and drives in-wheel motors by properly acting on the electric node.

The battery can be recharged by:

- rear wheels, when operating in generation mode;
- photovoltaic panels;
- a regular electric power outlet, when the vehicle is connected to the grid power in plug-in mode.

Table 1 Technical specifications of HSK.

Nominal ICE power [kW]	75
Fuel type	Diesel
Drag coefficient [/]	0.325
Frontal area [m^2]	2.05
Rolling radius [m]	0.295
Rolling resistance coefficient [/]	0.02
Base vehicle mass [kg]	980 kg
PV installed power [kW]	0.280 kW
PV mass [kg]	4.7 kg
Li-ion battery capacity [m]	4.4 kWh
Li-ion battery voltage [V]	96 V
Li-ion battery mass [kg]	45 kg
In-wheel motors power(*) [kW]	14 kW
In-wheel motors mass (*) [kg]	43 kg

A display on the dashboard may advice the driver about the actual operation of the system. A study on the technical and economic feasibility of the hybridization kit confirms that strong reduction of fuel consumption and CO_2 emissions (18-22%), comparable with HEVs benefits, but at lower investment cost, can be achieved. The results show that driving distance and type (urban vs. highway) and the availability of charging infrastructure play an important role in fuel economy, CO_2 emissions savings and pay-back time (Marano et al., 2013). Moreover, in spite of high cost of the flexible PV panels, the solutions with PV panels result in lower pay-back time with respect to solutions with wheel motors only. (G.Rizzo et al, 2013)

3. CONTROL SYSTEM AND DRIVER INTENTION

As previously mentioned, the vehicle management is realized through a Vehicle Management Unit (VMU) that takes data from the OBD port, available in all modern cars. The reason of this choice is to develop a kit that does not require any modifications to the original ECU and does not interfere with its operation. The control strategies implementable on this hybridized vehicle are different from those implementable on a full hybrid vehicle, since the choice of designing a control system parallel to the original ECU poses some specific limitations in terms of driving requirements and drivability. In fact, when the driver steps on the accelerator in the hybridized vehicle, so demanding higher vehicle power, an increase in the engine power will necessarily result; on the contrary, in a 'native' HEV the increase in vehicle power could be achieved even by reducing the engine power and, in parallel, by increasing the electric motor power. Similarly, in the hybridized vehicle a reduction in engine power will be always achieved when the driver releases gas pedal. It has to be remarked that the above limitations could be overcome if a Drive By Wire system would be adopted to decouple accelerator pedal from the original ECU. In this case, however, a more invasive modification to vehicle hardware would be required.

Consequently, the achievement of a given level of power splitting between thermal and electric motor can be obtained by inducing the driver to modulate the pedal position until the desired vehicle power would be reached. In other words, the driver will act as the vehicle is running downhill. On the contrary, the hybridized vehicle can operate in recharging mode when the in-wheel motors absorb part of the power generated by the engine: in this case, the driver will act on the pedal as the vehicle would run uphill.

A study of driver/vehicle interactions is so needed to develop implementable approaches for this kind of vehicle. In this context, the accurate real-time knowledge of the "Driver Intention" plays a fundamental role in order to allow an effective and safe control of the wheel-motors. Actual driving condition is defined by the position of gas pedal, brake pedal and, in cars with manual transmission, gear position and clutch pedal. In the proposed hybridized car, it is assumed that all the information on Driver Intention would be achieved by processing in real-time the data acquired via the OBD port. In this way, the adoption of additional sensors on the vehicle (i.e. gas, brake and clutch pedal, gear position) could be avoided. This would reduce the cost of the kit, and makes it possible the same configuration working on different cars. Since brake and clutch pedal position and active gear are not directly measured, they can be estimated by processing the other variables, and in particular gas pedal position, vehicle speed and engine speed. Braking torque can be computed by real time solution of the longitudinal model, starting vehicle speed and acceleration. The objectives of the OBD data processing are therefore the following ones:

- Detect if the gear is engaged or not and identifying the active gear, including the conditions of null or changing gear;
- Detect if the driver is going to upshift or downshift, since different actions to the wheel motors would be required;
- Estimate the vehicle torque and the engine torque; in particular, detect if a braking torque is needed to the wheel motors;
- Define the rules to drive wheel motors.

Studies on gear shifting strategies for reducing fuel consumption and emissions in both conventional and hybrid cars can be found in literature (Li et al., 2012; Ngo et al., 2012). Moreover, some studies on gear shift prediction are being performed by some OEM (i.e. BMW), within the "Predicting Driving". However, the analysis of the open literature does not evidence studies on gear detection and prediction from OBD vehicle data, similar to the ones addressed in this paper. In a previous paper (Rizzo et al., 2013), the development and the experimental validation of a dynamic model for detecting conditions of null gear has been presented, and a model for active gear detection has been introduced. In the following, this latter model is presented in more detail, and experimental validation over real on-road data is provided.

4. GEAR DETECTION

In order to develop and validate the model, some sets of data acquired with a FIAT Grande Punto in batch mode have been used. As a preliminary step for control applications, the transmission ratios of the active vehicle should be known. These ratios could be calculated from the previous knowledge of wheel radius and transmission ratios at gears and differential, provided by the car manufacturer. Anyway, these values could be identified on the real vehicle, both to take into account possible variations with respect to the theoretical values (i.e. due to effective wheel radius, or to different wheels), and to facilitate the application of the hybridization tool on different cars. To identify the active gear, the ratio *R* between the rotational speed of vehicle wheel and of the engine rotational speed has been defined and analyzed:

$$R=\frac{\omega_w}{\omega_e}=\frac{V60}{3.6\, r_w\, 2\pi\, rpm} \tag{1}$$

where r_w is the wheel radius. This ratio assumes some precise values when a gear is active, that can be calculated by the knowledge of the transmission ratios at the gear and at the differential:

$$\bar{R_\iota} = \frac{1}{\tau_i \tau_d} \quad i = 1, n_{gears} \tag{2}$$

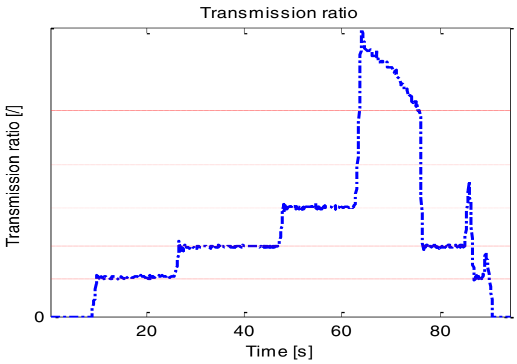

Figure 4 - Actual and reference values of transmission ratio R on a real driving cycle.

In Figure 4 the values computed for R are plotted, while dotted red lines represent the values corresponding to the five gears of the car. These gears refer to the experimental driving cycle whose speed is shown in Figure 6 - . Because of mechanical effects (Backlash, vibrations and elasticity effects in the transmission and in wheel wheel radius) and of the limited resolution of vehicle speed in OBD data, where only integer values are used, the value of R, as defined, is not the same during active gear phases, exhibiting several oscillation respect to a mean value for each gear (Figure 5). Although in most of the driving time the blue line stays over the red lines, so correctly detecting the active gear, there are many points where the active gear is not detected.

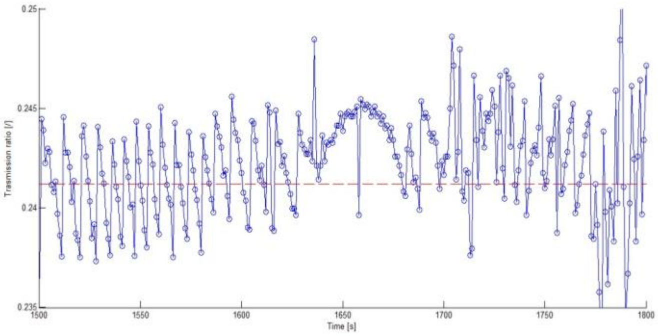

Figure 5 Zoom of Actual and reference values of transmission ratio R on a real driving cycle.

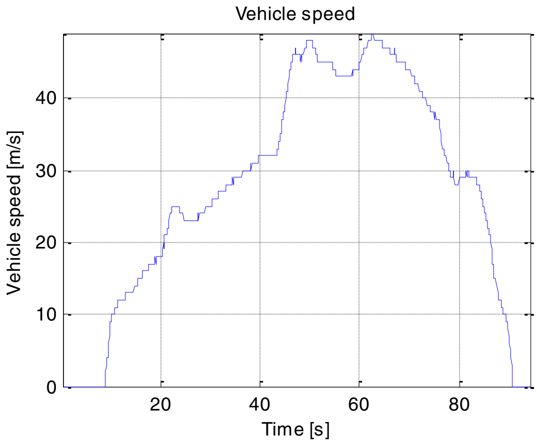

Figure 6 - Vehicle speed for an experimental driving.

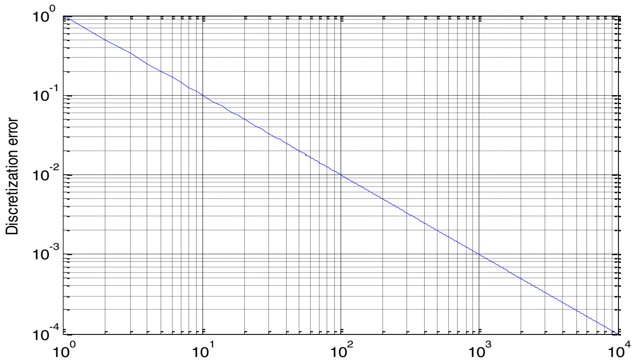

Figure 7 - Discretization error for an integer number vs. variable value.

Of course, this discretization effect of the order of 1/V is almost negligible at high vehicle speed, but becomes very significant when vehicle is running with first gear (Figure 7). Moving averages and digital filtering has been used to process vehicle speed data, to remove the effects of discretization. Reference values of vehicle speed have been obtained with Infinite Impulse Response (IIR) backward zero-phase filtering (filtfilt), in batch mode (use of future data also). Good agreement with reference value has been found by use of filter function (use of present and past data only).

In order to precisely identify the transmission ratios, in the first phase of data acquisition a frequency analysis of R values is therefore performed, assuming that all the gear ratios are used. The identified values are then taken as reference to detect the active gear in the following part of the driving test.

A model to detect current gear has been then developed and tested in real-time on a FIAT Punto. The flow chart is presented in Figure 9. The gear detection algorithm is based on the comparison of measured transmission ratio with the values corresponding to the five gears, considering a variable error range:

$$|R-R_i| \leq 2/v + 0{,}005 \quad i = 1, n_{gears} \qquad (3)$$

The algorithm has been tested over different real-world cycles made on the FIAT Grande Punto prototype. The simulation results have shown that the model has allowed a rather precise detection of the active gear over driving cycles, while some additional uncertainty remains in particular conditions, such as the engagement of first gear at low speeds.

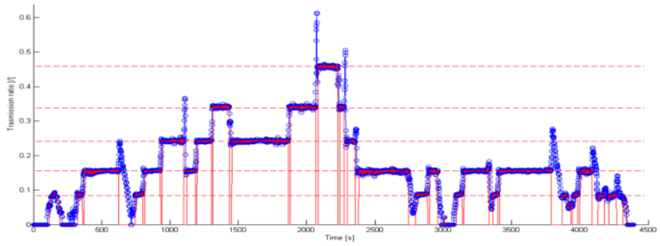

Figure 8 - Actual transmission ratio ad identification of the active gear.

Subsequently a software for on board test has been developed in LabView. In this way it has been possible compute in real time the engaged gear through the OBD port using the algorithm developed in this paragraph. For this end it was used the “MATLAB script” that allows you to integrate Matlab files, with appropriate changes, in LabView in order to be able to process real-time data from the OBD and to view the engaged gear on a notebook. In the front panel of the software, some data of the OBD gate, the engaged gear and the start button are visualized (Figure 10).

In order to validate the algorithm, an on road test has been carried out (Figure 11). A digital videocamera has been posed over the gearstick to compare the recorded time of gear shift with that computed by the algorithm. The knowledge of the reference time for gear shift would allow to optimize the algorithm, analyzing the contribution of each sub-model and identifying their optimal parameters.

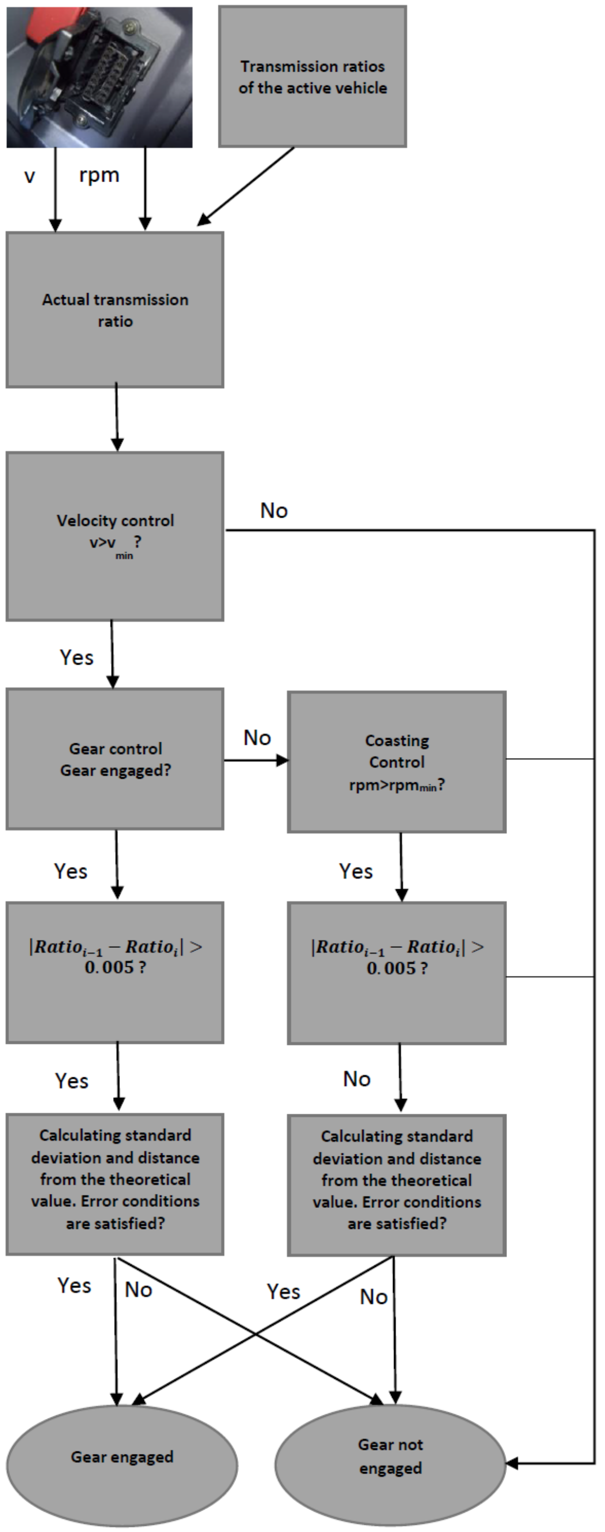

Figure 9 – Flow chart of the model for active gear detection.

A comparison between the video and the data in the same instants of time has confirmed that the algorithm is quite correct in detecting gear shifting. Moreover, the computational time of the model is compatible with time constraints posed by real-time data acquisition and control.

In order to evaluate the difference in time between video and data gear shift, they have been plotted on a graph (Figure 13), comparing to a bisector line: the agreement between computed and measured data is very high indeed.

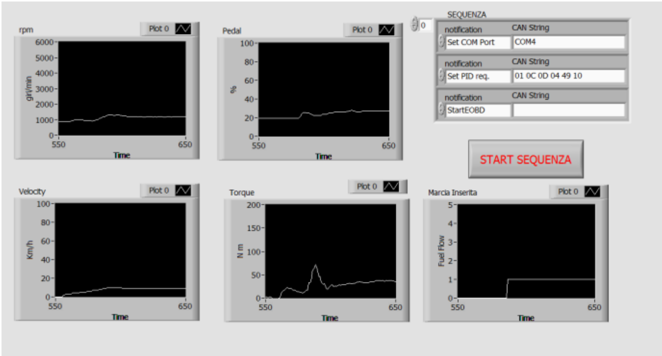

Figure 10 - Front panel of Labview.

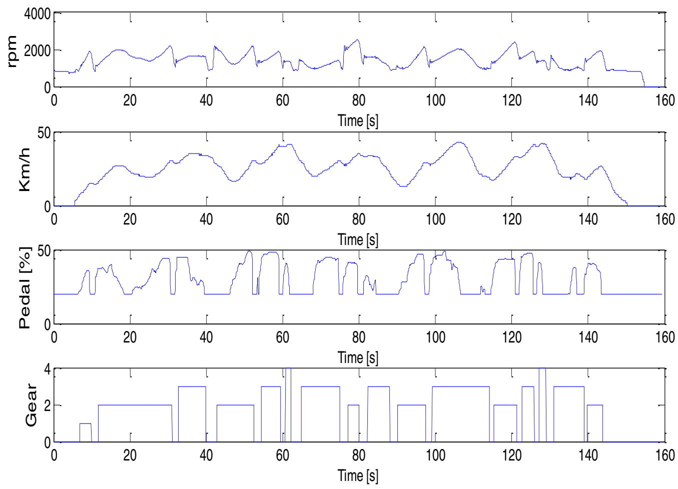

Figure 11 - Vehicle speed, engine speed and active gear for a real cycle.

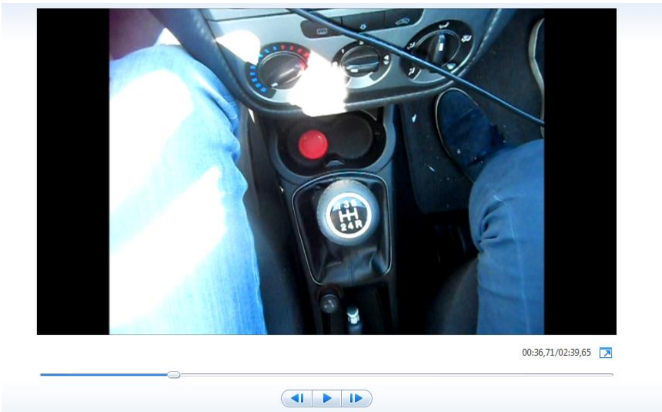

Figure 12 - View of the camera on the gear.

In order to validate the model, a relative error was defined as

$$e = \frac{TgV - TgD}{TgV} \qquad (4)$$

where Tgv is the time of each gear shift on the video and TgD is the time of the same gear shift on the data. The max error is 0,158 % and it has been obtained from a standing start condition in the engagement of first gear at low speeds. Moreover, has been calculated the 2-norm error and its value is 0.1596. The presence of a residual error is expected, since the gear is engaged after the actual release of the clutch, and at that time the value of the measured transmission ratio is still oscillating. In fact, without considering the first gear shift, the max error decreases to 0.0126 % and the 2-norm to 0.0194

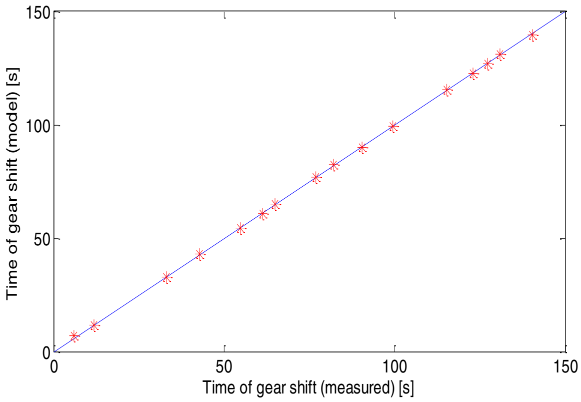

Figure 13 - Time of gear shift on the video VS time of gear shift on the data.

5. CONCLUSIONS

The active gear and engagement conditions are important additional variables in determining the Driver Intention on a vehicle with manual gearbox. The real-time detection of active gear plays therefore a relevant role for the control of a hybridized vehicle. A mathematical model for the identification of active gear, utilizing only data measured on OBD port, has been developed. A suitable mix of filtering algorithms and rules has allowed overcoming the problems due to uncertainty and discretization error in OBD velocity data. The model has been then successfully validated over on road test data measured on a FIAT Punto. The active gear model is being integrated with a dynamic model for detection of null gear into a fuzzy set of rules, to define the correct decision for torque deliver for rear wheel motors.

Further work is in course to develop and implement rule-based energy management strategies, based on the analysis of off-line optimal strategies obtained with Dynamic Programming approach (Pisanti et al., 2013). Future work will be also devoted to improve the aspects related to braking distribution, noise reduction and interaction with ABS/ESP.

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