ABSTRACT

For the last three decades clean automotive technology is the most focused area for the engineers. Clean environment is not a new slogan and there are major contributions put by engineers in the field of automotive design and engineering to protect the environment. Compressed natural gas (CNG) and air engine were introduced to contribute towards the stated objective and the former engine, enhanced the life of conventional diesel or petrol engines to some extent. However, conventional engines due to their power and high torque were never fully replaced.

Thus hybrid concepts were introduced and electric hybrid was the first prime vehicle that fulfills the demands of urban driving but demands of high torque remained the problem for engineers. From the last decade engineers are working on a hybrid vehicle that uses the hydraulic energy to deliver torque and power. Lately, hydraulic hybrid vehicle was invented for urban drive which saved 50% fuel. There are two fluid tanks known as high pressure tank or accumulator and low pressure tank or reservoir. The hydraulic pressure energy which is stored in accumulator is used to turn the wheels. After useful high pressure fluid drops down the certain level then engine turns on and excess energy (also during braking) is stored in accumulator.

In this work comparison of fuel consumed by diesel engine only and diesel hydraulic hybrid was determined. An algorithm is presented which measures the fuel consumption of hydraulic hybrid vehicle. At the end a comparison between hydraulic hybrid and conventional diesel engine is presented for urban driving conditions and also for highway cycle.

The aim is to model the system and then simulate its behavior. For this bond graph technique will be used which theoretically represent the saved energy in the form of graphs. Bond graphs are a domain-independent graphical description of dynamic behavior of physical systems. This means that systems from different domains (e.g. electrical, mechanical, hydraulic, acoustical, thermodynamic and material) are described in the same way. The basis is that bond graphs are based on energy and energy exchange. The research can be used for bond graph application in the field of automotive, hybrid systems. Here hybrid systems comprised of hydraulic and mechanical power sources.

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Muhammad Sajjad

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1.0 Introduction to hybrid technology

The word hybrid means "Mixture or combination of two things" and originated from Greek language. Hybrid vehicles have two or more power sources to attain optimum propulsion and operate vehicle at its peak efficiency [1]. Increasing environmental awareness, rising fuel prices and finishing resources are effecting decisions regarding businesses. All these reasons forced the engineers to find alternative solutions of energy which has relatively low impact on environment and economy. Due to hybrid technology conventional combustion engine demand is reduced and it gives the user two big advantages: comparatively low fuel consumption and relatively less emissions. For the last three decades clean automotive technology is the most focused area for the engineers. Clean environment is not a new slogan and there are major contributions put by engineers in the field of automotive design and engineering to protect the environment. Compressed natural gas (CNG) and air engine were introduced to contribute towards the stated objective and the former engine replaced conventional diesel or petrol engines to some extent. However, conventional engines due to their power and high torque were never fully replaced.

Thus hybrid concepts were introduced and electric hybrid was the first prime vehicle that fulfills the demands of urban driving but demands of high torque remained the problem for engineers. From the last decade engineers are working on a hybrid vehicle that uses the hydraulic energy to deliver torque and power. Lately, hydraulic hybrid vehicle was invented for urban drive which saved the 50% fuel.

1.1 Electric Hybrid vehicle

Hybrid vehicles were launched by combining the conventional engine and the electric batteries. The electric drive system consists of battery, converter (AC to DC), fixed gear, motor (to drive), and the differential gear [2]. Figure 1 shows the structure of electric hybrid vehicle. In hybrid electric vehicles two types of structures are available now a days, parallel and series. In series electric hybrid, traction for the vehicle is obtained by only one central motor. In this way decoupling is possible and this concept (series) may be chosen for two or multi motor propulsion system. In parallel electric hybrid, electric machines and internal combustion engine combines to different drive shaft which drive separately or combine the wheels. The electric energy is stored in batteries and when used for assists (or boost) it can be used. The batteries used for hybrid electric vehicles are characterized by a reduced energy contents and higher power requirements.

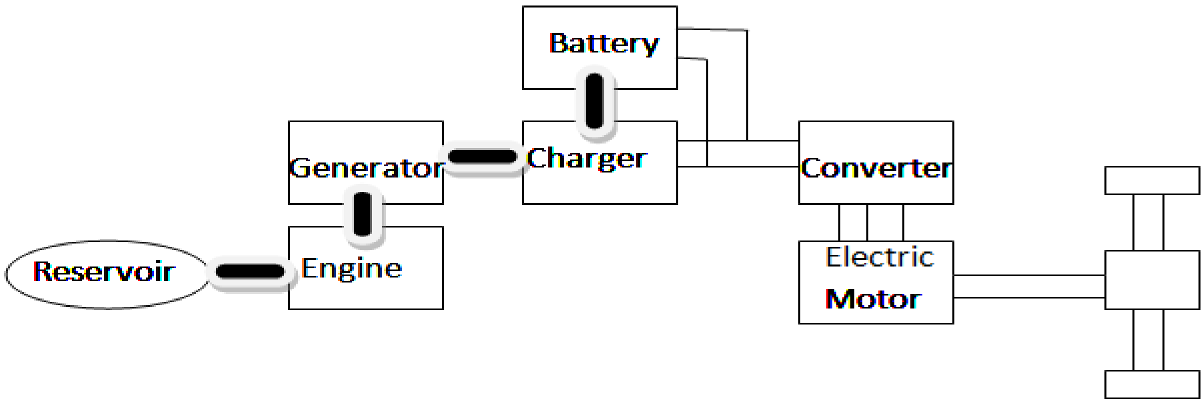

Figure 1.1: Structure of Hybrid Electric Vehicle

Electric hybrid technology has left great impact on automobile industry but still more serious effort needed to develop a valuable product in the market. There are certain issues in electric hybrid vehicles which should be in someone's mind during the design or selection of the vehicle. Batteries are critical part of electric hybrid vehicle which is the only storage component of vehicle. For more storage of energy, batteries of large size will be required and therefore the weight of vehicle will be much higher than conventional vehicle. The energy consumption at the mains of electric vehicles formulated as two mathematical equations which are as under [2]:

For medium to high energy consumption

$$C = 150 + \frac{100}{W}$$

And for normal to low energy consumption

$$C = 80 + \frac{80}{W}$$

Where C is the consumption in KWh/Km and W is weight expressed in tons.

Electric motors used in this type of vehicles should have much higher robustness. There is an expensive alternative but with higher efficiency, permanent magnet motor. There should be compromise between economy and efficiency. Inverters which changes AC to DC normally have very low efficiency which results the loss of regenerative energy, captured during braking. Electric Vehicles needs a proper charging and discharging infrastructure in which complex electrical electric circuits involved and for diagnosis of any fault in the entire system is difficult job. Also power failure and low power density of electric hybrid vehicles are some violent issues. Therefore Automobile engineers shifted his focus to other hybrid technologies like fuel cell, solar vehicle, air engines and more importantly hydraulic hybrid vehicles.

1.2 Hydraulic hybrid Vehicle

Environmental Protection Agency (EPA) USA worked on hydraulic hybrid technology since last decade. The goals of this project were very straight forward [3]. Firstly, to demonstrate the cost effective way to reduce harmful emission of conventional vehicles. Secondly, to reduce mechanical losses. Four sections of the agency (Clean ports USA, Sustainable Ports and Carriers, Northeast Diesel Collaborative, Clean Automotive Technology) worked together to identify incentives. The main theme of the project was to achieve ultra low pollution emissions, increase fuel efficiency and reduce the greenhouse gases. In 2009 a company of USA known as UPS launched its first hydraulic hybrid truck and after the field test claiming up to 70 % fuel economy which is much higher than electric hybrid vehicles.

The prime difference between HHV and other hybrid vehicles like electric hybrids is that instead of sending power to electric motor, which sends power to driveshaft, the accumulator sends its hydraulic energy (in the form of methane or nitrogen gas) directly to driveshaft[4]. As there are less mechanical couplings in HHVs than electric vehicles, therefore mechanical losses are low too. There are some strategies involved in invention of hydraulic hybrid vehicle. Firstly friction energy which normally lost during braking should be captured and then be re-used it. Engine should be shut off at idle, during braking and during regeneration. Regeneration means the phase, during which accumulator gives its energy directly to driveshaft. There are basically two types of hydraulic hybrid vehicles, parallel and series HHVs. In parallel hydraulic hybrid vehicle there exist a direct connection between engine and driveshaft, the pressurized fluid stored in accumulator used to give sudden thrust to vehicle [5]. One big disadvantage of parallel HHVs is that engine is running all the time. Figure 2 shows the structure of parallel hydraulic hybrid vehicle in which a single pump motor connected with engine is used to drive the wheels.

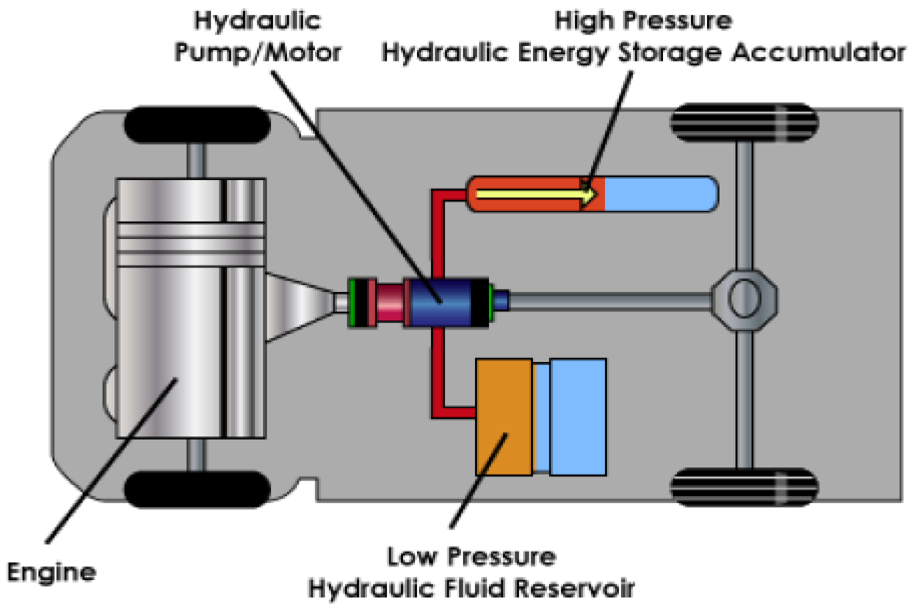

Figure 1.2: Parallel Hydraulic hybrid vehicle [4]

Unlike parallel configuration, series hydraulic hybrid vehicle, there is no direct connection between internal combustion engine and drive shaft. As engine has no direct connection with the road, shut-off strategy is easy in series configuration resulting better fuel consumption than parallel one. The structure of series hydraulic hybrid vehicle is shown in figure 3.

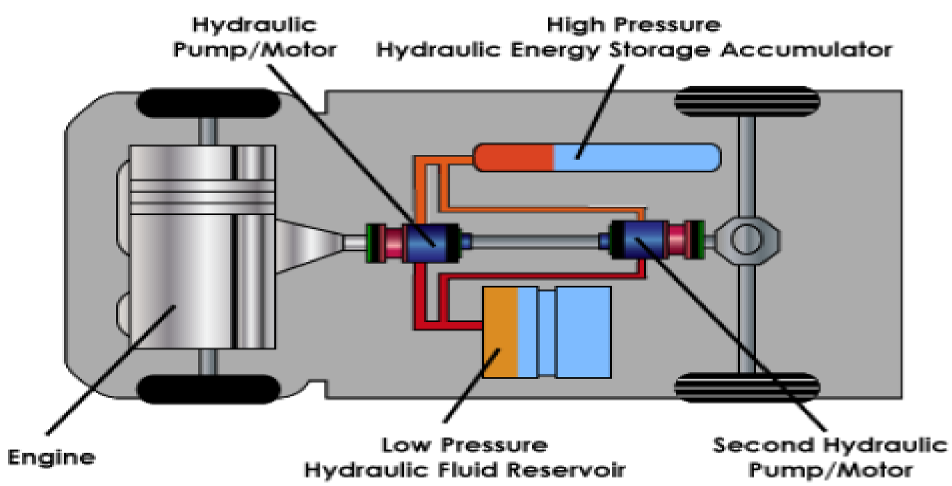

Figure 1.3: Series hydraulic hybrid vehicle [4]

1.2.1 Need of Hydraulic hybrid vehicles

A question suddenly comes in mind is that why HHVs is preferred over electric hybrid vehicles. Zhang Boya [6][2][7][15] and other authors compare different energy storage systems and made a conclusion about the hydraulic hybrid vehicle that in terms of power density, cost and efficiency, it is the best alternative of conventional power source. The main features of hydraulic hybrid vehicles are as follows:-

- High power density but low energy density, certain limit of energy that the accumulator can accumulate. In spite of low energy density, the charging and discharging of hydraulic energy take less time and available at any time when needed
- Braking energy, normally lost during conventional vehicle is captured and reused to drive the vehicles
- Less harmful emissions and so low pollution
- Reliability of functionality of hydraulic system is high and failure risk is very low
- lowest incremental cost
  - ❖ shortest payback to owner
  - ❖ highest lifetime savings
- Fuel consumption is reduced to preserve energy in HHVs
- More economical than other hybrid concepts

1.2.1.1 Why series hydraulic hybrid vehicles?

In series hydraulic hybrid vehicle there is no link between the internal combustion engine and drive shaft. So there is less mechanical loss compared to other vehicles. As now there is no connection with the engine and the road, so this vehicle can permit greater number of on-off strategies and also use the engine at its peak efficiency. Series hydraulic hybrid vehicle is saved 70% of fuel [7]. Engine is operated to pump hydraulic fluid at pressure to the high pressure accumulator (HPA). When there is sufficient pressure in the HPA, the internal combustion engine is placed in an off condition. When pressurized fluid in HPA is dropped down to certain level, a small amount of fluid is directed to the pump/motor to restart the engine, and this unit returns to motoring mode. The rear pump/motor operates the drive train of the vehicle. In motoring mode, it takes high-pressure hydraulic fluid from the accumulator to drive the axle. When braking, the axle drives the unit in pumping mode to re-pressurize the HPA. Braking energy normally lost in friction, recovered and used to drive the vehicles. Sergio et al. did the drive test of series hydraulic hybrid vehicle which they called launch assist mode. They found that on Environmental protection agency (EPA) test cycle, there is reduction of emissions: 21% of hydrocarbons, 30% of nitrides, 27 % of carbon monoxide and 19 % of carbon dioxide. Overall 23 % of fuel saved compared to conventional vehicles. Also Jinyu Qu et al. [8] studied the operational pattern recognition and control for hydraulic accumulator type braking energy regeneration system of bus. Various sensors are used to detect the behavior of bus. The four parameters are used to control the regeneration process which is as follows:-

- Pressure relief switch
- Reverse Switch
- Braking pedal switch
- Accelerating pedal switch
- Bus speed
- Hydraulic pressure sensor

1.3 Components of Hydraulic hybrid vehicle

Hydraulic hybrid vehicle has some extra parts other than internal combustion engine. These are:-

a. High pressure Accumulator (HPA)

b. Low pressure Accumulator (LPA)

c. Hydraulic pump/motor

d. Directional Valves

High pressure accumulator stores high pressure fluid and pressure is up to 5000 psi; while low pressure accumulator is at atmospheric pressure or little higher than it. Hydraulic pump/motor is convertible machine worked both as pump and motor. In accelerating phase it worked as motor while in braking phase, worked as pump to pump the fluid from low pressure accumulator, pressurize it and then send it to HPA. Directional valves usually worked as ON-OFF switch which are controlled by controller. Figure 4 shows the basic components of hydraulic hybrid vehicle and their topology.

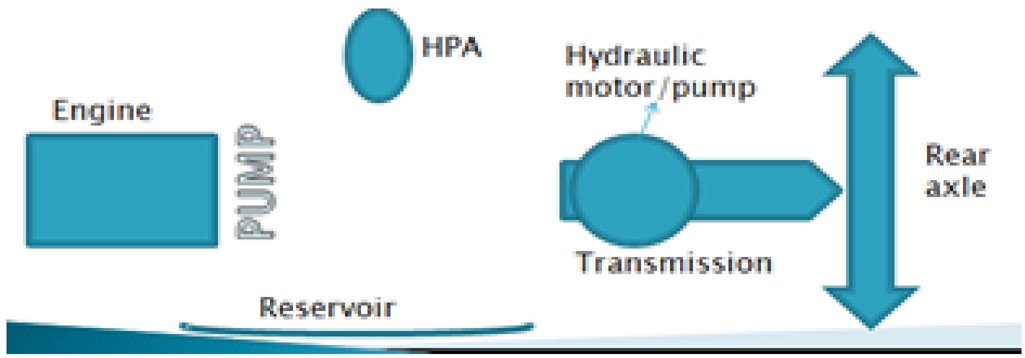

Figure 1.4: Components of HHV

1.3.1 Hydraulic Accumulator

There are two hydraulic accumulators in the system, high pressure and low pressure accumulator. Assuming low pressure accumulator as sump of hydraulic fluid maintain as 35 bar. The state of charge of any accumulator is defined as the ratio of instantaneous fluid volume in the accumulator over the maximum fluid capacity, thus when SOC=0, the accumulator is empty and when SOC=1, the accumulator is full [4]. The volume of accumulator can roughly determine by evaluating the required power to move the vehicle. Figure 5 shows different states of accumulator [9].

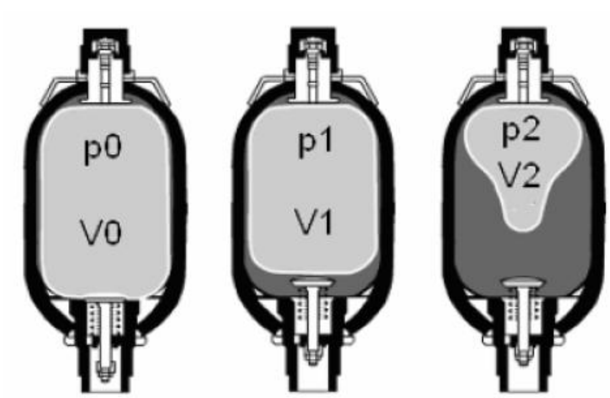

Figure 1.5: Different states of accumulator

Po and Vo is minimum pressure and volume of gas respectively. p1, V1 for pre-charge pressure and volume and p2, V2 corresponds to maximum pressure and volume of high pressure hydraulic accumulator. There are three types of hydraulic accumulators.

- Bladder
- Piston
- Diaphragm

Figure 6 shows the types of accumulator [9].

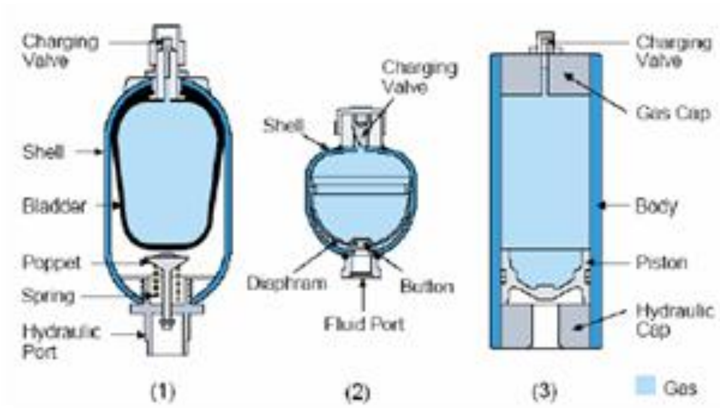

Figure 1.6: Types of accumulators

Sizing of hydraulic accumulators can be done due to power basis, energy storage capacity or desired regeneration time [10].

As we know that hydraulic accumulator is a storage element, stores the hydraulic energy. Mathematically ideal gas law can be applied to model the hydraulic accumulator.

$$p.e = (mg * rg * T)/state\_gas$$

p.e is the pressure, mg is the mass of gas, rg is gas constant, T is temperature (note that temperature increased when fluid entered into hydraulic accumulator) and state_gas is gas volume. The source for the hydraulic power in HHV is high pressure accumulator. The power used by the hydraulic accessories system cannot exceed the available power by the high pressure accumulator. Also, the time for using this power should be within the time taken to discharge the accumulator at a given pressure and flow rate [11]. Also high pressure fluid is used as a ready supply of pressurized fluid in case of power failure and also serves as shock absorber in high velocity flow lines.

1.3.2 Hydraulic Pump/Motor

In hydraulic hybrid vehicle, hydraulic motors convert fluid pressure energy into mechanical energy available at motor shaft. Motors are rotary or piston type, however mostly piston type motors are used in hydraulic hybrid vehicle Two commonly used piston pumps/motors are swash plate and bent axis. The power equations of pumps and motors are exactly opposite which are as follows [12].

PUMP: Power in = Torque * RPM

Power out = Pressure * Flow

MOTOR: Power in= Pressure * Flow

Power out= Torque * RPM

Rotary motors are generally classified in terms of displacement or torque. They can be fixed displacement or variable displacement motors [13]. Fixed displacement motors have constant torque. Variable displacement motors have variable torque and speed. Normally in hydraulic hybrid vehicle variable displacement motors are used. Greg Browne et al. Model the pump as ideal source of flow which loses energy due to pump resistance which is coefficient of pressure [14]. According to energy addition classification, there are two types of pump: dynamic and positive displacement pumps. In dynamic pumps energy is continuously added to liquid to increase its velocity, so the flow rate. Example of this type is centrifugal pumps. Piston pumps are example of positive displacement pumps in which energy is periodically added by the direct force acting on the moving element and energy is independent of applied pressure. Based on the literature survey, we will introduce bond graph in next chapter and also modeling of different components of hydraulic hybrid vehicles in the mentioned modeling tool.

2.0 Introduction

Professor H. Paynter was the first person, who gave the revolutionary idea about bond graph [16]. The idea was further developed by many other authors who were and still now working in multi-domain systems. Bond graph is a modeling tool, which gives a unified approach to model and simulate the dynamic systems: whether it is electrical, mechanical, hydraulic, pneumatic, chemical, thermodynamics and combination of different domains. Dynamic behavior of physical systems can be described by bond graph models and these models are solely depending on principle of power and energy conservation. One of the great advantages of bond graph environment and its simulation is that depending upon the complexity of system; it supports various levels of decomposition [17]. Bond graph gives the graphical representation of physical systems by keeping the topological structure and then provides the computational structure. Topological structure basically tells the important information about the system. It shows the power exchange between different components of the system and also the influencing subsystems' characteristics of different subsystems due to this energy change [18]. On can define bond graph as a diagramming the flow of power and energy within a dynamic system. The structure of bond graph also facilitates the derivation of differential equations that governs the response of dynamic system [19].

Other than bond graph various graphical techniques also using by engineers like block diagrams, signal flow graph and circuit diagrams. Block diagrams consist of blocks and paths. Blocks represent the actuators and paths are basically served as signals and all are interconnected. While in signal flow graph each path in block diagrams is converted into a node and path is replaced by a block, hence one can say that both are dual representation of each other. Both methods solve the computational behavior of the system while the topological structure does not prevail. If a slight change comes in the system, it will change the entire diagram and structure of computation will also be changed [20]. For example take probability function of system of vacuum cleaner, whose prime function is to clean dust from different positions. Here take as two positions A and B as shown in figure 2.1. Now as we know the states of any system is basically the multiplication of number of variables. Here vacuum cleaner has two positions A and B, there is a chance that A has dust or not and in position B also. So there are totally eight states of the system comprised two positions of vacuum cleaner, Chances of dust in A and also in B. so for a state space model, there are eight states available.

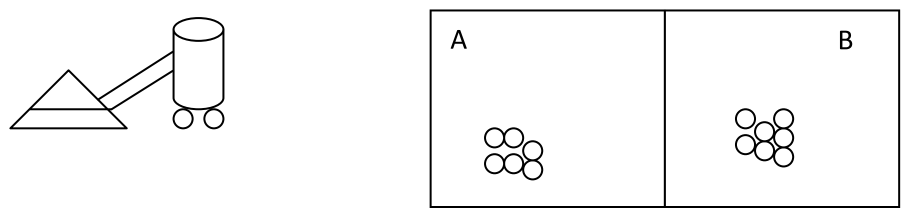

Figure 2.1: Vacuum Cleaner and its positions

As we know state space representation of the system is:-

$$\dot{x} = Ax + b$$

Where x is the states of the system, A is the coefficient matrix and b is the constant matrix. Now in this case A becomes 8*8 matrix. If we suddenly realize that position is 3 instead of two then it becomes 24 states so you have to change your algorithm again. There are basically two variables associated with one power flowing element: one across variable and one through variable, like potential and current respectively in electrical circuits. Block diagrams and signal flow graphs do not give the information of both variables at a time and thus disturbing the topological structure of the system. However circuit diagrams shows the computational as well as topological structure of the system but its application is restricted to electrical circuits. Bond graph is only tool available which models the multi-domain system quite accurately and only concerned with conservation of energy.

A brief introduction of bond graph is presented here. Further details can be found at [21] and [22].

2.1 Power and Energy Variables

First law of conservation of energy states that energy can neither be created nor destroyed but it changes its forms. Hence if the energy is flowing in or out, there must exist a rate of energy (E) per time which is defines as power (P).

$$P = \frac{dE}{dt}$$

In various energy domains two variables when multiplied together give power. Power is basically the combination of two variables: extensive variables, which is proportional to amount and intensive variables, independent of amount. In bond graph language we call them effort and flow variables. Like in electrical circuits voltage (effort) and current (flow) multiply to give power; while in mechanical translational domain, force (e) and velocity (f) combine to give power.

$$P(t) = e(t) * f(t)$$

Effort and flow variables for various energy domains are shown in Table 2.1. A power bond is represented in bond graph as a half arrow showing effort and flow to above and below the bond respectively. Figure 2.2 shows the power bond.

Figure 2.2: Power bond with effort and flow variables

Table 2.1: Effort and Flow variables for various energy domains

Energy domain	**Effort e(t)**	**Flow f(t)**
Electrical	Voltage	Current
Mechanical (Translational)	Force	Velocity
Mechanical (Rotational)	Torque	Angular Velocity
Hydraulics	Pressure	Volume flow rate
Thermodynamics	Temperature	Entropy flow rate
Chemical	Chemical potential	Molar flow

Figure 2.3 shows the mechanical translation system in iconic form, also the bond graph model of the system is given. Due to energy flows in engineering systems, subsystems shows the vertices

of bond graph also knows as bond graph elements (R, C and I in figure 2.3), while edges, called power bonds represents the energy flow between them [23]. Ports have been named to nodes of bond graphs where energy can enter or exit.

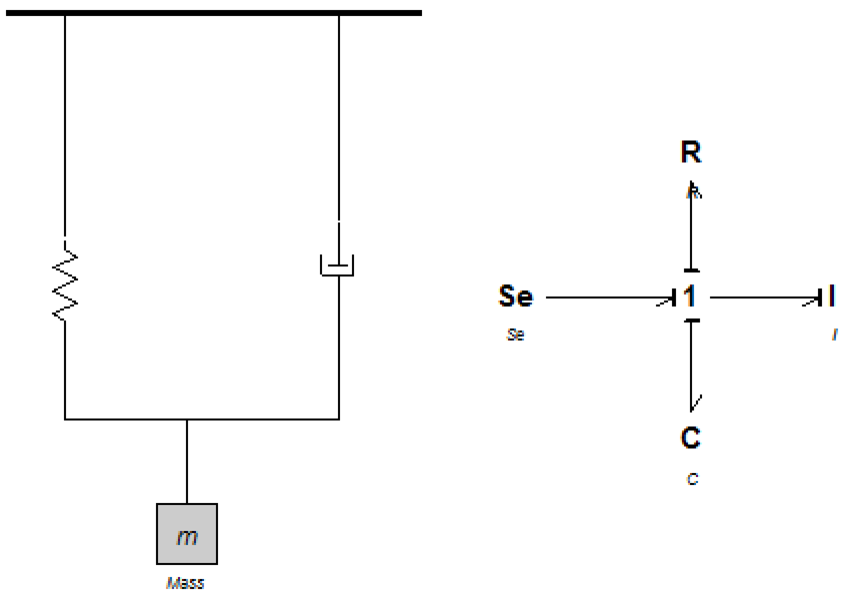

Figure 2.3: A mechanical translation example

Effort and flow are power variables. There are two other variables, the energy variables which can be related to power variables known as generalized momentum p(t) and generalized displacement q(t). The generalized momentum is defined as the integral of effort.

$$p(t) = \int e\,(t)dt \ldots\ldots\ldots.(1)$$

This means that effort is time rate of change of momentum. The generalized displacement is defined as integral of flow.

$$q(t) = \int f\,(t)dt \ldots\ldots\ldots.(2)$$

This implies that flow is time rate of change of displacement. As we know that;

$$E(t) = \int P\,(t)dt = \int e(t)f(t)dt \ldots \ldots \ldots .(3)$$

Putting differential equations of (1) and (2) in (3), we get

$$E(t) = \int e\,(q)dq \ldots \ldots \ldots potential\ energy\ equation$$

And

$$E(t) = \int f\,(p)dp \ldots \ldots \ldots kinetic\ energy\ equation$$

2.2 Bond Graph standard Elements

There are four basic standard elements of bond graph methodology classified as:

1. One port passive elements
2. Basic two active elements
3. Basic two port elements
4. Basic junctions

2.2.1 One port Passive elements

There are basically three on port passive elements named as R, C and I elements. Let discuss them one by one.

2.2.1.1 R-Element

One port resistor is an element in which the effort and flow variables at the single port are related by a static function.

$$e = R * f$$

As there is static relationship between effort and flow so R has open direction of action according to situation of the system. It can take effort as input and flow as output to system and vice versa too.

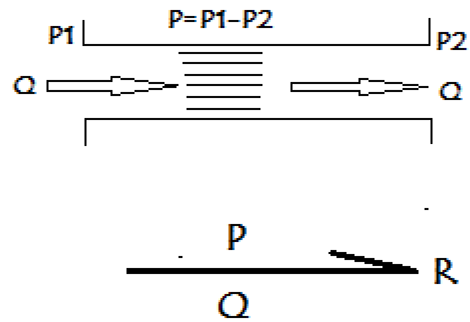

Figure 2.4: Hydraulic Resistor: section of pipeline

Figure 2.4 shows an example of hydraulic resistor (porous plugs) in fluid lines. When fluid is moving in the pipeline then due to line resistance of pipe there is loss of pressure. Power bond of R element is shown in the figure in which P is pressure and Q is volume flow rate. Other examples are electrical resistors and mechanical dampers.

2.2.1.2 C-Element

A one port capacitive element is a device in which a static constitutive relation exists between an effort and a displacement. Such a device stores and gives up energy without loss.

$$q = \int f dt \qquad so \quad e = K \int f dt \ldots \ldots . . (spring\ case)$$

$$q = \int i dt \qquad so \quad e = 1/C \int i dt \ldots \ldots . (capacitor\ case)$$

Also we know that energy stored in capacitor at any time t is

$$E(t) = \int_{q0}^{q} e(t) f(t) dt + Eo$$

Eo is the energy stored at time =0. As C element is storage component so in hydraulics hydraulic accumulator and tires are examples of hydraulic capacitive elements. Figure 2.5 shows the bladder which is an example of C element. Other examples are electrical capacitors, springs, torsion bars, gravity tanks. Remember that in C elements flow is the cause and deformation (effort) is the consequence.

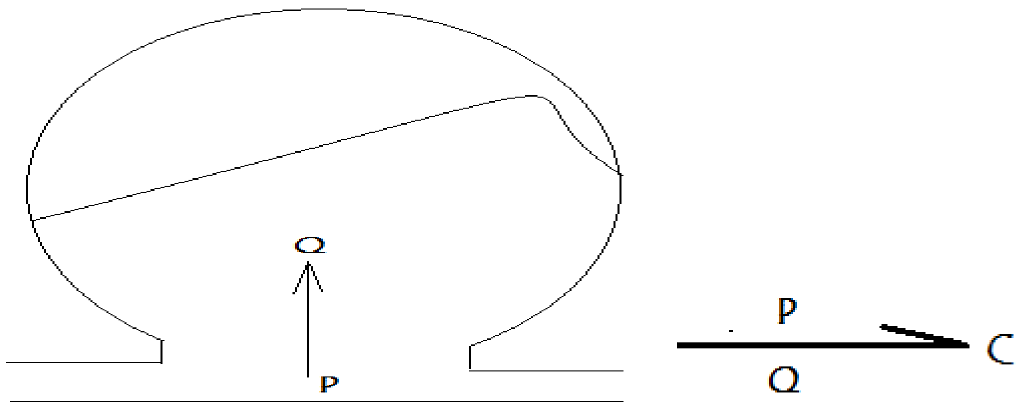

Figure 2.5: Air bladder

2.2.1.3 I Element

If the momentum p, is related by a static constitutive law to the flow f. such an element is called an inertial element.

$$p = \int edt \ldots\ldots so \ \ f = 1/m \int edt \ldots\ldots\ldots. Mechanical\ translational$$

In mass-spring-damper system spring corresponds to capacitive element, damper corresponds to R element and mass is I element which is basically inertia. Power bond of I element is shown in figure 2.6 based on mechanical translational system.

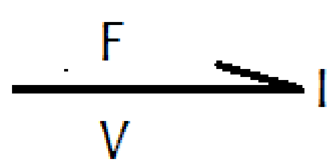

Figure 2.6: Power bond of I element

F is the force which is effort and V is velocity of any mechanical translational system. Other examples are inductance and inertia effect in hydraulic systems. Remember that in I element effort is the cause and flow is the consequences.

2.2.2 Basic two active elements

There are basically two active elements known as sources. They are used as ideal representation of effort and flow sources in systems.

2.2.2.1 Effort source Se

As the name suggests, an effort source supplies the effort into the system, which can be constant or time varying. For example voltage source in electric circuits which sends the information of voltage to system.

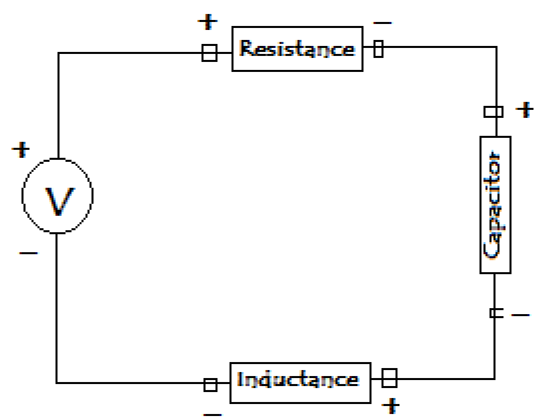

Figure 2.7: An electric circuit

Circuit shown in figure 2.7 has a voltage source which is basically the control parameter of system. if voltage source breaks all the system collapse. Voltage source supplies effort so in bond graph it is known as source of effort (Se). When source of effort is changing by an external signal, that source is modeled in bond graph as modulated source of effort (MSe) .

2.2.2.2 Flow source Sf

Flow source supplies flow to the system, like velocity input which comes out from the shaker. For example a small pump is mounted to give the water above ground. Now pump act as source of flow. Also in electric circuits current source is source of flow. like MSe there is MSf if there is external signal controlling the Sf.

2.2.3 Basic two port elements

There are two two-port elements; Transformer and gyrator.

2.2.3.1 Transformer

Transformer does not create, store or destroy energy it conserves power and transmits the factor of power with proper scaling.

$$\frac{e1}{f1}\ \ddot{TF}\ \frac{e2}{f2}$$

$$e1 = r * e2\ and\ f2 = r * f1 \ldots.r\ is\ modulus\ of\ transformer$$

Figure 2.8 shows the hydraulic ram which is modeled as transformer in bond graph.

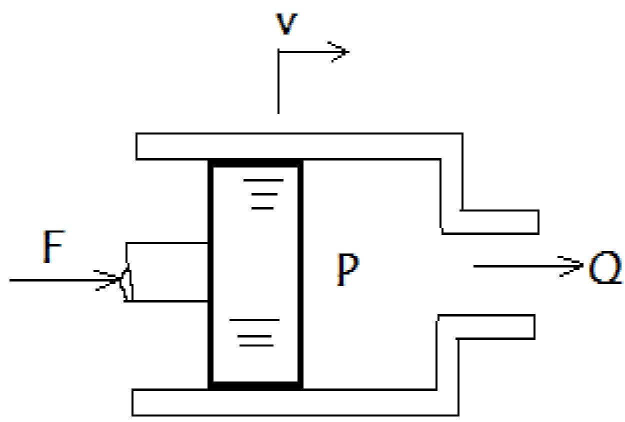

Figure 2.8: Hydraulic ram

Ram is moving with velocity v as a result of effort F. it resulted the increase in pressure and therefore flow is bit higher than normal. Here F changed to P, v changed to Q and modulus is area of piston. Mathematically it can be written as:-

$$F = AP \ldots\ldots\ldots\ldots..AV = Q$$

F/P which is e1/e2 is equal to Area, which is modulus of transformer.

2.2.3.2 Gyrator

Transformer relates effort to effort and flow to flow while gyrator relates effort to flow and flow to effort. In general, gyrators are used in most of the cases where power from one energy domain is transferred to another, viz. electrical to rotational, electric to magnetic and hydraulic to rotational.

$$\frac{e1}{f1}\ \ddot{GY}\ \frac{e2}{f2}$$

$$e2 = u * f1 \; and \; e1 = u * f2 \; \ldots . u \; is \; modulus \; of \; gyrator$$

Figure 2.9 shows the electrical gyrator modulus of gyrator is voltage of first circuit divided by flow of second circuit.

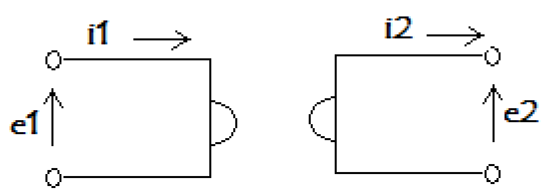

Figure 2.9: Electrical Gyrator

2.2.4 Basic junctions

Now for interconnecting the elements two kinds of junction are introduced in bond graph named as 1 and 0. They conserve power and are reversible.

2.2.4.1 1 Junction

1 junction has equality of flows and efforts some up to zero with the same power orientation. Such a junction can represent a:-

a. Common mass point in a mechanical system
b. Series connection in electrical network (same current flow)
c. Hydraulic pipeline (flow continuity)

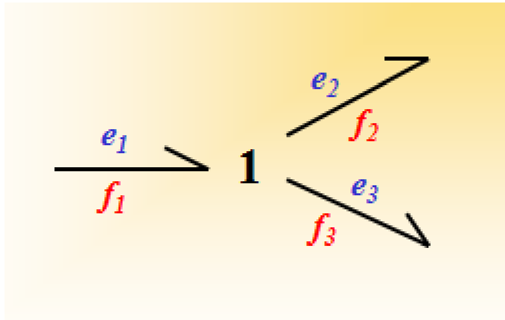

Figure 2.10: 1 Junction

$$f1 = f2 = f3 \ \ and \ e1 + e2 + e3 = 0$$

2.2.4.2 0 Junction

0 junction has equality of efforts while the flows sum up to zero. Such a junction can represent a:-

a. Mechanical series
b. Electrical node point
c. Hydraulic pressure distribution point or pascalian point

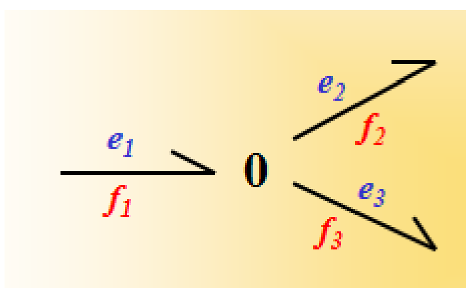

Figure 2.11: 0 Junction

$$e1 = e2 = e3 \ and \ f1 + f2 + f3 = 0$$

2.3 Causality

Causality establishes the cause and effort relationships between the effort and flow variables. In bond graph, causal stroke indicates the input and output variables. The causal stroke indicates the direction in which effort signal is directed. If the end of the bond has not causal stroke, then the flow signal is directed towards this end. Causality of storage elements assigned keeping in mind the integral form of the respective element. Figure 2.12 shows the causal elements.

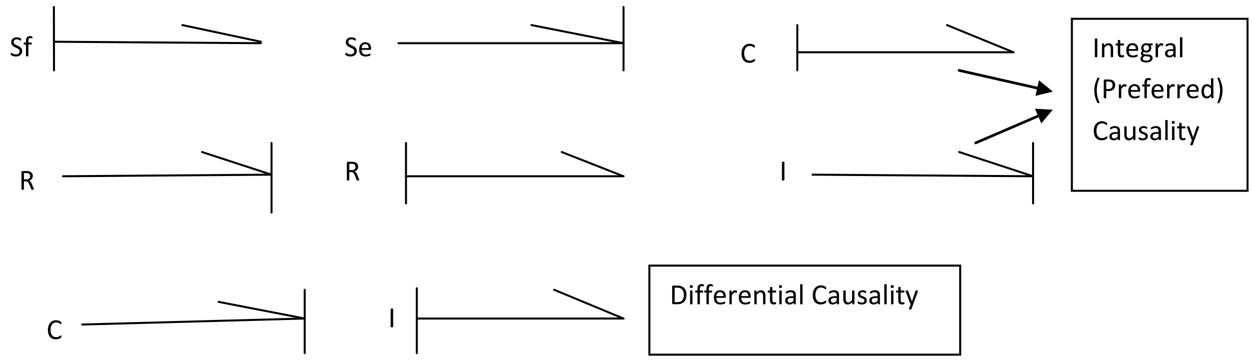

Figure 2.12: Causality of elements

Causality of R element is free. Preferred causality of C element is that it takes flow and gives back the effort to system. While integral causality of an inertial element is that it takes effort from the system and gives back the information of flow.

2.3.1 Why to avoid differential Causality?

Sometimes the causal strokes will have to be inverted, which means the causality of storage elements is inverted from its integral causal form. Now the constitutive relationship for an element is written as a differential equation. For example velocity in a spring is the derivative of force over stiffness. Such causality pattern is called differential causality. Now the question is why we have to avoid differential causality? Firstly the signal returned from the differentially causally element is the time derivative of that signal which is received by element [24]. For example let take an example of linear spring in which velocity is proportional to derivative of effort signal i.e.

$$f = \frac{1}{K}\frac{de}{dt}$$

Derivative is not a causal operator. To find the derivative of effort, there are two ways forward and backward differentiation.

$$\frac{de}{dt} = \lim_{\Delta t \to 0} \frac{e(t) - e(t - \Delta t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{e(t + \Delta t) - e(t)}{\Delta t}$$

In the second form of derivative, to find the present value of e the future value is necessary which seriously violates the notion of causality. One may say that a differential causality may disturb the energy balance of the system.

2.4 Word bond graph of hydraulic hybrid vehicle

As already discussed the components of hydraulic hybrid vehicle, here in this section we applied the concept of bond graph on this vehicle. As source is pump which is connected to engine, pump usually taken as source of flow. Controller sends signals to almost every components of vehicle. Accumulators are energy storage element which is denoted as C element. Motor uses energy and dissipates as heat, so it is modeled in bond graph as R. Full model will be discussed in chapter 4, 5 and 6. Figure 2.13 shows the word bond graph of hydraulic hybrid vehicle. Modulated transformer is used here not to transform effort and flow but for switching, as valves.

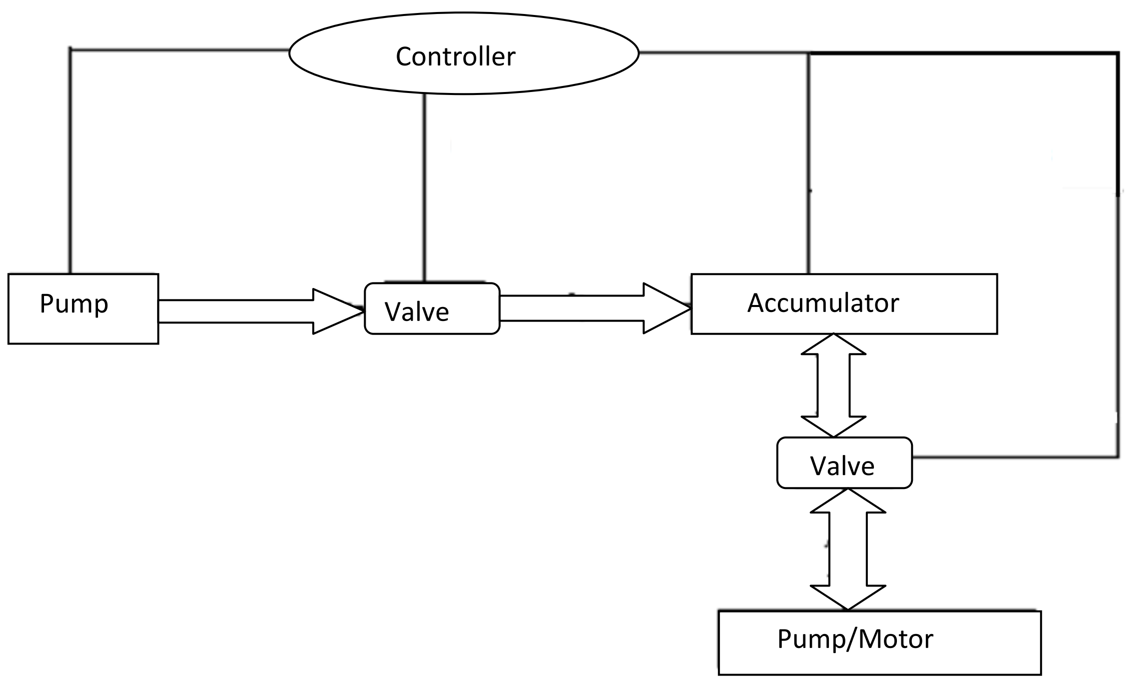

Figure 2.13: Word Bond Graph of Hydraulic hybrid vehicle

The flow from accumulator to pump is not possible whereas accumulator to motor and motor to accumulator are possible. Valves are basically switching elements controlled by controller.

3.0 Introduction

Last few decades have seen efforts towards minimization of fuel consumption and emissions of vehicles. Recent technologies like compressed natural gas, bio-gas and hybrid electric vehicles just not only to clean environment but also to minimize the fuel consumption. Low-power density of batteries is a big problem in hybrid electric vehicles. Maximum efficiency could be attained in an internal combustion engine by pointing some points like cylinder volume would be as large as possible with minimum boundary surface [25]. Working speed of engine should be greatest to achieve favorable efficiency. Also the pressure at the beginning of expansion and expansion ratio would be greatest. Fuel consumption of an internal combustion engine is an important parameter to predict the behavior of an engine in terms of economy and working. Diesel engine was invented by Rudolph Diesel in 1897 by injecting the liquid fuel directly into the combustion chamber. For this the air in combustion chamber should be more heat up than spark ignition engine so that by mixing fuel with heated air suddenly catches fire that's why diesel engine has comparatively very high compression ratio. Like SI engine, diesel engine cycle has also four strokes namely intake, combustion, evaporation and exhaust [26]. The main difference is in diesel engine there are no carburetor and spark plug. Flow of fuel is controlled by either governor or pump, situated in fuel tank. Indicated torque has given much information regarding engine performance. Also indicated torque plays an important role for fault diagnosis of engine combustion and fuel tuning [27]. As all know indicated torque can be calculated from the measurements of cylinder indicated pressure. Once an indicated torque of an engine would be known then it is easy to measure the angular velocity and torque at wheels by imposing the load torque of engine. Different authors implemented different ways to model the diesel engine [28] [29]. One method is to present the comparison of representation model which is basically the identification of the system with the knowledge model which contains algorithmic description. Mean value modeling of diesel engine was presented by various authors in which simulated and experimental performance parameters was presented for both steady state and dynamic operation.

In this chapter comparison of fuel consumed by diesel engine only and diesel hydraulic hybrid was determined. An algorithm is presented which measures the fuel consumption of hydraulic hybrid vehicle. At the end a comparison between hydraulic hybrid and conventional diesel engine is presented for urban driving conditions and also for highway cycle.

3.1Vehicle model

Different vehicle's models have been presented by different authors in literature. All have their own criteria to simulate the vehicle behavior. Mike Blundell et al. model the vehicle by splitting the model into four sub models, chassis (suspension, steering, brakes, tires), engine (valve train, crank train, chain belt, acc. drives), driveline (transmission, clutch, differential, Axles) and body (body-in-white, frame, seating, restraint) [30]. Also modeling of vehicle has been done on control strategies [31]. Iconic modeling of hydraulic hybrid bus is presented in [32]. Here our prime focus to investigate the hydraulic part of vehicle, the mechanical part is here to establish the demand of torque and speed. Also it also determines the resistances offered to vehicle. A vehicle driven on the road generally influenced by following forces [33]:

- Aerodynamic force
- Rolling force
- Force caused by gravity
- Disturbances from environment

Mathematically it has the form,

$$mv * a = Ft - (Fa + Fg + Fr + Fd)$$

where m_v is the mass of vehicle, a is the acceleration of vehicle, Ft is the tractive force needed to propel the vehicle, Fa is the aerodynamic resistance, Fr is the rolling resistance, Fg is the gravitational resistance when vehicle is not on the horizontal roads and Fd is all disturbing forces. Neglecting Fd, the mathematical description of other forces are as follows.

3.1.1 Aerodynamic resistance

Force caused by air on vehicle is written mathematically as:-

$$Fa = \frac{1}{2} * \rho a * Af * Cd * v^2$$

Where ρa is the density of air, Cd is is coefficient of aerodynamic resistance, Af is frontal area of vehicle and v is the velocity of vehicle.

3.1.2 Rolling Resistance

Usually rolling resistance Fr, is modeled as

$$Fr = Cr * mv * g * \cos(\propto)$$

Where Cr is the coefficient of rolling resistance, g is gravitational constant and α is for non horizontal roads.

3.1.3 Gravitational resistive force

When vehicle is moving on the non-horizontal roads, the resistive force influences the vehicle behavior. This force written as mathematically:

$$Fg = mv * g * \sin(\propto)$$

All these resistive forces combines with inertial component of vehicle give the desired tractive force which must be needed to propel the vehicle. Table 1 shows key parameters of vehicle.

Mass of vehicle	5000 Kg
Density of air	1.29 Kg/m^3
Frontal area of vehicle	4.5 m^2
Cd	0.3
Cr	0.015
α	0
Radius of tire	0.468 m
Road pattern	ECE city cycle

Table 3.1: Key parameters of Vehicle used in this research

ECE city cycle is basically the MVEG-95[9] European test cycle, which typically shows the driving pattern of vehicle. There are frequent gear changes in the cycle which is evident for those who used to drive vehicle frequently in cities. Hydraulic hybrid vehicle was invented primarily for cities and for there where stop and go condition occurs. On highway HHVs are similar to any of other conventional vehicle because no braking occurs on highway and due to that no regeneration can takes place. So concept of fuel minimization in HHVs is only valid when vehicle is moving in the city. ECE city shown in figure 3.1 gives the vehicle speed for 200 seconds. Repeating four times gives to complete cycle. However for understanding the model in its true form, let the cycle to 200 seconds. A simple block diagram model was established to get the torque as output. Figure 3.2 shows the block diagram model of vehicle. 20 SIM is used for modeling the vehicle.

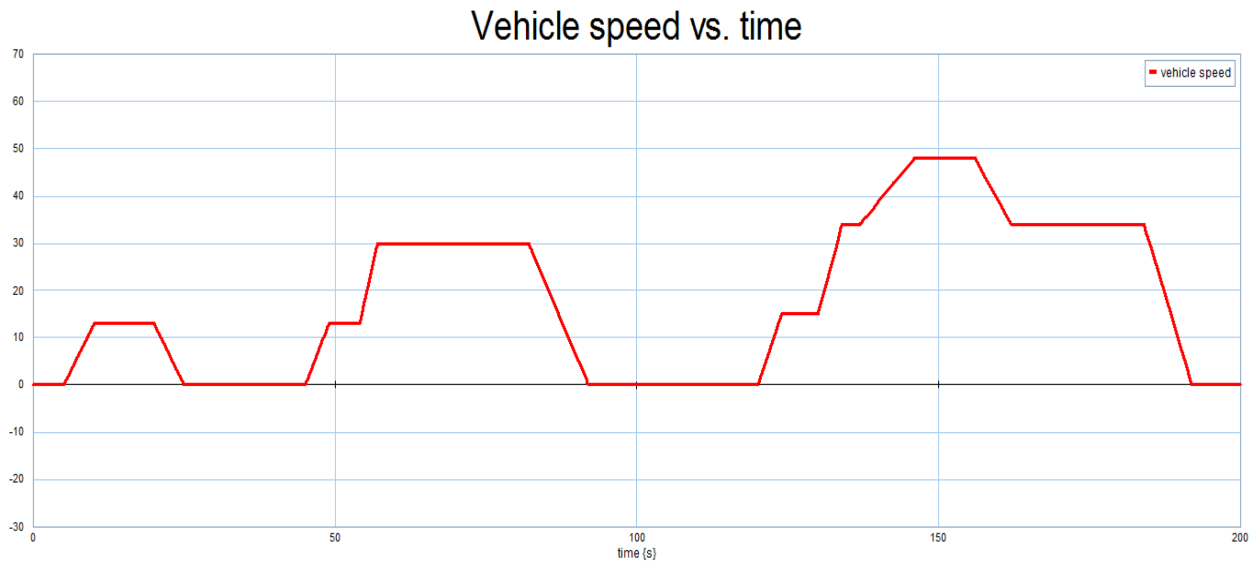

Figure 3.1: ECE city cycle

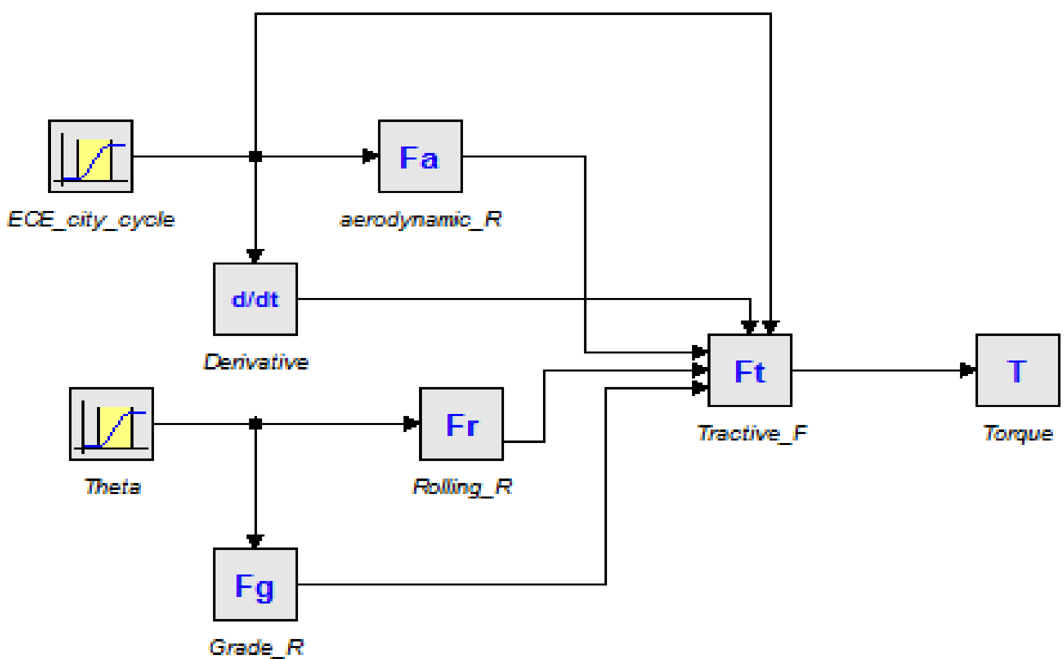

Figure 3.2: Vehicle model

Derivative block gives the acceleration of the vehicle by derivation the vehicle speed which is coming from ECE city cycle. Theta is basically the grad ability of the road which we take zero in our analysis. Ft is the tractive effort which is sum of aerodynamic, rolling and grade efforts. Multiplying the tractive effort with radius of tire gives us the torque of vehicle which is demand in our system.

3.2 Fuel Comparison

As already mentioned the invention of hydraulic hybrid vehicle took place just to ensure that fuel should be less consumed and extra energy which lost in environment would ripple back to vehicle to move the vehicle. Energy like friction lost in braking can be recovered and use when desirable. So for this purpose while braking vehicle kinetic energy is a source to pressurize the fluid in the high pressure accumulator and when needed, hydraulic energy can be transformed in to kinetic energy. The parallel HHVs are different from series in this regard that in parallel configuration engine is running all the time. However series hydraulic hybrid vehicle shuts off the engine also when the vehicle is in idle mode. So series is 70 percent fuel efficient while parallel is 40 to 50 percent in urban conditions according to environmental protection agency USA (EPA). Note that this efficiency is only for city traffic, on highway it is same as conventional vehicle because stop and go is desirable in case of hydraulic hybrid vehicle. The strategies which increase average vehicle efficiency in case of series hydraulic hybrid vehicle are as under:-

- Energy lost during braking is captured and re-used it. (Regenerative braking)
- Shut off engine at idle
- Shut off engine while braking
- Shut off engine while the vehicle is in regeneration mode
- Vehicle must be used in city traffic (recursive stop-go situation)

For fuel consumption at constant throttle note the last two points, however here did not account for regeneration because at regeneration engine is also off. Hence algorithm developed here that engine is off when the vehicle is stopped and while braking. Note that test cycle comprised of city and highway cycle, distance of 11.4 Km and duration is 1200 sec. Figures 3.3 and 3.4 shows the results of volume consumed by conventional engine on city and highway cycle respectively.

Now for throttling, consulting our automobile lab in college, an engine had been found with their fuel Pump characteristics. Manufacturer's plot of volume flow with rod position and crankshaft shaft speed had been found. Engine and fuel pump specifications are shown in table 3.2.

Engine Model	HINO EC 100	**Pump Type**	Bosch, Nippon Denso
Engine Type	Diesel 4 stroke, 6 cylinder, in line, water cooled	**Rod positions**	5 to 8 mm
Bore & Stroke	70 - 113 (mm)	**Pump revolution**	½ * engine rpm
Piston displacement	5.01 liters	**Density of fuel**	840 Kg/m^3
Compression ratio	20.3 : 1	**Hu**	42.5 MJ/Kg
Weight of engine	450 kg	**Density of air**	1.29 Kg/m^3

Table 3.2: Engine and Pump specifications

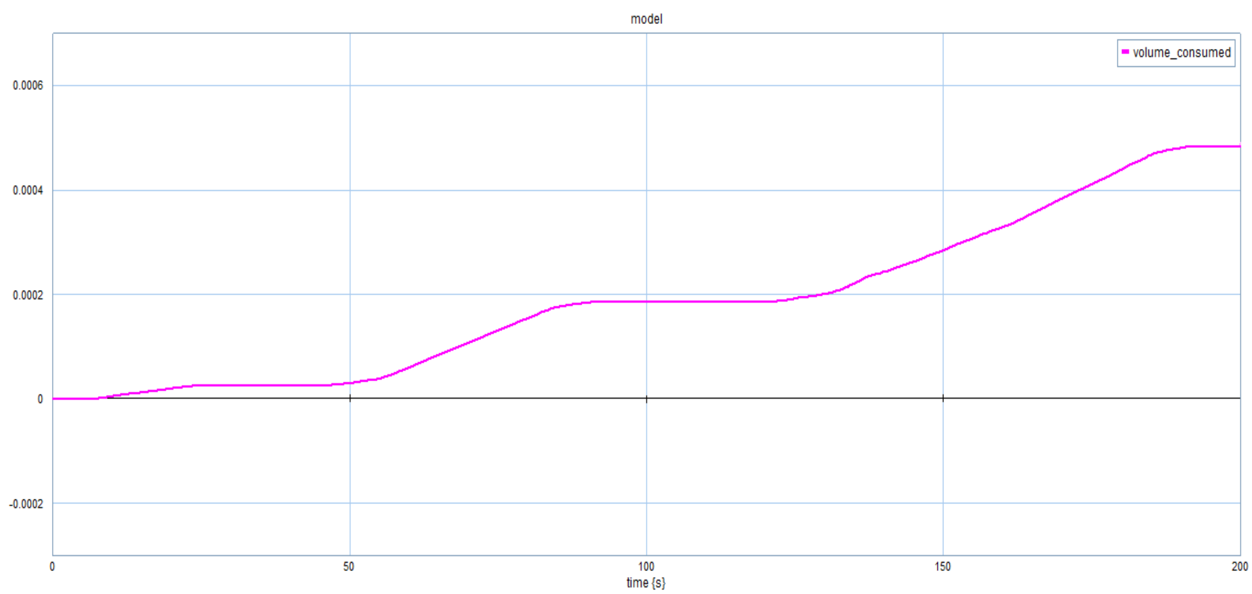

Figure 3.3: Volume Consumed by IC engine (City cycle)

On city cycle total distance is almost 4 km and fuel consumed by conventional engine was 2 liters while on highway cycle total distance is 7.4 km and fuel consumed by engine was 2.1 liters. By looking two values, it is strange to compare both of them. The reason is that in city cycle, there are too much stops and braking and engine was running at the time. Unlike city traffic, on highway cycle there was a smooth running and fuel was almost burnt while the vehicle is in motion.

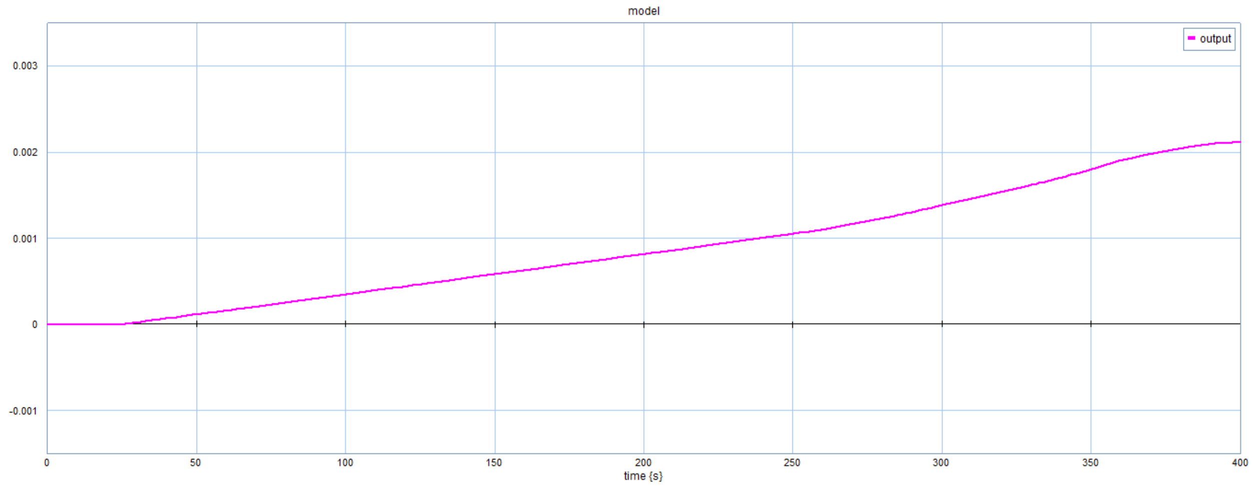

Figure 3.4: Volume Consumed by IC engine (Highway cycle)

As mentioned before most of the fuel energy lost while braking and idling. Applying algorithm based on hydraulic hybrid vehicle to simulate its behavior. Figures 3.5 and 3.6 show the fuel consumed by series hydraulic hybrid vehicle on city and highway test cycle.

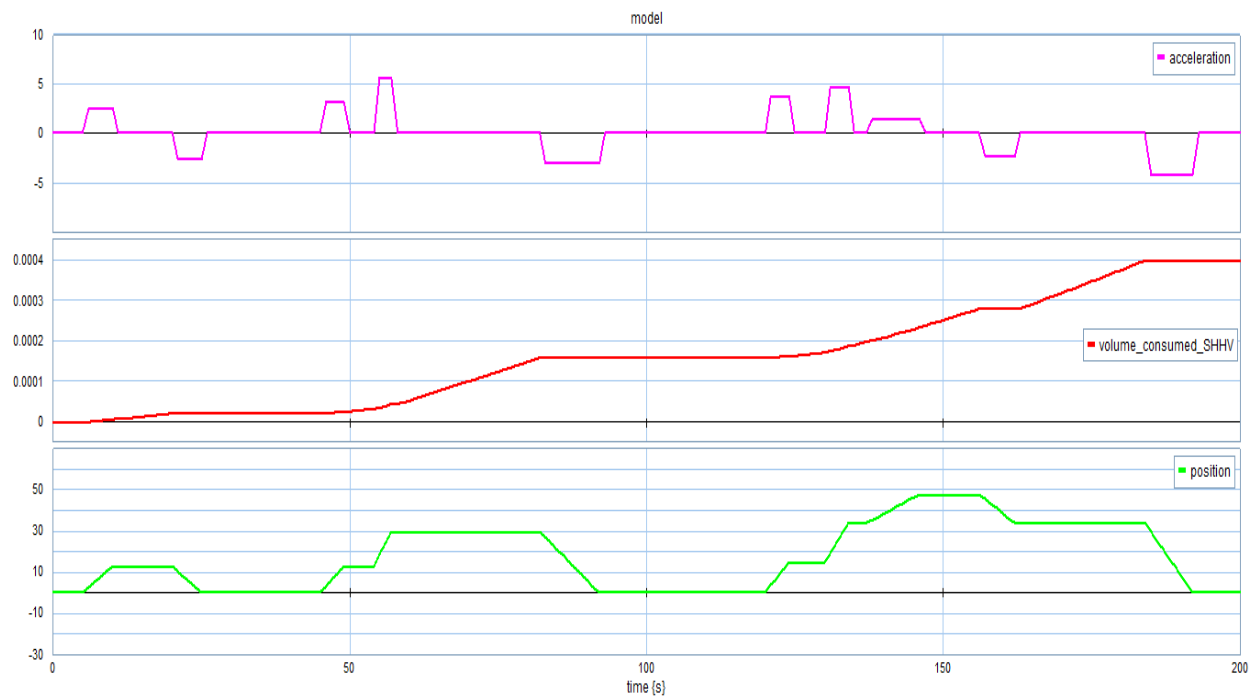

Figure 3.5: Volume Consumed by SHHV (City cycle)

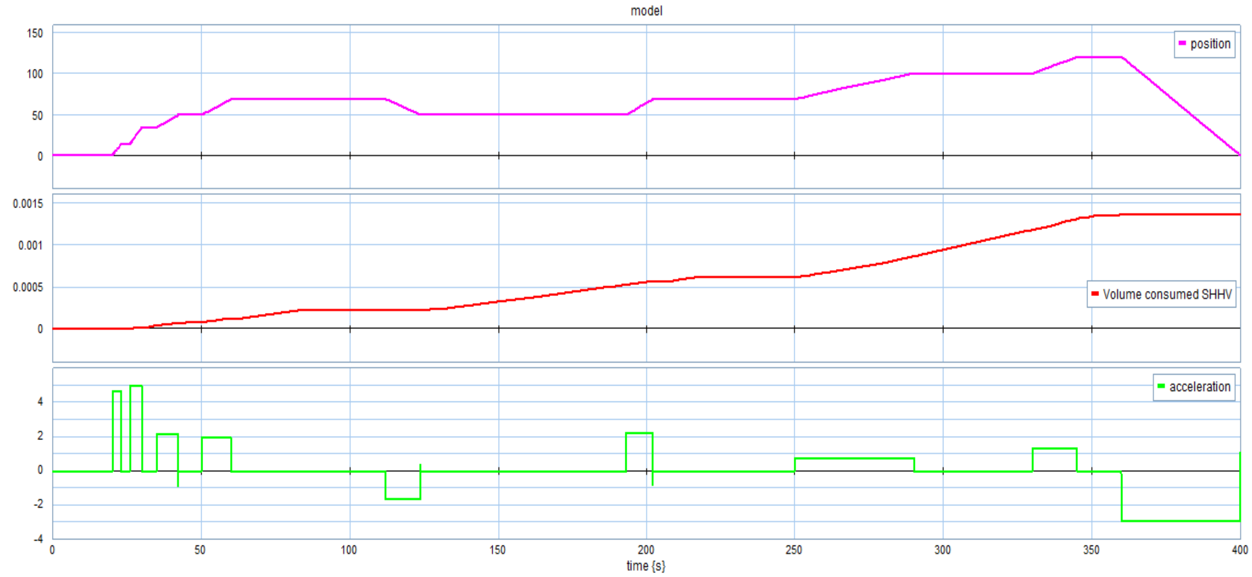

Figure 3.6: Volume Consumed by SHHV (Highway cycle)

It is obvious from above two graphs that engine shuts off when the vehicle has been idling and braking. Thus fuel energy lost was saved and lost energy would be recovered in case of HHV. Table 3.3 shows results of volume and mileage of ECE city and EUDC highway cycle. So cycle of 11 km saves almost 1 liter fuel while considering both city and highway cycle. Limiting to city cycle about 50 % of fuel saved in 1 km of 200 seconds. More distance the vehicle travel, the percentage of saved fuel increased.

	ECE city cycle			
Time (second)	**Fuel consumed (liters)**			**Distance (km)**
	Conventional engine	**SHHV**	**Difference**	
0-200	0.4	0.21	0.1	0.98
200-400	0.5 (0.9 total)	(0.46 total)	0.1	0.99 (1.97 total)
400-600	0.5 (1.4 total)	(0.7 total)	0.1	0.98 (2.95 total)
600-800	0.5 (1.9 total)	(0.87 total)	0.1(0.4 whole cycle)	0.99 (3.94 total)
	EUDC Highway cycle			
800-1200	2.1	1.4	0.7	7.3

Table 3.3: Fuel consumption results

3.3 Conclusion

Fuel consumed by conventional vehicle and series hydraulic hybrid vehicle has been determined according to European test cycle (ECE city cycle + EUDC highway cycle). 54% of fuel saving in city cycle while percentage of fuel saved on highway cycle is 33%. For the complete cycle comprising city and highway cycle, 43% of fuel can be saved in series hydraulic hybrid vehicle. More the distance vehicle has been covered percentage of fuel saved would be increased. Environmental protection agency (EPA) USA tested the series hydraulic hybrid vehicle made by UPS on its test area and it was concluded that vehicle has been fuel efficient up to 70%. However this result was totally based on city traffic. So hydraulic hybrid vehicle is successful in city traffic where too much stop and braking resulted regeneration phenomena. In future commercialization of hydraulic hybrid passenger cars is another landmark for automobile engineers.

In next chapter we introduce a model from which one can easily understands the paths of hydraulic hybrid vehicle. The paths are actually phases of vehicles which switched according to the instructions of controller.

4.0 Introduction

Modeling is an art to display the things in your own form on the virtual environment. After taking suitable assumptions in your model, it gives results approximately closer to real scenario. One can suggest (expert of certain field) or give comments on the topology and strong points of model by checking its values/results. Remember that a model cannot tell the full information of system's behavior. When someone says full it means the hundred percent of system information could not be depicted from the model. However it gives or analyze the behavior the engineering systems close to reality. Thus the satisfactory results are what? When one can get results near to real scenario and it shows the systems topology at the system's level. In this research, two types of model are proposed, both modeled in bond graph, named as:-

1. Paths-way model
2. Topological Model

The first model is discussed in this chapter while the later will be elaborated in next one. Before discussion on any one model, let rephrase our system for the understanding of the readers that what are certain aspects upon which logic or algorithm would be developed? Hydraulic hybrid vehicle is our required system. In this model charging and recharging of high pressure accumulator is the task of the system. In hydraulic hybrid vehicle there are three phases.

4.0.1 Accelerating

When the drive pedal is pressed, the pump motor takes fluid from high pressure tank or accumulator and uses the pressure from fluid to turn the wheels. Now un-pressurized fluid is stored in low pressure tank or reservoir.

4.0.2 Cruising

When the vehicle has been cruising and the useful high pressure fluid drops beneath the certain level, the engine turns on. Engine is connected to a hydraulic pump which pressurizes this low pressure fluid to pump motor to continue to drive the wheels, any excess high pressure fluid produced by the engine pump is stored in the high pressure accumulator (HPA). High pressure accumulator is a storage tank to store hydraulic fluid up to 500 psi (Approx.).

4.0.3 Braking

When the brake pedal is pressed, the engine shuts off and the pump motor slows a vehicle down by using vehicle's kinetic energy to pressurize fluid pumping it back into high pressure accumulator. The driver wants to accelerate again, only the saved energy will be used to turn the wheels.

Based on above three phases, an algorithm has been developed in both of the named models.

4.1 Paths-way model

In pathway model, for the better understanding of the behavior, topology of the system has been separated. There are three paths developed based upon the three phases of hydraulic hybrid vehicle discussed above. Every path has its own characteristics controlled by a common controller. According to vehicle speed which is established as ECE city cycle the controller sends different signals to three valves which is in ON-OFF mode. The three paths in pathway model are:-

a. Pump to Motor (Accelerating-Cruising)
b. Motor to HPA (Braking)
c. HPA to Motor (Enough energy to turn the wheels)

As we know that a hydraulic pump is connected with an engine. In this model pump output is not constant but it is controlled by controller based on the requirement of vehicle torque and angular velocity requirements which were discussed in vehicle's model section in chapter 3. There are certain assumptions which must be in mind while evaluating the model which are as under:-

- Pump volumetric efficiency is 0.90 and mechanical efficiency is 0.95
- No fluid compressibility
- No line resistance
- No line inertia
- Gas pressure in the accumulator equals the fluid pressure at accumulator inlet
- Engine is running at 2700 rpm

Based on these assumptions we have to model the hydraulic system. Note that power requirement which has to be tome from vehicle model, modeled in block diagrams must be in the overall model.

4.1.1 Pump to Motor

The bond graph of pump to motor is shown in figure 4.1. MSf is the modulated source of flow, activated by controller. Q sensor is used to find the current volume of fluid drawn from the pump. MTF is modulated transformer serves as valve here controlled by controller. Motor is basically a resistive element normally modeled in bond graph as an element R, but here due to changing resistance as the vehicle moves, torque and angular velocity also changes, it is modeled as MR, modulated resistor controlled by external signal. Appendix A and B contain the algorithm of controller and Motor respectively.

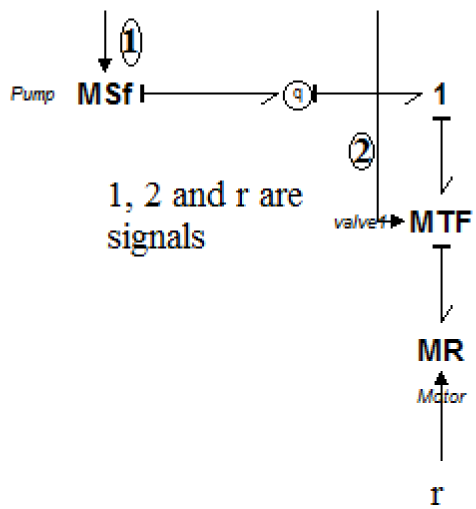

Figure 4.1: Pump to Motor Path

Signals 1 and 2 are coming from controller and r is coming from vehicle model multiple of torque and angular velocity. 1 is basically quantity of flow and 2 is basically signal ra (0 or 1) apply on valve1 controlled by controller. The q sensor is located in between the model just to find out the total volume used in working process. The equations of q sensor are as follows:

$$p2.f = p1.f;$$

$$p1.e = p2.e;$$

$$q = int\ (p1.f);$$

Equations clearly show that it neither changes the flows nor the efforts. It only integrates the coming flow which is flow in this case and gives the volume. In this path engine is on and no regeneration takes place.

4.1.2 Motor to HPA

In this path conditions applied when the vehicle is in braking and valve 2 is opened which is controlled by controller. Motor served as pump here which takes fluid from low pressure accumulator and feed it into high pressure accumulator. High pressure Accumulator is modeled in bond graph ass C element. For description of HPA please refer to Appendix C. Figure 4.2 shows the modeling of this path in bond graph.

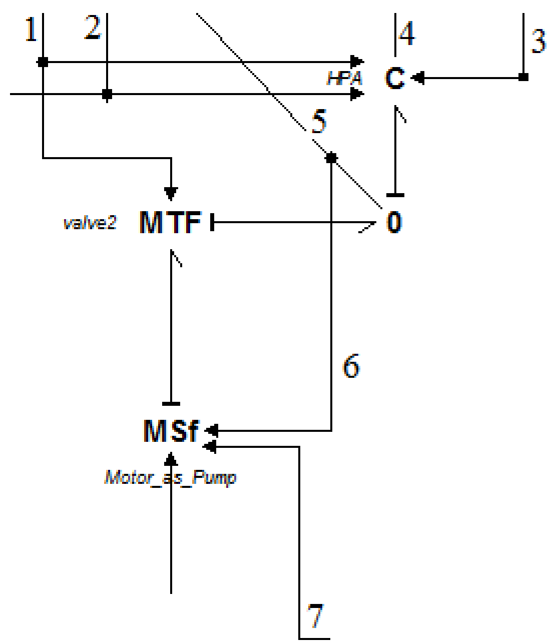

Figure 4.2: Motor to HPA Path

Signals 1, 2 and 3 are valve ON-OFF modes, coming from controller. Signal 4 is state of high pressure accumulator; its value is going in to controller for necessary algorithm, to control the HPA. Here we take motor as a pump, instead of torque braking torque is effort here. This phase works when the vehicle is in braking mode. Vehicle's characteristics are shown in Appendix D.

4.1.3 HPA to Motor

In this path HPA worked as a source and fulfills the demand of motor (torque and angular velocity) which is basically the wheels. After braking when the high pressure accumulator is fully charged or charged up to certain level the hydraulic energy which is stored in HPA, is used to drive the wheels. In this phase engine is completely off, so saving of fuel is accomplished again here. Motor to HPA path is shown in figure 4.3.

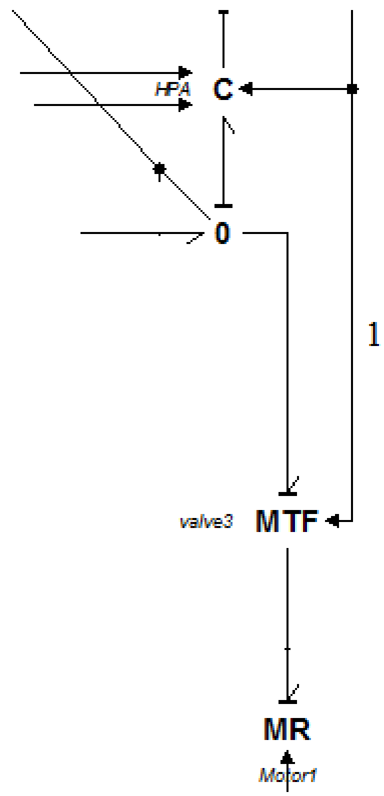

Figure 4.3: HPA to Motor Path

In this path causality indicates that motor takes the effort which is coming from high pressure accumulator. Motor1 is same as Motor, just to understand the behavior of system, both motors worked independently for different paths. Signal 1 is coming from controller to open and close the valve. Junction 0 cumulates the flow (integrates the flow) while the effort is common, which is actually coming from HPA which integrates flow and gives out effort which is pressure in this case. Valve 1 and 2 should be close in this path. How much energy is present in HPA? And will it be efficient to fulfill the demand of motor? All this based solely on controller here in this case.

4.1.4 Complete Model

All the above discussed paths and vehicle's model (which actually tells the demand of vehicle) are collaborated in a single model to evaluate the results. Bond graph is a suitable tool for this type of problem presented here. It tells the effort and flow at a time in a system and also the energy propagation. Figure 4.4 shows the complete paths-way model in which three paths which were separated before are clearly seen and one can easily depicts the behavior of each and every component of the system. Motor and Motor 1 are same and it is evident from the model because both have same r.

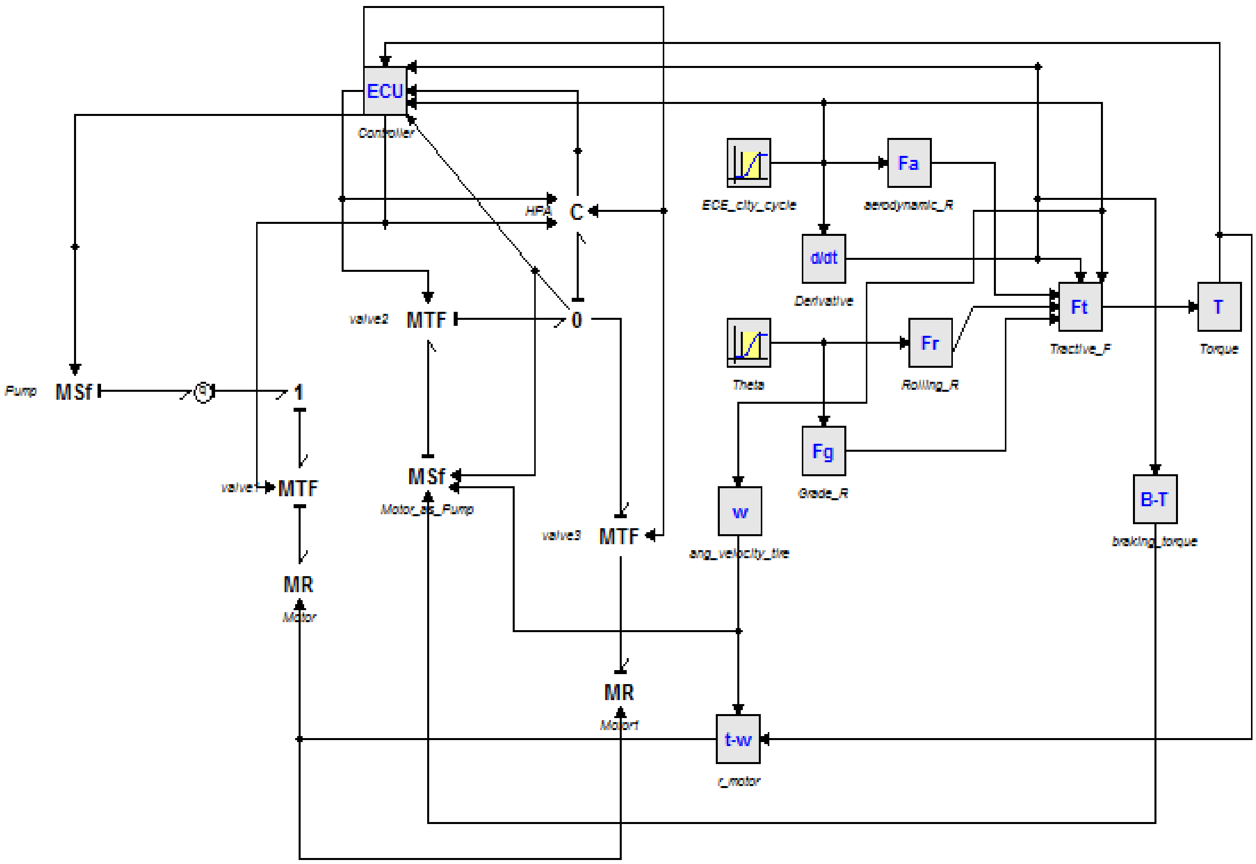

Figure 4.4: Complete Paths-way Model

4.2 Results

After simulating the model in 20 SIM, one can evaluate the system's performance on the basis of values. Figure 4.5 shows the state of HPA which is basically the volume of high pressure accumulator, changes with the vehicle speed coming from ECE city cycle which is European standard test cycle for city traffic. The space which marked in the figure is the paths when HPA supplies power to motor and it approximately 13 seconds for 200 seconds. If more braking occurred in this cycle regeneration time will be increased. The straight line indicates that volume of HPA is constant in this phase because vehicle's velocity is zero. When next acceleration comes, the HPA's energy will be used instantaneously. This is the main difference of hydraulic

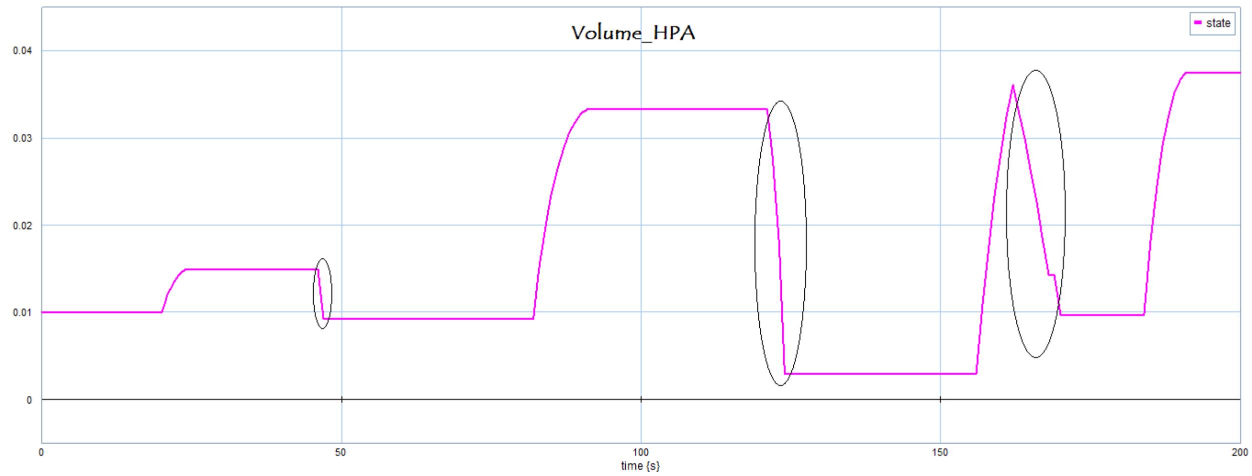

Figure 4.5: Volume of HPA

hybrid vehicle and electric hybrid vehicle that later stores energy in batteries and used when needed, while in hydraulic hybrid stored energy is used after the first acceleration comes after braking. So more stop and go in hydraulic hybrid vehicle more fuel consumption. Figure 4.6 shows the flow of pump which is controlled by controller by demand of vehicle.

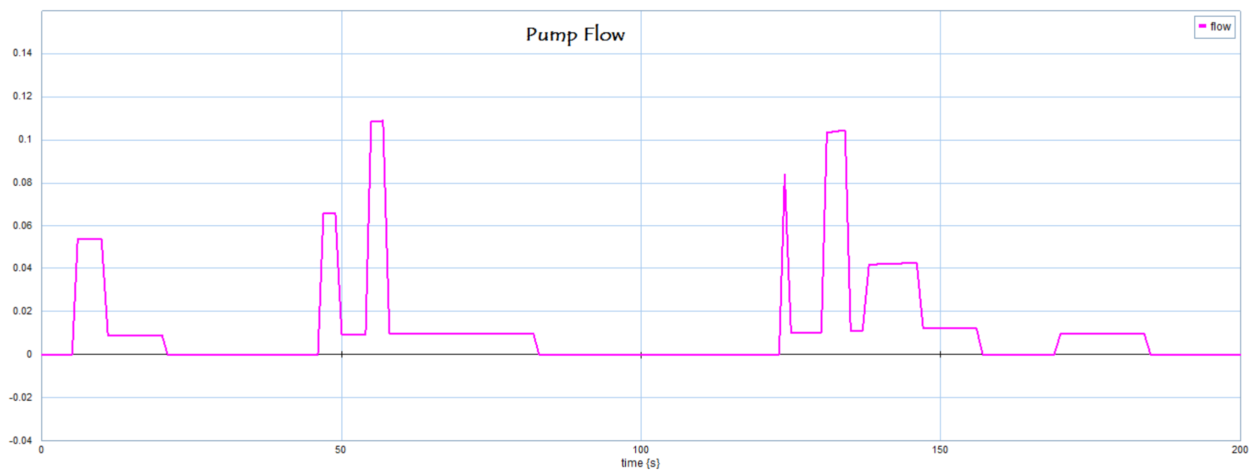

Figure 4.6: Flow of Pump

Note that pump is off while the vehicle is in idling mode and also the system is in regeneration mode. Pump is actuated by engine and Pump off means the engine is not working which saves the overall fuel. By seeing the torque demand (Appendix D) graph of pump flow is easily understandable. How and when peak is achieved in graph is solely depends upon the demands of vehicle. Motor is very critical part in this system and motor's signal r which is changing throughout the system, needs special attention here. Figures 4.7 and 4.8 show the motor's r and effort-flow graphs respectively.

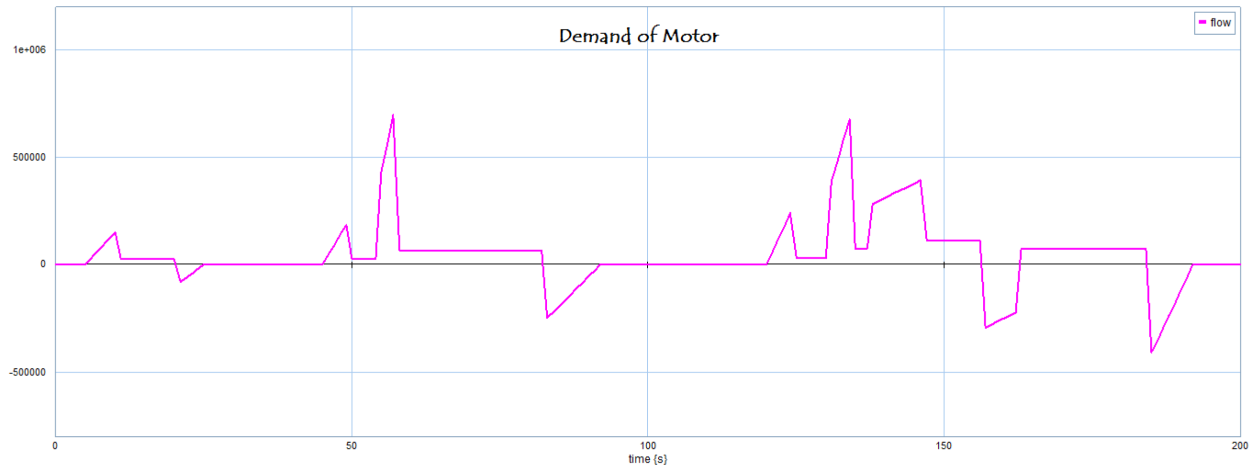

Figure 4.7: Motor's signal

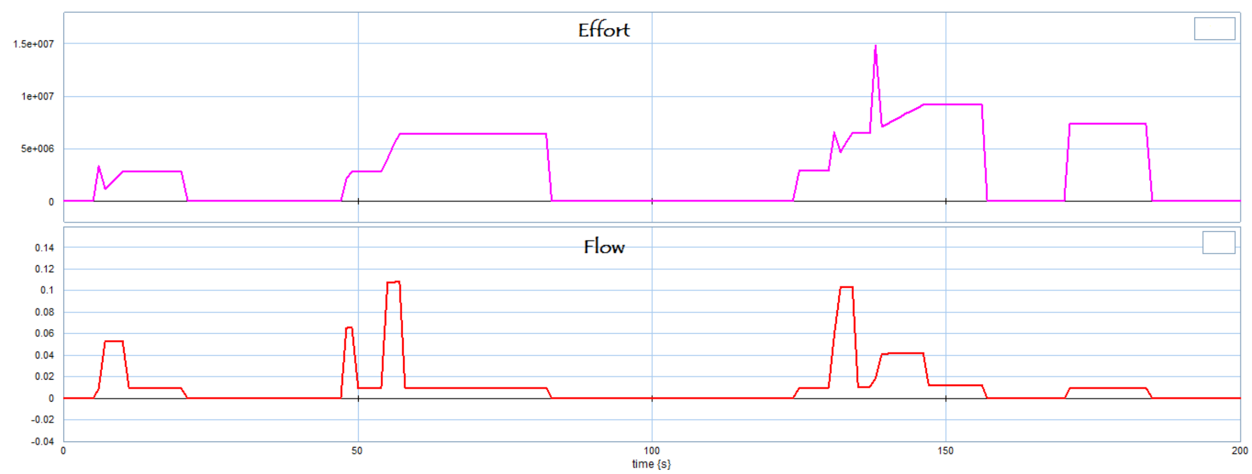

Figure 4.8: Effort and Flow of Motor

Negative values signal in figure 4.5 indicates the braking torque when motor acts as source due to negative resistance. Pattern of both graphs is nearly the same; both increase or decrease simultaneously, validating the law of power. Also it is evident from the graphs that in regeneration or generation mode no flow comes to motor and demand are obviously zero. Note that here we force motor to act as a source: in topological model it acts automatically as source. As motors are different for two paths so effort and flow to both motors are different. This motor works only when engine is on and therefore the pump. However motor 1works only in regeneration mode. Figure 9 shows the motor1's characteristics including r, flow and effort.

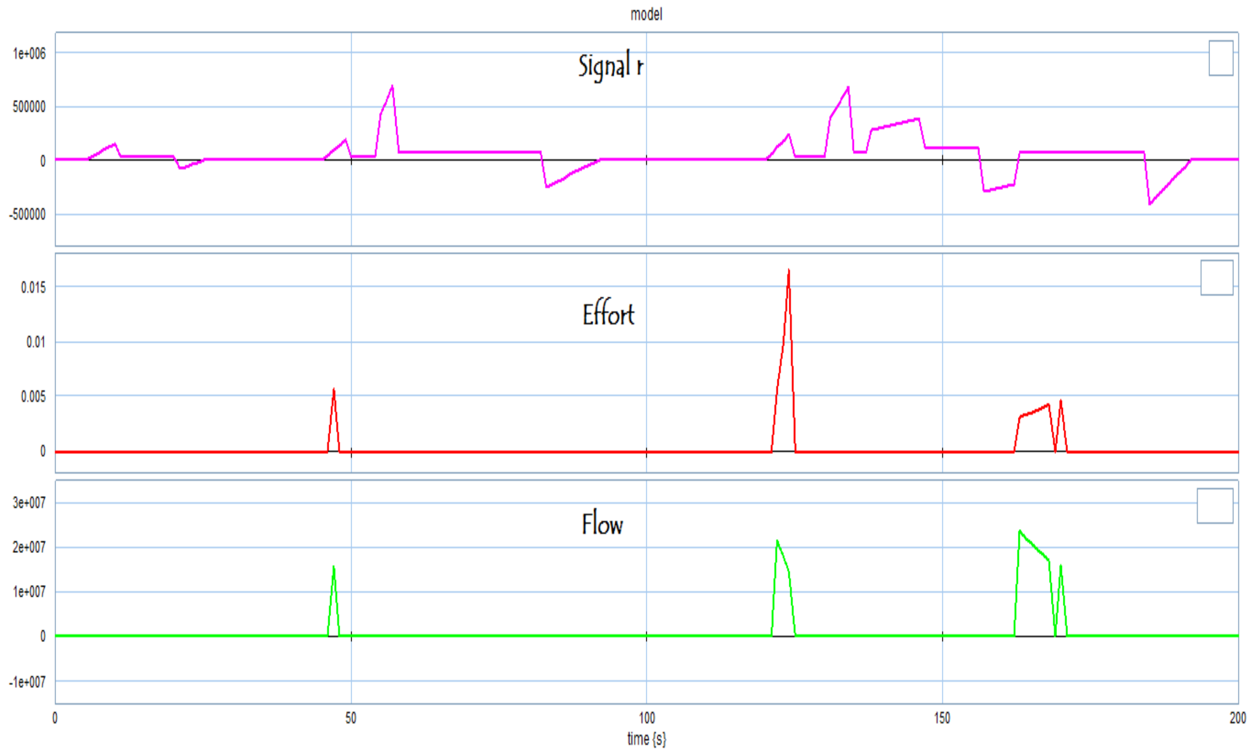

Figure 4.9: Motor1 characteristics

It can be obvious from the figure 4.9 that signal r of motor1 is same as motor but in case of motor 1 it is operated only when there is enough energy in high pressure accumulator, means regeneration mode. Flow and effort of motor1 happened only in short intervals; 13 seconds of whole cycle same as regeneration time.

Paths-way model simulate the behavior of hydraulic hybrid vehicle and easily understandable. Low pressure accumulator is assumed to be a sump. Sizing of low pressure accumulator is also important but here it is not case. Also we concluded that more stop and go prevent more fuel consumption.

5.0 Introduction to Topological Model

When someone says that system is topological, this means that placement of components in the model is same as they are placed physically. For this type of model one can easily understand the behavior of system and formulate the equations easily. In the paths-way model we separated three parts of hydraulic hybrid vehicle which represent actions of vehicle just to understand the inter linking of components of vehicle separately. Figure 5.1 represents topological block diagrams model of hydraulic hybrid vehicle.

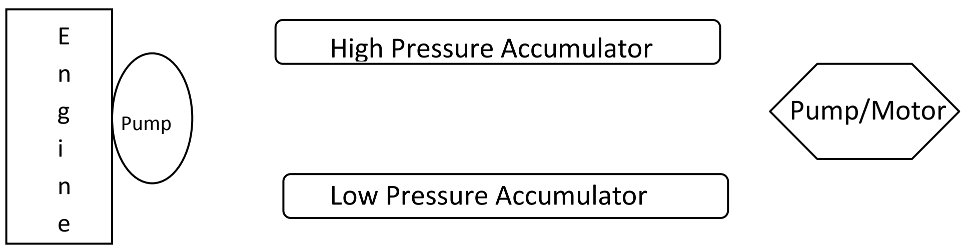

Figure 5.1: Topological representation of HHV

As clear from the figure, pump is connected to engine. In accelerating or cruising pump takes fluid from low pressure tank which is at atmospheric or litter higher than atmospheric pressure, to motor which turns the wheels. Any excess fluid is stored in high pressure accumulator which stored pressure up to 5000 psi. This excess fluid to HPA is added in this model because in paths-way model it was the assumption that any excess flow is going to low pressure tank resulting loss of energy. Topological model gives the information of system working for example in presented model one can easily determine or measure the flow which going in or out of any components. This only means that conservation of energy is valid in topological model because no energy can lose to environment but it takes one form to another, hydraulic energy to mechanical energy. Modeling of series hydraulic hybrid vehicle is easy in this sense that drive train of SHHV do not involve mechanical components because hydraulic fluid is responsible to turn the wheels. As previously mentioned motor is connected to wheels, which is responsible for motion of the vehicle. As there is no linkage of engine to the road, so therefore no mechanical losses in series hydraulic hybrid vehicle. Pump/motor is convertible component which act as motor when the vehicle is in accelerating or cruising phase while it acts as a pump while braking pushing the fluid in to high pressure accumulator.

5.1 Topological Model Construction

Based on the above discussion topological model has been made to simulate the hydraulic system behavior of hydraulic hybrid vehicle. Model is based on certain assumptions which are as follows:-

- No fluid compressibility
- No line resistance
- No line inertia
- Gas pressure in the accumulator equals the fluid pressure at accumulator inlet
- Supply of pump is constant

The block diagram model which tells the demand of vehicle is also in the final topological model.

5.1.1 Controller Design

Controller design is different here from the previously described paths-way model. In the paths-way model ECE city cycle is a pattern and based on that pattern we decide where to fill HPA and where to empty it. Also the excess fluid drops down to low pressure accumulator which is not suitable and unlikely to structure of hydraulic hybrid vehicle. In that model motor acts as pump only in braking phase, therefore HPA fills only in braking mode. The stored hydraulic energy is instantly used in next accelerating phase. Here as excess fluid is stored in high pressure accumulator also in accelerating and cruising phase. So it is an appropriate chance that HPA fills before braking phase. So in topological model as actually hydraulic hybrid works whenever high pressure accumulator fills up to certain level its hydraulic energy will used at once until it drops down to certain low level. In this way much more energy saved than the paths-way model. Also the time from HPA to motor is comparatively increased than previously discussed model.

5.1.2 Negative Resistance

As motor has dual function, pumping and motoring actions during different phases of vehicle run. In paths way model we developed different path of motor when it acts as a pump but in reality it does not happen, motor changes its characteristics to pump the fluid to high pressure accumulator. For example swash plate or bent axis motor the entry of fluid determines whether it acts as a pump or motor. Here in this model motor act as pump or motor just as in reality and this is possible only due to characteristics of negative resistance. When there is involved negative resistance it acts as a source. Just as in our model r of motor is responsible of sign of resistance when r becomes negative resistance becomes negative too. Negative resistance acts a s a source, will prove it graphically in results section.

5.1.3 Topological Model

Topological model which shows the system level study of series hydraulic hybrid vehicle is shown in figure 5.2. Here pump acts as a constant source of flow. MSe does not mean that flow of pump is varying but it modulates the ON-OFF characteristics of pump controlled by controller.

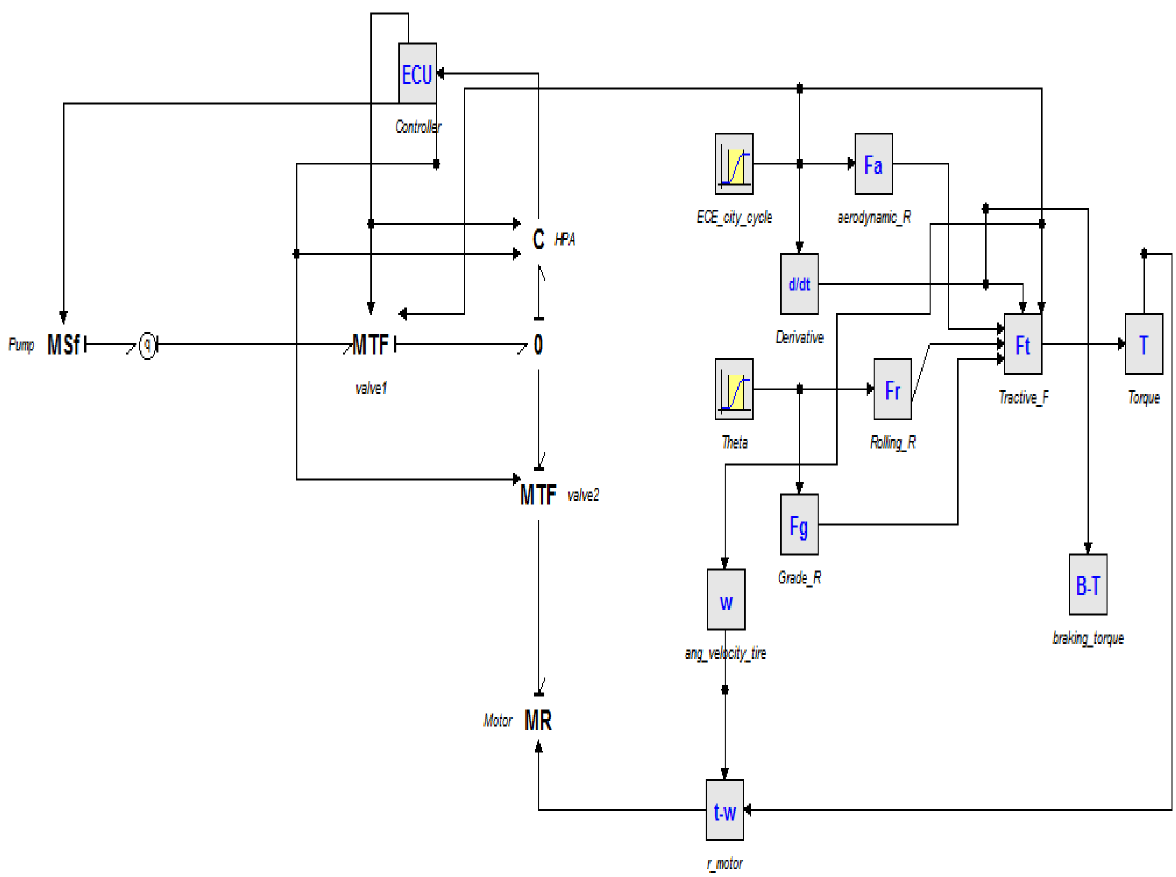

Figure 5.2: Topological Model of SHHV

Note that here are only two valves as compared to paths-way model which has three. Valve 1 is ON in accelerating and cruising phases while it is OFF when motor acts as pump or HPA loses its hydraulic energy. Valve 2 is open all the times due to motoring and pumping action. From the graph clearly indicates that flow of pump minus flow to the motor can enter to the high pressure accumulator according to causality principle. It is also noted that motor can sent information of flow to pump through HPA. Also as previous model we have taken care of pressure of high pressure accumulator in the equations, here there is no need to formulate the equations because pressure of HPA directly formulate the model. As seen from the model pressure of HPA is responsible for overall pressure of the system because all other accessories are at low pressure. Braking torque has no use in this model because motor can become a source when the signal r of motor becomes negative.

5.2 Results

Volume of high pressure accumulator is key parameter of hydraulic hybrid model. When it fills and empty, pressure and temperature changes in the accumulator, time of providing hydraulic energy to motor and also the effects of these parameters to overall system. Figure 5.3 shows the volume of HPA during the cycle.

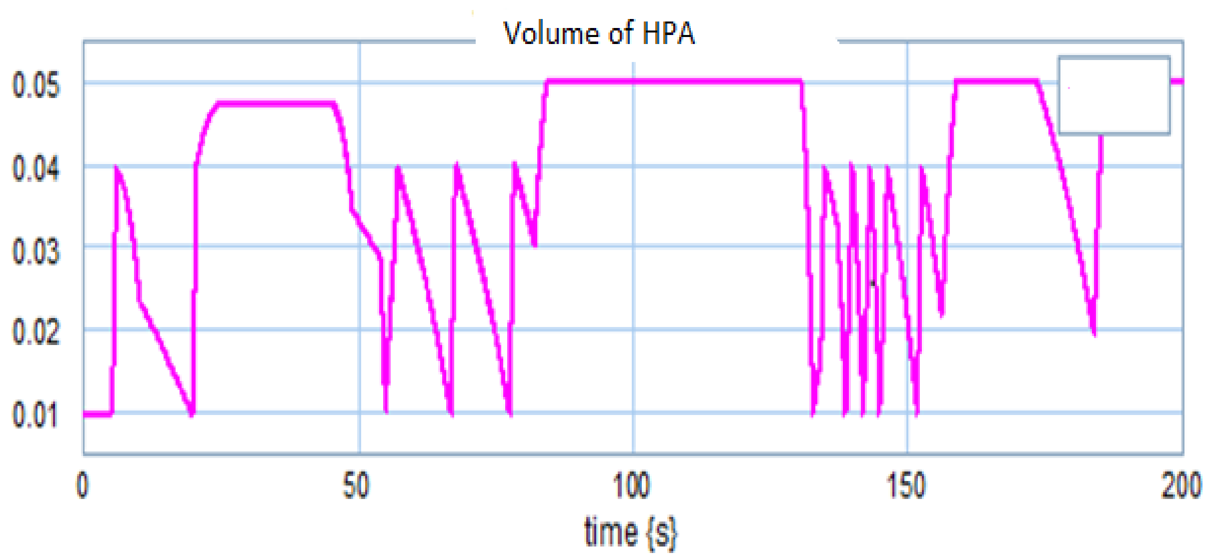

Figure 5.3: Volume of HPA

The upper limit of HPA is set to 40 liters and lower limit is 10 liters. When the fluid is store above or up to 40 liters, it can be used until the fluid level drops down to 10 liters or below it. so controller is designed just to ensure the upper and lower limit of state of high pressure accumulator nothing else. City cycle is accommodated in vehicle's demand which is coming to motor as signal r. the time when the HPA gives energy to vehicle is up to 101 seconds which is 45 percent of total time of cycle. Also note that due to higher demand of vehicle we fix the pump supply to meet the peak demand of vehicle, due to which when there comes lower demand much of the excessive fluid go to HPA and that's why energy is saved. Corresponding to state of high pressure accumulator figure 5.4 tells us about the pump flow during the cycle.

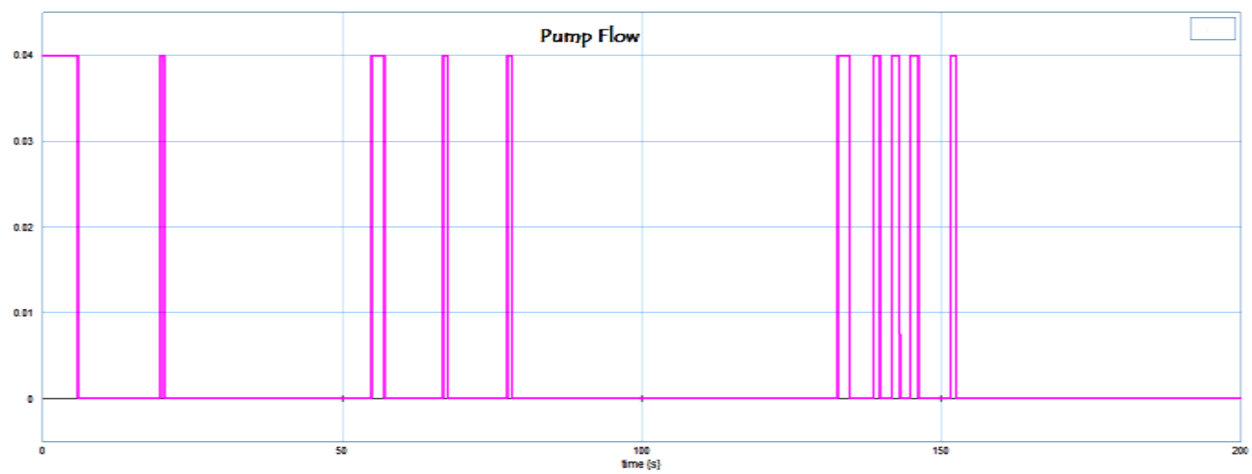

Figure 5.4: Pump Flow

Flow is constant in different phases of cycle when there is low fluid in HPA and also when the vehicle is in idle mode or when HPA acts as a source of energy. While discussing the model we talked about the negative resistance where resistance can acts as a source. As a result pressure of motor and high pressure accumulator will increase also the flow of HPA has negative value. Figure 5.5 shows the motor's effort and flow characteristics and upon comparing the motor's r in figure 5.6 one can easily see the flow of motor is negative due to negativity of r but as a result pressure is increased signing that it acts as a source and flow is going to the HPA. Another parameter of motor which is very much same to parameter of HPA i.e. Pressure of both the components. The reason is simple for those who know basic bond graph; due to zero junction all the pressures are same because it is basically a flow adder. Valve 2 is not transforming anything in effort and flow but it is used here just to switch the model between pump to motor or motor to

HPA and vice versa. Note that when value of r is negative this means braking torque applies. Here one cannot see the direct interconnection of braking torque in the model with the components; this is solely due to the introduction of negative resistance.

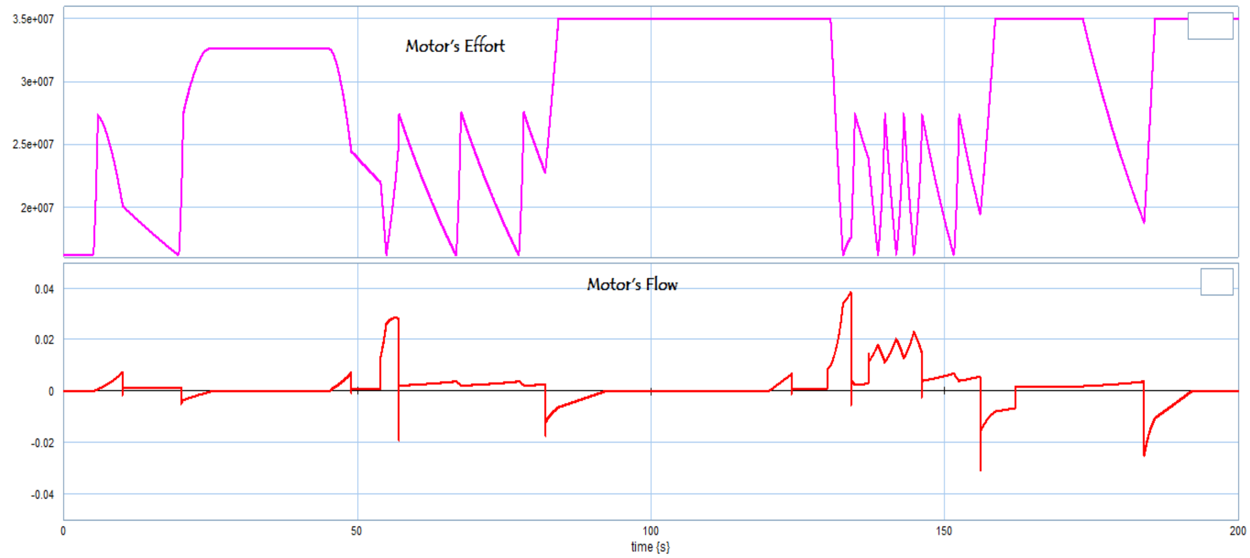

Figure 5.5: Motor's effort and flow

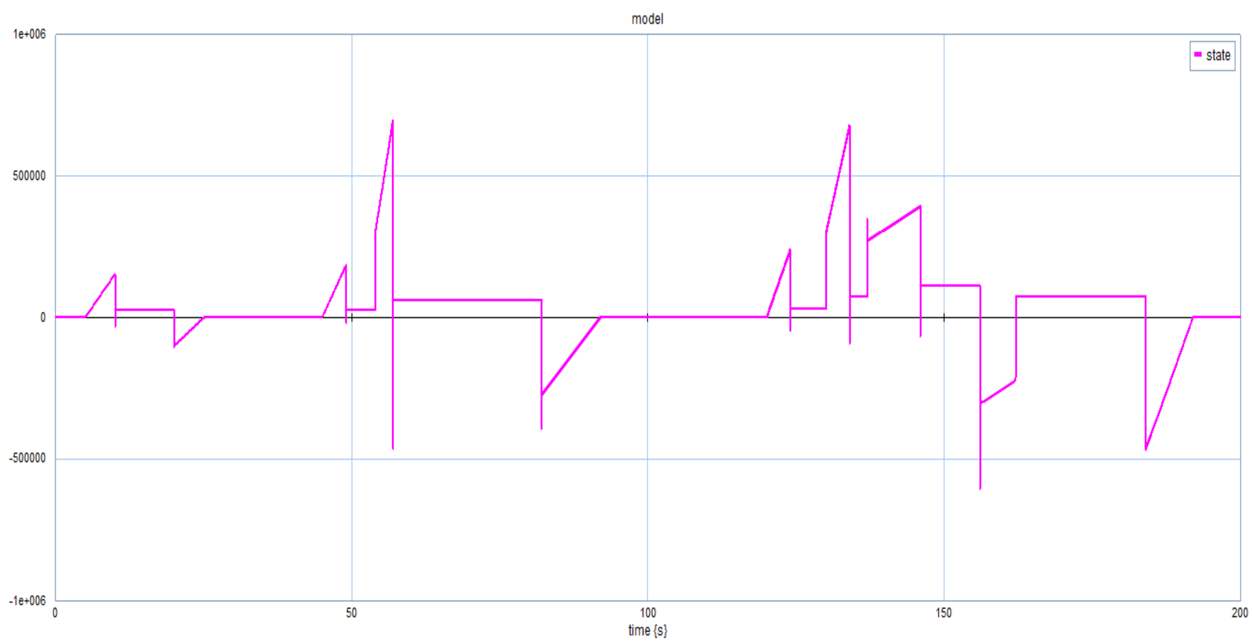

Figure 5.6: Motor's r

In figure 5.5 the maximum pressure of the motor is 350 bars which is actually the maximum pressure of HPA. So it is obvious that pressure of the system is dependent solely on high pressure accumulator in this model. There is another parameter in HPA upon which we couldn't focus i.e. temperature. The temperature range is 300 to 375 Kelvin given by EPA, at minimum charge pressure it should be at STP. As we know temperature is directly proportional to pressure depicted in figure 5.7, which shows the temperature and pressure of HPA.

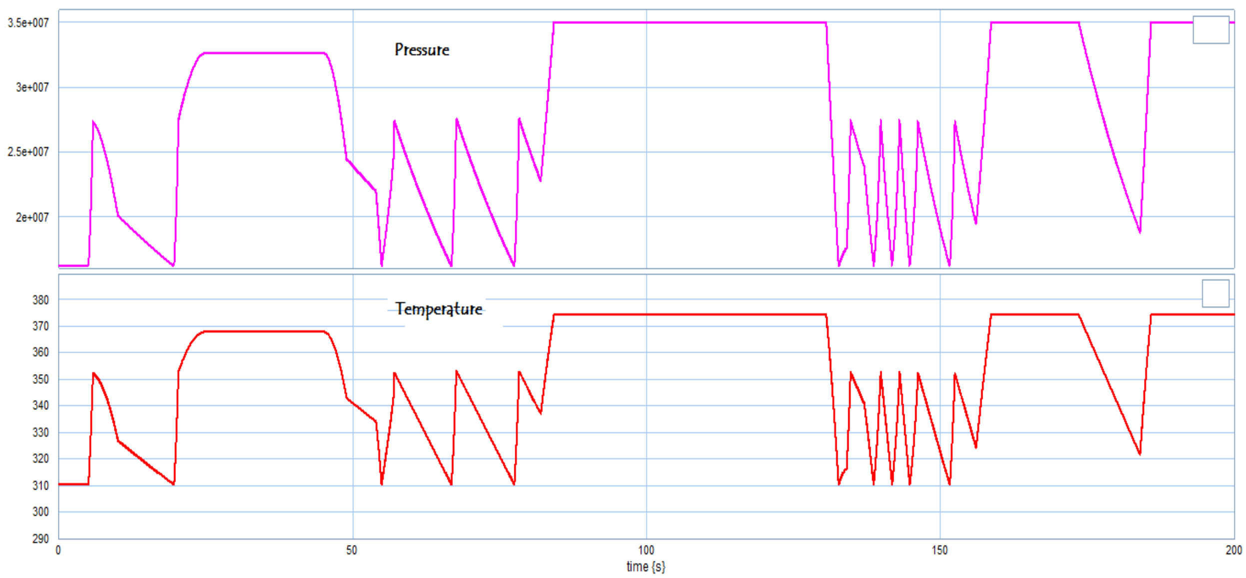

Figure 5.7: Pressure and Temperature of HPA

As clearly seen on the above figure the sketch of both the parameters are exactly the same. This is due to ideal gas equation which we used for the formulating the system of high pressure accumulator. Flow of HPA is another important parameter which one should fully understand to judge and evaluate the model. It is because of the fact that in this model every move of the controller is dependent on the state of the HPA and state is dependent on the flow. Also having a glimpse on the flow of HPA, one can easily tell what is going on the system? Which part of the system is active? Figure 5.8 shows the selected part of model which influence characteristics of HPA, mostly flow because it takes flow from the system and generates effort to the system, so flow is important parameter to judge the high pressure accumulator efficiency. We named the power bonds which is coming in or out at the junction which is connected to HPA. Power bond 1 is coming from pump, 2 is going into HPA and 3 is heading toward motor. as we know the characteristics of zero junction so

$$e1 = e2 = e3$$

In case of flow when pump is working and f1 is coming then

$$f1 = f2 + f3 \dots \dots \dots (a)$$

$$f2 = f1 - f3 \dots \dots \dots (b)$$

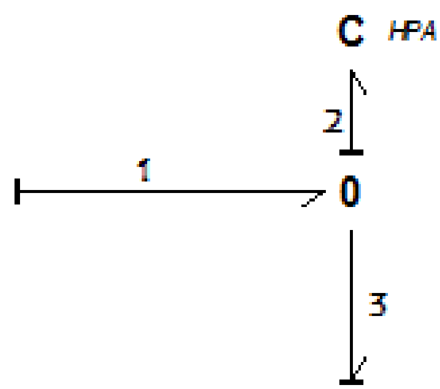

Figure 5.8: Estimation of HPA’s flow

So flow from pump is after reaching to the zero junction is split into two parts (eq. a) and HPA’s flow is difference of pump flow and motor flow (eq. b) because f3 is going to motor as there is no restriction of flow (see assumptions). But interesting fact only comes when pump is off and HPA is delivering power or motor is delivering power. When HPA is delivering power then

$$f2 = -f3$$

And when motor is delivering power then

$$f3 = -f2$$

It is obvious from above two equations that whenever flow of HPA is negative whether the pump is working or the motor acts as a source. Whenever flow of HPA is positive on the graph it simply means HPA has much hydraulic energy. Figure 5.9 shows the HPA’s flow which clearly second our discussion.

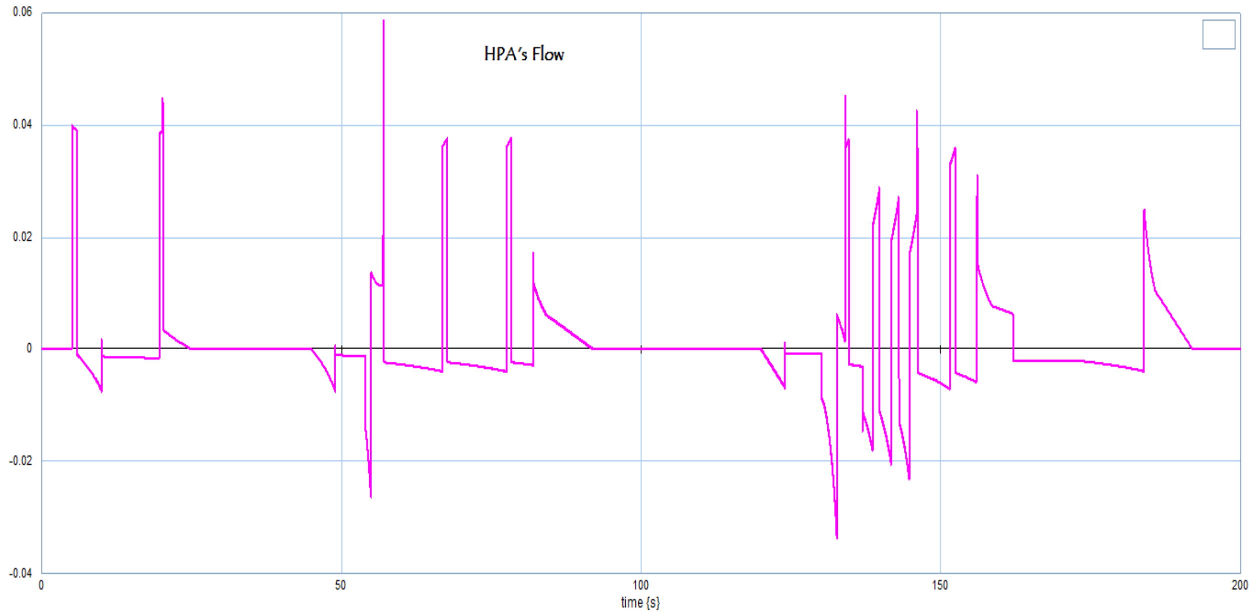

Figure 5.9: HPA's flow

Up till now we discussed paths-way model which tells us about the different paths of hydraulic hybrid vehicle. In this chapter we discussed the topological model which shows the topological model of hydraulic hybrid vehicle with no compliances and resistances. In next chapter we have to discuss the topological model which includes the resistances and compliances of the system.

5.3 Topological Model-II

Topological model-II is almost same as topological model-I except the assumptions. The assumptions we have taken in topological model-I are that we neglected all the resistances of line and fluid compressibility. As in reality this was not the case; every line has resistance and hydraulic inertia which creates some genuine issues to fluid's flow. Also hydraulic oil is not non-compressible so compressibility of any fluid should take into account. Due to addition of resistances into the model the results of topological model I is slightly scaled down to this model. The time during which HPA acts as a source will be small than topological model I. The controller design and all the other parameters are same as previous model.

5.4 Fluid Compressibility

The dynamics of hydraulic system can be influenced by fluid stiffness just like the spring compressibility's in the mechanical system. As fuel enters the pipe, there will be an apparent loss of fluid flow due to its compressibility. In literature usually bulk modulus is used to measure the oil stiffness in the dynamic system which relates the change in pressure to change in volume of a closed vessel [34]. Mathematically it can be written as:-

$$\Delta p = \beta \left(\frac{-\Delta V}{V} \right) \ldots \ldots (1)$$

Where β is the bulk modulus of hydraulic fluid, ΔV is the decrease in volume of fluid due to pressure and V is the volume of fluid. By seeing equation (1), the term V/ β gives us stiffness which is basically the constitutive law of one port C element. Table 5.1 shows the parameters of line and fluid.

Parameter	**Value**
Length of line	0.5 m
Diameter of line	10 mm
Density of hydraulic fluid	850 Kg/m^3
Viscosity of fluid	7.9 * 10^{-4}
Bulk Modulus	1.6 * 10^9 Pa

Table 5.1: Parameters of line and Fluid

Assuming 4 liters/s flow as discussed in previous chapter of fluid in a line, hydraulic fluid capacitance is

$$C = \frac{V}{\beta}$$

$$C = \frac{0.004}{1.6 * 10^9}$$

$$C = 2.5 * \ 10^{-12} \ \frac{m^3}{Pa}$$

5.5 Line resistance

There are always leakage paths in hydraulic circuit and they act when the pressure drops are imposed [34]. The resistance of pipe varies based on the nature of the fluid flow that passes through it. The resistance of pipe is given by:-

$$R = \frac{32 \, \mu \, l\rho}{AD^2}$$

Where μ is the absolute viscosity of fluid, l is the length of line, ρ is the density of hydraulic fluid, A is the area of line and D is diameter of cross section of line. The above equation is valid only when Reynolds number is less than 2000 which is range of laminar flow so assuming here laminar flow for our system. So the resistance is

$$R = \frac{(32 * 7.9 * 10^{-4} * 0.5 * 850)}{\pi * 0.01^4}$$

$$R = 341.992^6 \ \frac{Pa.s}{m^3}$$

5.6 Line inertia

The resistance due to line inertia is basically the viscous friction which generally opposes the fluid movement. The pressure drop due to line inertia is given by

$$\Delta p = IQ^{\cdot}$$

$$\Delta p = \frac{\rho l}{A} Q^{\cdot} = \frac{4\rho l}{\pi D^2} Q^{\cdot}$$

So line inertia is given as $I = \frac{4\rho l}{\pi D^2}$ modeled as an I element.

$$I = \frac{4 * 850 * 0.5}{\pi * 0.01^2}$$

$$I = 5.411^{10} \frac{Kg}{m^4}$$

5.7 Complete Model

Summing all resistances and capacitances in the topological model I gives us the final complete topological model. Figure 5.10 shows the model with the two sets of above three elements which are discussed above. As there are normally two paths Pump to motor and motor to pump, so we take two lines and their resistances respectively.

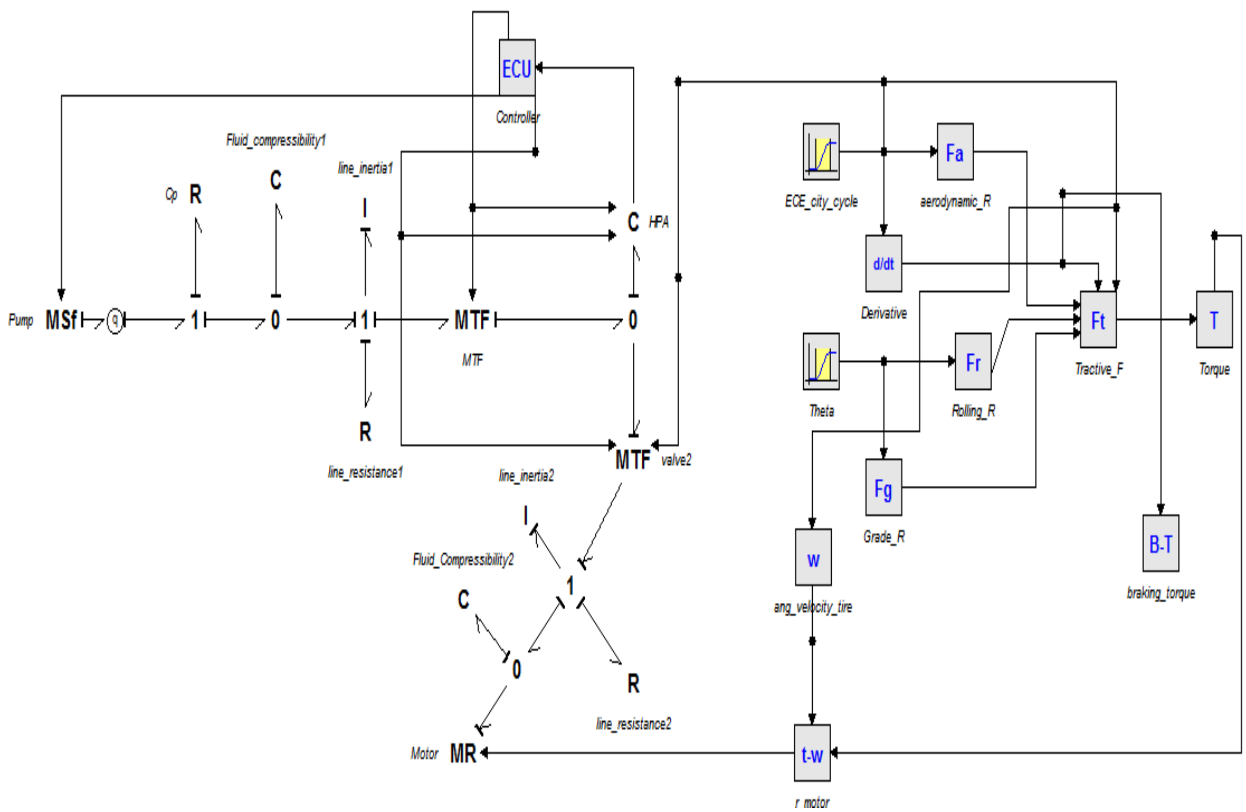

Figure 5.10: Complete Topological Model

As we can clearly see on the model that C is connected on the zero junction which indicates that it takes difference of flow to give back the effort to system. Likewise I element is connected to one junction which takes difference of pressure as input and gives back the flow. So in one sense these elements are used for controlling of effort and flow when desirable. For example by inserting an R element one can control the pressure of whole system. Rest of the whole model is same as topological model I.

5.8 Results

As mentioned before results are typically the same as topological model I but scaled down to some extent. Scaled down does not refer to the values of pressure and volume but time of HPA in which it becomes a source. Figure 5.11 shows the deviation of volume of HPA based on ECE city cycle.

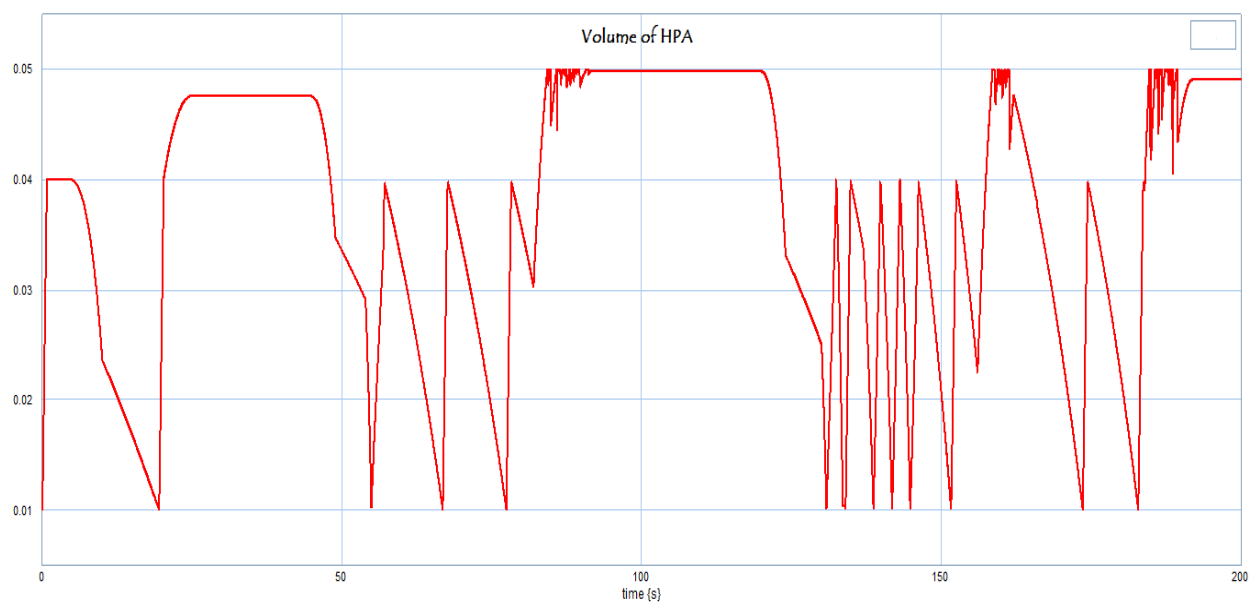

Figure 5.11: Volume of HPA

As we are interested in the time when the HPA becomes the source, which was 101 seconds in topological model I. Here in this model it reduced to 88 seconds which is 12 % less than the time of previous model. Figure 5.12 shows the flow of the pump which is more active than the previous model because of the resistances it has to overcome. Also it should be in mind that the upper limit of high pressure accumulator is 40 liters and lower limit is 10 liters. When volume of

HPA exceeds 40 liters it acts as a source until it drops down to 10 liters. After reaching the lower state in HPA the pump is ON and the hydraulic fluid starts flowing towards the motor. There is sudden sparks due to compressibility's and resistance in the system but it will settle down as the cycle progress.

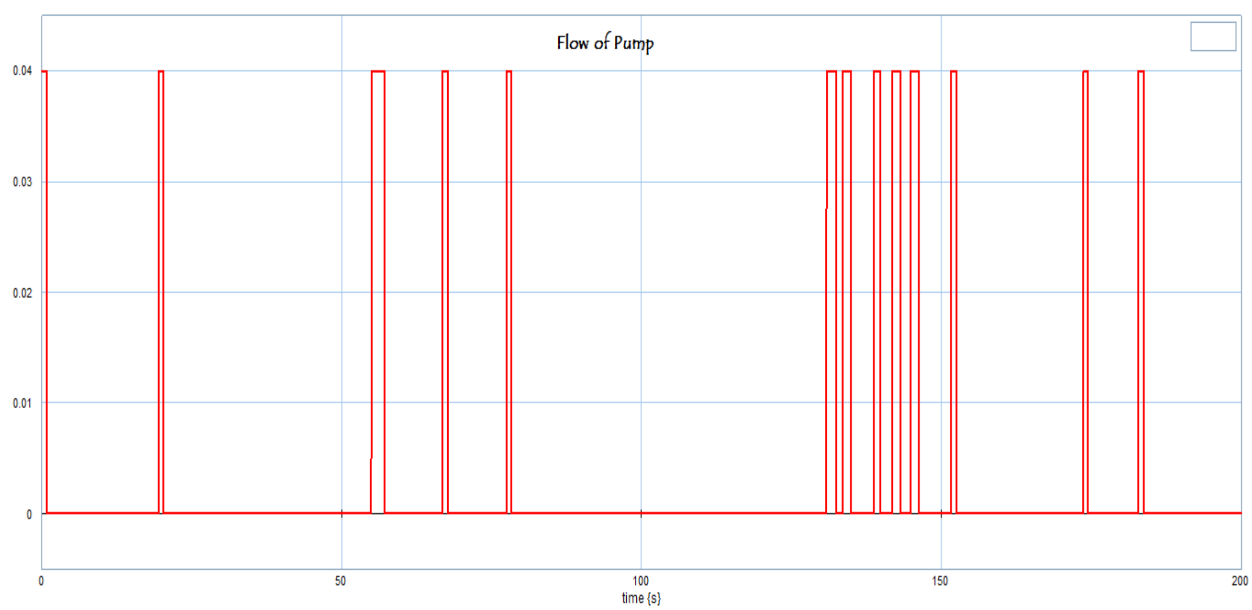

Figure 5.12: Flow of Pump

Pump is delivering the constant flow as in the previous model. Results of various parameters are so complicated (not shown properly on scale) that could not be easily understand the behavior of any components. So we limit our cycle to 50 seconds to figure out the motor's effort and flow, in order to understand how both deviate with time. Motor's characteristics are shown on figure 6.13 which are same as in topological model I. Due to sudden spikes in the model and due to extremely small values of capacitance and resistance; the whole figure of motor's characteristics cannot be easily evaluated. So we take small time to formulate the results. Note that now the pressure of the system is not same as the pressure of high pressure accumulator, same in topological model I. This is solely due to the introduction of resistances in the model. Maximum pressure is less than HPA's maximum pressure due to resistances. Also the flow of the whole hydraulic circuit is also influenced by the resistances.

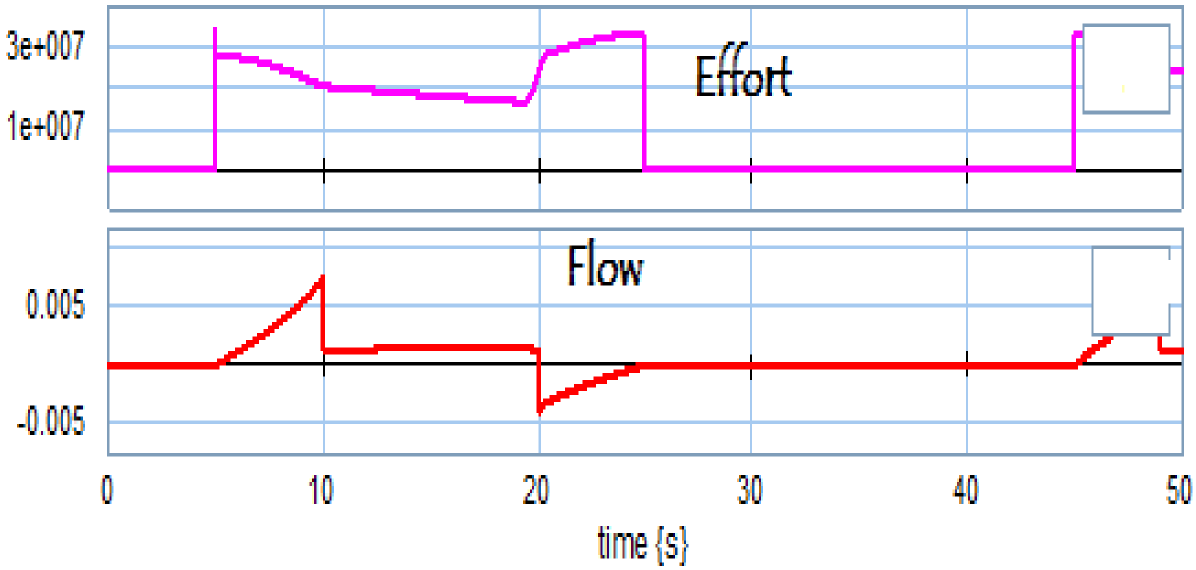

Figure 5.13: Motor's effort and flow

Chapters 5 show the two types of topological models with non-resistance and resistances. Also fuel consumption of an IC engine is affected by this model. Previously we calculated the model with two strategies that engine is OFF while idling and braking. After counting the regeneration effects in the model fuel consumption also slows down, this is shown in Appendix E. It will tell us about the Fuel consumption of an IC engine based on topological model I and II.

Conclusion

Fuel consumption of parallel hybrid vehicle was determined analytically and percentage of saved fuel in case of ECE city cycle is 40%. The strategies of saving fuel consumption in parallel hydraulic hybrid vehicle are different from series hydraulic hybrid vehicle. There are no mechanical losses in case of series hydraulic hybrid vehicle as there is no mechanical linkage of engine with road. Bond graph is a very specialized tool for multi-domain systems and here we see as an example of this statement. Tool is used for modeling the hydraulic system at the system's level. Firstly for the understanding of the readers' three paths of hydraulic hybrid vehicle was introduced. Topological model introduces correct formulation of the components of hydraulic hybrid vehicle. Volume of high pressure accumulator is important parameter throughout the research work. We basically interested the time when HPA becomes source of hydraulic energy, more the time more fuel is saved. In topological model I without resistances and compliances gave us the time of 101 seconds and in topological model II 12% less time of when HPA acts as a source. Fuel Consumption in series hydraulic hybrid vehicle is estimated to 75 % based on European test cycle.

The main benefit of hydraulic hybrid vehicle is the fuel consumption of the vehicle. Focusing on this unique and cost-effective technology, we achieve ultra low pollution emissions, increase fuel efficiency and reduce green house gases. Series hydraulic hybrid vehicle is most cost effective option out of any hybrid vehicle. It allows optimum engine operation for efficiency and emission reductions.

In this research work switching non linearity occurs. Valves are not open at once just like Boolean operator 1 or 0 in split second. it takes time and proper modeling of valves should be incorporated in the model. Demand of vehicle is solely based on ECE city cycle. Driving pattern of vehicle could be inserted in the model to get the values closest to reality.

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APPENDIX A

Controller Strategy in Modeling Approach 1

As there are three valves in model proposed in chapter 4, which only dictates the readers the three paths or phases of hydraulic hybrid vehicle. So based on these valves a control strategy was developed and three signals originated from controller to controller the valves, namely:-

Signal	**Path**
ra	HPA to Motor
rb	Pump to Motor
rc	Motor to HPA

There are four parameters involved in the algorithm of controller described as follows:-

Parameter	**Value**	**Description**
state_initial	0.01	Initial state of HPA
vol_eff	0.90	Volumetric efficiency of Pump
mech_eff	0.95	Mechanical efficiency of Pump
p_lpa	35e05	Pressure of low pressure accumulator

Algorithm

As previously mentioned there are three phases in hydraulic hybrid vehicle discussed as below:-

HPA to Motor Phase

Enough pressurized fluid in high pressure accumulator to run the motor. In this phase pump and engine are not working.

Pump to Motor Phase

When the fluid in HPA drops down to certain level, engine is on which actuates the pump to fulfill the demand of vehicle.

Motor to HPA Phase

This phase is also known as deceleration phase in which motor acts as a pump which stores hydraulic energy in to the HPA. Pump and engine are OFF in this phase.

Code

```
parameters

        real state_initial = 0.01;
        real vol_eff=0.90;
        real mech_eff=0.95;
        real p_lpa=35e05;

variables

        real temp;


equations

        if ECE_city_cycle==0 and acceleration==0 then    //No velocity
                ra=0;
                rb=0;
                rc=0;
                flow=0;
        end;

        if ECE_city_cycle>0 and acceleration>0 then    //HPa to Motor

                 if state>state_initial and state<=0.05 then
                        rb=0;
                        rc=1;
                        ra=0;
                        flow=0;
                else
                        ra=0;
                        rb=1;
                        rc=0;
                        temp=((p_hpa-p_lpa)*vol_eff*mech_eff);
                        flow=(torque*2700*6.3)/(temp*60);
                end;
```

```
end;

if ECE_city_cycle>0 and acceleration==0 then    //Pump to Motor

           if state>state_initial and state<=0.05 then
                    rb=0;
                    rc=1;
                    ra=0;
                    flow=0;
          else
                    ra=0;
                    rb=1;
                    rc=0;
                    temp=((p_hpa-p_lpa)*vol_eff*mech_eff);
                    flow=(torque*2700*6.3)/(temp*60);
          end;
end;

if ECE_city_cycle>0 and acceleration<0 then    //Motor to HPA
          ra=1;
          rb=0;
          rc=0;
          flow=0;
          else
          ra=0;
          end;
```

APPENDIX B

Characteristics of Motor

Motor's characteristics are same whether it is in Modeling Approach 1 or Topological model I and II. Also the signal which changes the behavior of motor is same. The motor algorithm is solely depends on the energy change from one domain to another. When it acts as a source it mechanical energy is converted to hydraulic energy whereas in case of motor hydraulic energy from HPA or pump is responsible to turn the wheels.

Algorithm

As power is conserved at the motor so

Hydraulic energy=Mechanical energy

p.e * p.f = torque * angular velocity

p.e * p.f = r_motor=r

p.e = r/p.f

p.e and p.f are the effort and flow of motor (correspond to hydraulic fluid) whereas torque and angular velocity is the demand of vehicle.

Code

```
equations

        if r==0 then
                p.e=0;
        else if p.f==0 then
                p.e=0;
        else
                p.e=r/p.f;
        end;
        end;
```

APPENDIX C

High Pressure Accumulator (HPA)

High pressure accumulator is the device to store hydraulic fluids up to 5000 psi and whenever needed it act as a source to fulfill the demand of vehicle. One can model HPA as ideal gas law

$$P = (m * r * T)/v$$

Firstly discuss some of the parameters used in coding of HPA.

Parameter	Value
Gas used	Methane
Mass of gas	9 kg
Gas constant	520 J/Kg.K
Minimum temperature	300K
Max volume of HPA	100 litres
Min volume of HPA	50 litres
Max volume of fluid in HPA	50 litres
Pre-charge pressure	140 bar
Max pressure	350 bar
Fluid density	850 Kg/m^3

Code

```
parameters

    real mg=9;

    real rg=520;

    real vmax=0.1;

    //real gamma=1.32;

    real tmin=300;

    //real vmin=0.05;

    real a= -0.32;
```

```
variables
        real T;  //Temperature
        real r;  //compression ratio
        real b;
        real state_gas; //state of gas


equations
        state = int(p.f);
          if state>0.05 then
                state=0.05;
                state_gas=0.05;
        else
                state_gas=0.1-state;    //total volume - volume of fluid
         end;
         r=state_gas/vmax;     //remaining gas volume in HPA/max volume=r(compression ratio)
         b=r^a;
        if rc==0 and rb==0 and ra==0 then  //when velocity==0…HPA is not working
        T=0;
        else
        T=tmin*b;
        end;
         p.e = (mg * rg * T)/state_gas ;
```

APPENDIX D

Model of Vehicle

As discussed in chapter 3, a vehicle generally influenced by following forces:-

- Aerodynamic force
- Rolling force
- Force caused by gravity

The mathematical description of vehicle model is described in chapter 3. Here we presented the block diagram model of vehicle which is basically the demand of vehicle which must be fulfilled by hydraulic section. Figure 1 shows the model of vehicle, added the braking torque for paths-way model and signal r to motor later for all modeling approaches.

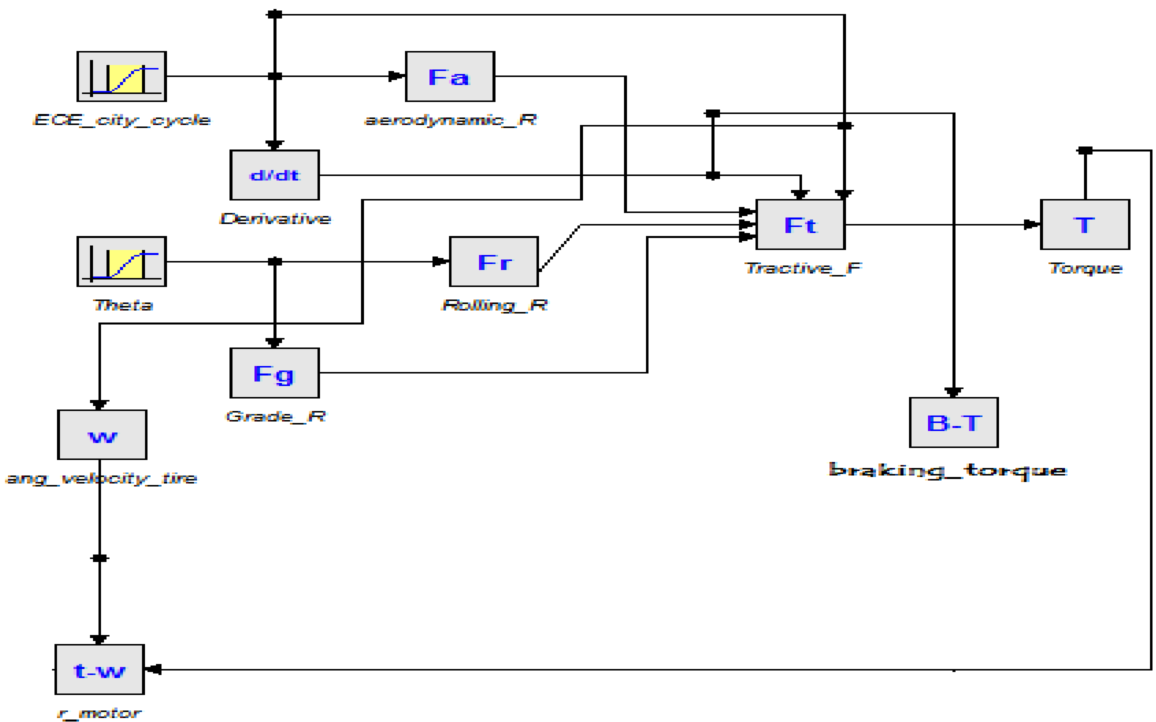

Figure 1: Vehicle's Model

All the forces summed at Ft which is the tractive effort, to give us the torque of the vehicle. Braking torque is active only when the vehicle is in deceleration phase. Angular velocity of tire multiplied the torque gives us the r for motor which is actually the demand of vehicle. In figure 2

ECE city cycle on which vehicle is tested, its acceleration, torque, braking torque and demand of vehicle are presented.

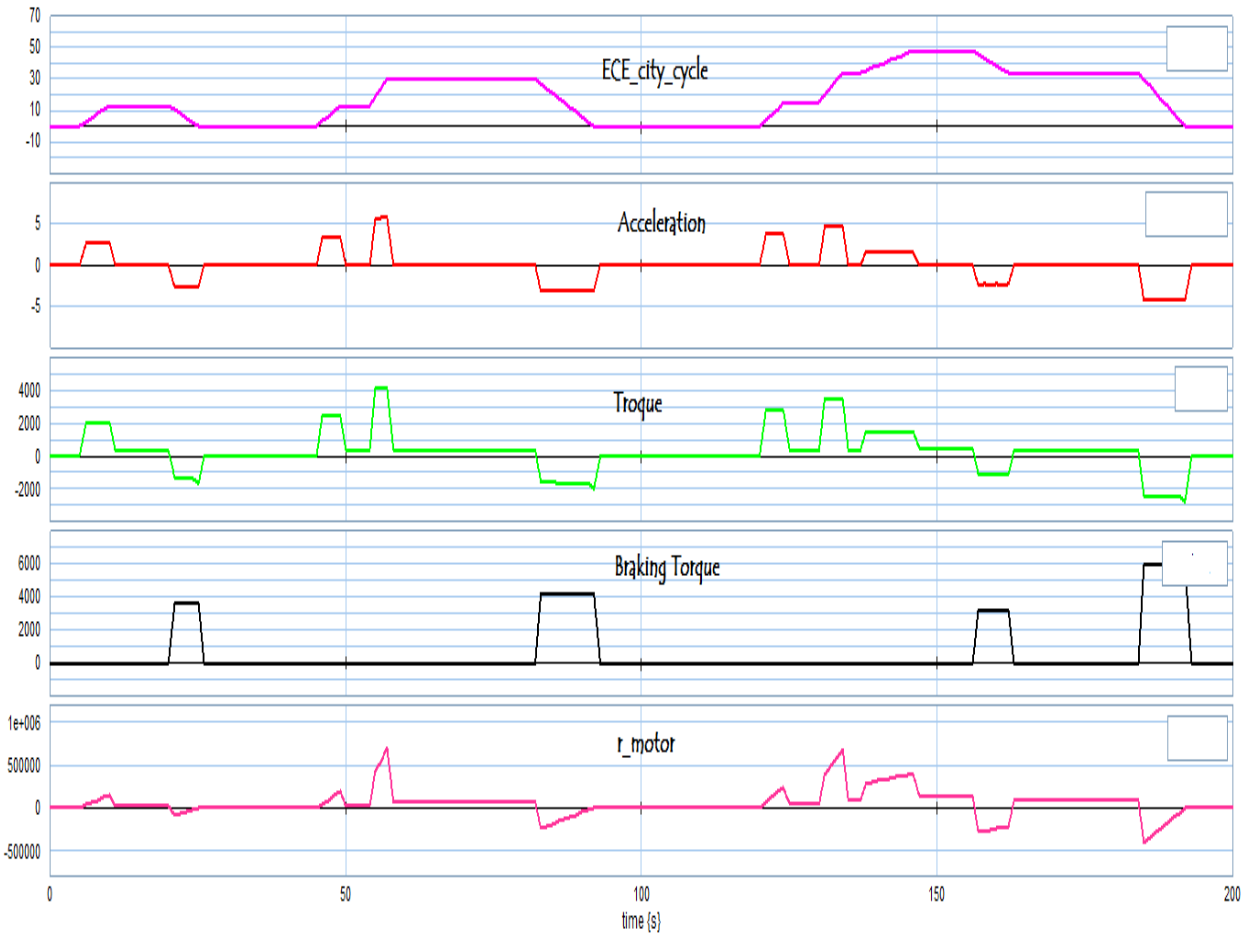

Figure 2: Simulation results of Vehicle

As clearly seen on above figure that braking torque is active only when acceleration of the vehicle is negative and that interval r_motor is also negative, which means that resistance (motor) acts as a power source.

APPENDIX E

As described in chapter 3, 54% of fuel saved in ECE city cycle which is a standard cycle to test the vehicles on virtual environment. Environmental protection agency (EPA) claims that in series hydraulic hybrid vehicle 70% of fuel can be saved. In chapter 3 we analyze the vehicle with two strategies.

- Engine is off when vehicle is in idle mode
- Engine is off when the vehicle is in braking mode

We did not discuss the regeneration time or when HPA acts as a source, in which pump and engine are supposed to switch off. A block diagram model is presented for fuel consumption and later on putting the model in topological model I and topological model II. Figure a shows the model.

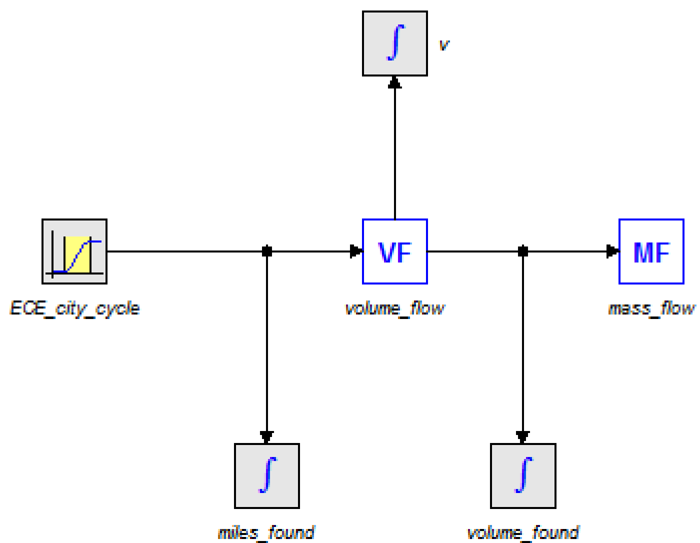

Figure a: Fuel Consumption Model

Block named *miles_found* gives the cycle's mileage and *volume_found* shows the volume consumed by any specific vehicle. By putting the model in topological models, it was observed that results are quite match able and after rounding the figures results are same which are shown in table a.

ECE City Cycle	
Time (sec)	**Fuel Consumed (liters)**
0-200	4.68e-05
200-400	8.98e-05
400-600	0.13
600-800	0.17
EUDC Highway cycle	
800-1200	0.8

Total fuel consumed by SHHV on ECE city cycle=0.17

Total fuel consumed by SHHV on EUDC highway cycle=0.8

Total fuel consumed by SHHV on Full cycle=0.17+0.8=0.97

Total fuel consumed by conventional vehicle on full cycle=4

So percentage of saved fuel is

$$\%SF = \left(\frac{4 - 0.97}{4}\right) * 100$$

$$= 75\ \%$$

For full cycle 75 % of fuel is saved as a result of topological model.

APPENDIX F

Parametric Study

Sizing of high pressure accumulator is an important issue in hydraulic hybrid vehicle. Although carbon fibers are used to manufacture the accumulators; so minimizing the weight of overall vehicle, but the packaging of accumulators is main issue in the vehicle. As low pressure accumulator is normally three times of high pressure accumulator in respect to volume. In our models we take high pressure accumulator which has the capacity of 100 liters; 50 liters each for gas and hydraulic fluid. In this parametric study, the volume of gas in the high pressure accumulator is constant and varying the volume of hydraulic fluid. The important consequences of this parametric study will be fuel efficiency, maximum pressure and temperature in the high pressure accumulator. Table 1 shows the result of parametric study.

Max Volume of HPA (Liters)	**ECE (Fuel consumption)**				**EUDC**	**Max. Pressure (bar)**	**Max. Temperature (Kelvin)**	**Fuel efficiency (%)**
	0-200 (sec)	200-400 (sec)	400-600 (sec)	600-800 (sec)				
80	0.0406	0.077	0.11	0.15	0.77	326	349	77
90	0.045	0.082	0.12	0.16	0.78	339	362	76.5
100	**0.048**	**0.088**	**0.13**	**0.17**	**0.8**	**350**	**375**	**75**
110	0.0511	0.095	0.14	0.19	0.82	361	386	74.75
120	0.0577	0.108	0.16	0.2	0.84	371	396	74
130	0.0594	0.11	0.16	0.21	0.85	381	407	73.5
140	0.067	0.12	0.18	0.24	0.87	390	417	72.25

Table 1: Results of Parametric study

For the MVEG-95 cycle results of parametric study gives the understanding of different varying parameters like fuel efficiency, maximum pressure in HPA which is 350 bar in model and maximum temperature in HPA which is 375 Kelvin in topological model. Figure 1 shows the graph between max volume and fuel efficiency for our cycle.

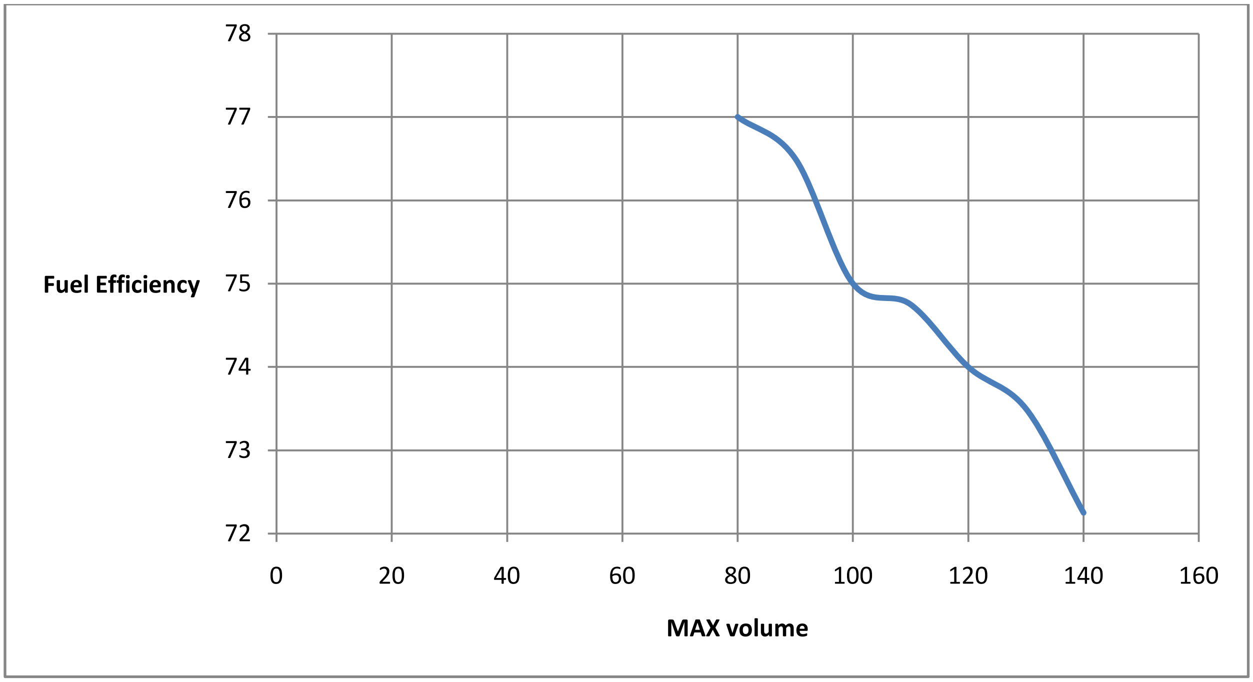

Figure 1: Max Volume of HPA vs. Fuel Efficiency

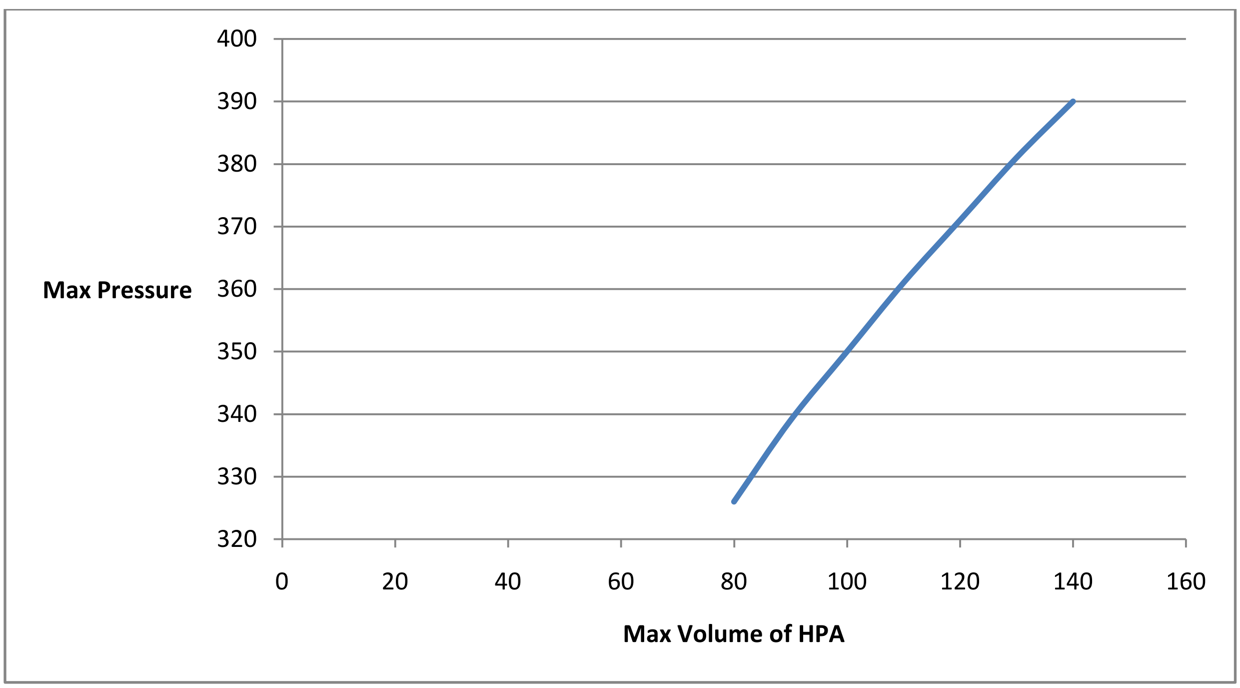

Figure 2: Max Volume vs. Max Pressure of HPA

As evident from figure 1 that there is no significance change in the fuel efficiency in ECE cycle. While maximum pressure of high pressure accumulator is increased with the increase of maximum pressure in the HPA. Figure 3 shows the maximum temperature effect in high pressure accumulator which shows the same trend as the maximum pressure.

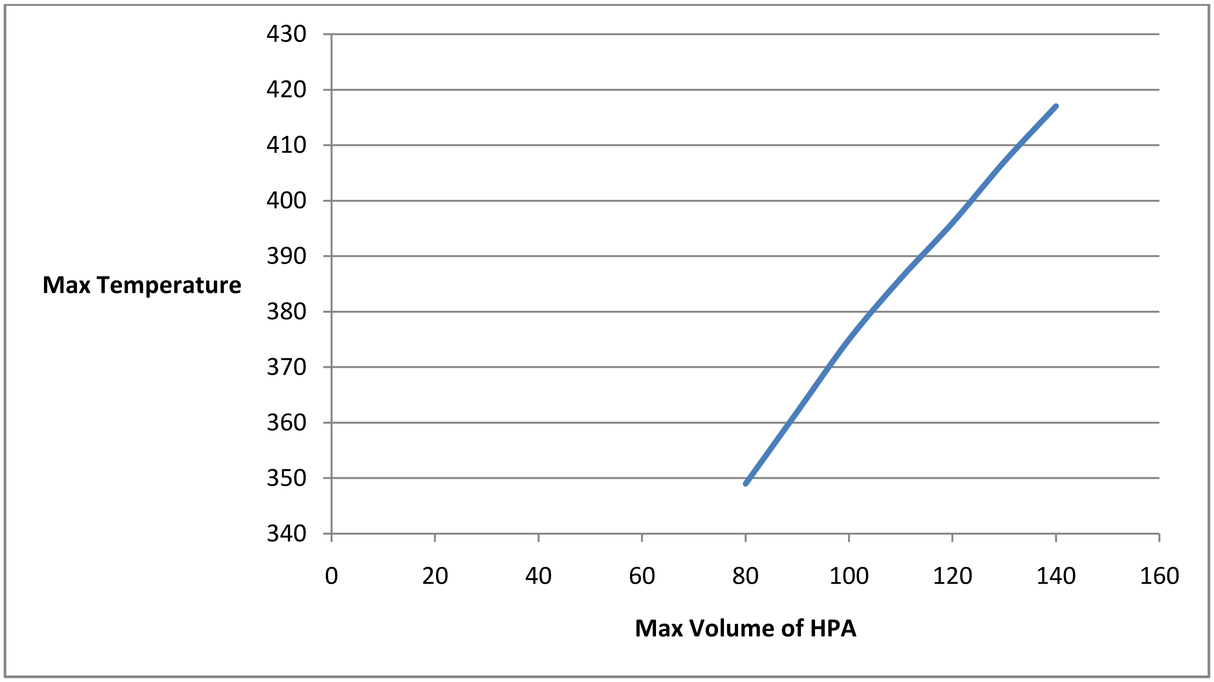

Figure 3: Max Volume vs. max temperature of HPA