A Study of Vehicle Fuel Consumption Simulation using VHDL-AMS Multi-domain Simulation

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Abstract – The vehicle system is a multi-domain system that requires many branches of science and engineering. Therefore the development of the vehicle system requires the use of design methodologies that utilize simulations, which have grown increasingly sophisticated in recent years. Our research group proposed a simulation modeling method based on the VHDL-AMS language. This paper describes how VHDL-AMS is used to model of vehicle fuel consumption simulation. The fuel consumption is shown using proposed simulation model on the Japanese 10-15 mode. We examine the influence of the vehicle system with electrical load and hill climb resistance in the vehicle running resistance.

Keywords: Vehicle, Fuel consumption, System simulation, Multi-domain simulation

1. Introduction

The setting of a stricter carbon dioxide emissions reduction target due to global warming has led to several discussions on environment-responsive system car. Air pollution in major urban centers is also an extremely important environmental issue, and the need to reduce traffic accidents and increase safety, are further considerations related to the use of vehicles [1]. To meet these demands, technologies related to vehicle development have continued to increase in complexity in recent years. Then, the usage of simulation technology in the design and development phase has become increasingly indispensable [2]. The vehicle system is a multi-domain system that requires many branches of science and engineering, such as mechanical, heat, magnetic, hydraulic and electrochemical fields, as well as the electrical circuits and control circuits that drive them. Therefore, we considered modeling using VHDL-AMS (Very High Speed Integrated Circuit Hardware Description Language-Analog and Mixed Signal) [3]. The VHDL-AMS is a general-purpose circuit description language, which has the possibility of applying Kirchhoff's law to the multi-domain energy simulation using the same topology of electrical circuits. And so, we proposed a vehicle system simulation, and reported various analysis results [4]-[7].

This paper describes how VHDL-AMS is used to model a vehicle fuel simulation. We describe the calculation model of the amount of fuel supply and fuel consumption

by using the VHDL-AMS. The fuel consumption results are shown in consideration of the power-network system comprised of the alternator, battery and electrical load. In addition, we examine the influence of hill climb resistance in the vehicle running resistance.

2. Multi-Domain Simulation

To discuss the optimization of a whole vehicle, as discussed before, we should consider multi-domain energy at the same time and an effective integrative simulation tool that takes amount of these energies. Previously, the analysis of simulation was focusing on the development of each vehicle components. This means that the purpose of simulation was the optimization of each component. However for the past-mentioned reasons, to optimize whole vehicle system and exhausted carbon dioxide, the technology that can consider whole vehicle energy is needed. For that purpose, it is necessary to develop a simulation model, which can consider the behavior of energy conservation law in multi-domains simultaneously. By this development, it is possible to discuss the interaction with different technical fields. Physics in vehicle can be mostly discussed by analogue derivation. The analogue derivation can be expressed by through quantity and across quantity. Here, for example of the electrical domain, the through quantity and across quantity means current and voltage respectively. Figure 1 shows the notion of through quantity and across quantity in the Kirchhoff's law. The law is also energy conservation law. The Table 1 shows the application of the Kirchhoff's law to other technical domain [3]. The IEEE 1076.1 adopts the law. Therefore we decided

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that IEEE 1076.1 (VHDL-AMS) is the most effective technique during the study of whole vehicle modeling[4]-[7].

Fig. 1. The notion of Kirchhoff's law

Table 1. Multi-domain Physics

	Electrical	Translational_V	Rotational_V
Across quantity	Voltage (V)	Velocity (m/s)	Angular velocity (rad/s)
Through quantity	Current (A)	Force (N)	Torque (Nm)

3. Modeling of Vehicle System

3.1 Model for Calculating the fuel consumption

The engine rotational speed is calculated using the vehicle running speed as the input. Equation (1) is used for the calculation.

$$N_e = \frac{1000}{120\pi} \cdot \frac{i_m \cdot i_f}{r} \cdot V \quad (1)$$

Where, N_e is the engine rotational speed [r/min], V is the vehicle running speed [km/h], r is the effective tire radius of the drive wheel [m], i_m is the gear ratio, and i_f is the final reduction gear ratio, respectively.

The engine torque T is calculated using the vehicle running resistance as following equation (2), (3).

Case of $R \geq 0$

$$T = \frac{r}{\eta_m \eta_f i_m i_f} \cdot R \quad (2)$$

Case of $R < 0$

$$T = \frac{r \cdot \eta_m \eta_f}{i_m i_f} \cdot R \quad (3)$$

Where, T is the engine torque [Nm], η_m is the power transmission efficiency of the transmission, η_f is the power transmission efficiency of the Differential Gear.

Also, a running resistance is generated which decreases a

vehicle driving force. The running resistance R has the rolling resistance R_r , the air resistance R_a , the hill climb resistance R_g and the acceleration resistance R_i . These are represented by the following equation.

$$R = R_r + R_a + R_g + R_i \quad (4)$$

$$= \mu_r Mg + \kappa v^2 + Mg \sin \theta + (M + M_r) \alpha$$

Where, R is the vehicle running resistance [N], μ_r is the rolling resistance coefficient, κ is the air resistance coefficient, θ is the slope angle, M is the vehicle weight [kg], M_r is the equivalent weight of rotating parts [kg], α is the vehicle acceleration [m/s/s], g is the gravitational acceleration, respectively.

Equation of motion is represented by the relationship between the vehicle running resistance and the driving force, as in equation (5).

$$F = \mu_r Mg + \kappa v^2 + Mg \sin \theta + (M + M_r) \alpha \quad (5)$$

Also, engine power is calculated using equation (6).

$$P = \frac{2\pi N_e T}{60} \quad (6)$$

The fuel consumption f_i [g/s] is calculated using general fuel consumption contour line as shown Fig.2, and using the relationship between the engine rotational speed, equation (1), and the engine torque, equation (2)(3). The relationship between the fuel consumption ratio f [g/kWh] and the fuel consumption f_i is represented using the engine power as in equation (7).

$$f_i = \frac{f \cdot P}{3.6 \times 10^6} \quad (7)$$

Fig. 2. Fuel Consumption Map

Fig. 3. Simulation Model

```

----- VHDLAMS MODEL re_vehicle_reist -----
Library IEEE;
use IEEE.MECHANICAL_SYSTEMS.all;
use IEEE.MATH_REAL.all;
----- ENTITY DECLARATION re_vehicle_reist -----
ENTITY re_vehicle_reist IS
Generic(
  u_r  : REAL := 0.013;  --rolling resistance coefficient [-]
  m    : REAL := 1220.0; --car weight [kg]
  mr   : REAL := 33.3;  --car inertia [kg]
  cd   : REAL := 0.29;  --air drag coefficient [-]
  rho  : REAL := 0.125; --air density (pho/g)[kg*s^2/m^4]
  as   : REAL := 1.83   --frontal area [m^2]
);
Port(
  Quantity  v_in  : in REAL;      --input velocity [km/h]
  Quantity  s_in  : in REAL;      --input slope [%]
  Terminal  whl_out : TRANSLATIONAL_VELOCITY
                                --to wheel model [m/s][N]
);
.....
BEGIN
  vel == v_in/3.6;                --[km/h] to [m/s]
  acc == vel'dot;                 --reduce accel [m/s^2]
  arg == s_in;                    --angle [%]
  arg == tan(theta)*100.0;         --[%] to [rad]
  r_grd == m*g*sin(theta);         --grade resistance [N]
  r_air == 0.5*cd*rho*as*vel*vel; --air resistance [N]
  r_inr == (m+mr)*acc;             --inertia resistance [N]
  f_out == r_rol+r_air+r_inr+r_grd; --total vehicle resistance [N]

  v_out == vel;                  --vehicle velocity [m/s]

```

Fig. 4. Vehicle Running Resistance Model

3.2 Description of Models

The whole simulation model for fuel consumption calculation is shown Fig. 3. This model consists of the driver, engine, transmission (differential gear, gear box), wheels, shift select, running resistance and power-network. The driving pattern is used the Japanese 10-15 mode as the driver model. Three domains, Electrical, Translational_V and Rotational_V, are mixed in the whole simulation model. The constitution and description using VHDL-AMS for each model element are discussed below.

```

Port(
  Terminal res_in  : TRANSLATIONAL_VELOCITY;
                                --to vehicle resister model [m/s][N]
  Terminal dif_out : ROTATIONAL_VELOCITY
                                --to diff model [rad/s][N*m]
);
END ENTITY re_wheels;
-- ARCHITECTURE DECLARATION arch_re_wheels --
ARCHITECTURE arch_re_wheels OF re_wheels IS
  Quantity V_IN across F_IN through res_in;
  Quantity OMG_OUT across dif_out;
  Quantity TRQ_OUT through ROTATIONAL_VELOCITY_REF to dif_out;
BEGIN
  V_IN == tire_r*OMG_OUT;
  TRQ_OUT == F_IN*tire_r;

```

Fig. 5. Wheel Model

Fig. 6. Wheel Model

(1) The Vehicle Running Resistance Modeling

This model is described as vehicle model with motion equation. In this model, the driving force is derived from the rolling resistance, the acceleration resistance, the air resistance and the hill climb resistance. The vehicle velocity also is derived. The part of the description of this model using VHDL-AMS is shown in Fig. 4.

(2) The Wheel Modeling

This model exchanges the Translational_V domain of the resistance model for the rotational_V domain of the differential model, as shown Fig.5 and Fig.6. Those

relations, velocity and angular velocity, force and torque, are calculated the radius of the tire.

(3) Differential Gear Modeling

The part of the description of the differential gear model by VHDL-AMS is shown in Fig.7. The relations of input and output are defined by the efficiency (η) and the ratio (ratio) of differential gear in this model. The rotational_V domain is used in this model.

```
BEGIN
  OMG_OUT == OMG_IN*ratio;           --angular velocity[rad/s]
  If TRQ_IN >= 0.0 use                --torque[N*m]
    TRQ_OUT == TRQ_IN/ratio/eta;
  else
    TRQ_OUT == TRQ_IN/ratio*eta;
  end use;
```

Fig. 7. Differential Gear Model

(4) Gear Box Modeling

The efficiency and the ratio of transmission gear are defined in this model. And also the torque and the speed for engine are derived in this model. The part of the description of the gear box model by VHDL-AMS is shown in Fig. 8. The gear ratio is selected by shift position depending on the driving pattern.

(5) Engine Map Modeling

The engine map model is described using fuel consumption contour line as shown Fig.2. The fuel consumption rate is derived from the relationship of the engine speed and the engine torque. The part of the description of the gear box model by VHDL-AMS is shown in Fig. 9.

(6) Fuel Consumption Calculation Modeling

This model calculates the fuel consumption from fuel supply and the mileage, as shown in Fig. 10.

(7) Alternator Modeling

This model exchanges the rotational_V domain of the engine and gear model for the electrical domain of the battery model, as shown in Fig. 11 and 12. The alternator is a claw-pole field type synchronous generator with field winding and a three-phase full-wave rectifier circuit. The modeling of the alternator can be described using the voltage and motion equation. But for the purpose of simplification, It is possible to model by using a look-up table from experimental or analysis result data. In this case, the experimental current vs. speed table is used in this model as shown in Fig. 13.

```
if s_shift = 1.0 use
  ratio_gear == first;
  if (TRQ_IN >= 0.0) use
    TRQ_IN == eta*ratio_gear*trq;
  else
    TRQ_IN*eta == ratio_gear*trq;
  end use;
.....
elsif s_shift = 5.0 use
  ratio_gear == fifth;
  if (TRQ_IN >= 0.0) use
    TRQ_IN == eta*ratio_gear*trq;
  else
    TRQ_IN*eta == ratio_gear*trq;
  end use;
else
  ratio_gear == neutral;
  TRQ_IN*ratio_gear == eta*trq;
```

Fig. 8. Gear Box Model

```
if ( rpm_in < 800.0 ) use
  rpm == 800.0;
else
  rpm == rpm_in;
end use;
if ((rpm >= 800.0) and (rpm <= 1000.0)) use
  if ((trq >= 0.0) and (trq <= 20.0)) use
    f == 500.0;
  elsif((trq >20.0) and (trq <= 25.0)) use
    f == 400.0;
  .....
end use;
```

Fig. 9. Engine Map Model

```
BEGIN
  vel == v_in/3.6;
  len == vel'integ;
  f_all == ft_in'integ;
  f_all == sg*cc_all;
  f_cns == len/cc_all;

END ARCHITECTURE arch_fuel_cns_clc;
```

Fig. 10. Fuel Consumption Calculation Model

```
Function alt(rpm : REAL) Return REAL is
  Constant x      : REAL_VECTOR := (1000.0,1500.0,...,12000.0);
  Constant y      : REAL_VECTOR := (0.0,40.0,...,120.0);
  Variable res : REAL := 0.0;
Begin
  if rpm < x(0) then res := y(0);
  else
    if rpm < x(1) then res := y(0)+(rpm-x(0))/(x(1)-x(0))*(y(1)-y(0));
    else
      .....
    end if;
  end if;
  Return res;
End function alt;
BEGIN
  rpm_out == OMG_OUT*60.0/math_2_pi;
  I_IN == -alt(rpm_out);
  OMG_OUT*TRQ_OUT == -I_IN*V_IN;
```

Fig. 11. Alternator Model

Fig. 12. Alternator Model

Fig. 13. The current – speed characteristic

(8) Battery Modeling

The lead-acid storage battery is widely used in today's vehicles. The chemical reaction of the battery electrodes causes the acidic concentration to be lower near the electrodes during the discharge state. The diffusion of acidic molecules between the upper and lower concentration regions was modeled using the equivalent circuit shown in Fig. 14, by using diffusion resistance, in addition to a slow- and fast-charging and discharging capacitor [8]. Part of the model description by VHDL-AMS using the equivalent circuit from Fig. 14 is shown in Fig. 15.

(9) Load Modeling

For this research, the load was modeled as ideal resistance. For the electrical load, R_1 is 0.9Ω and R_2 is 7Ω . R_1 is equivalent to using the lights and air-conditioning, and R_2 simulates the hazard lights [9].

Fig. 14. Equivalent Circuit of Battery

```

Terminal t1,t2 : ELECTRICAL;
Quantity v_ri across i_ri through p to t1;
Quantity v_rd across i_rd through t1 to t2;
Quantity v_cf across i_cf through t1 to ELECTRICAL_REF;
Quantity v_cs across i_cs through t2 to ELECTRICAL_REF;
.....
.....
q_all == ((cf*factor)*v_cf)+((cs*factor)*v_cs);    --(Q=C*V)
soc_out == q_all/q_max;                          --(SoC=Qtotal/Qmax)

v_ri == ri_val*i_ri;                             --(V=R*I)
v_rd == rd*i_rd;                                 --(V=R*I)
v_cf'dot == 1.0/(cf*factor)*i_cf;                --(dV/dt=I/C)
v_cs'dot == 1.0/(cs*factor)*i_cs;                --(dV/dt=I/C)

```

Fig. 15. Battery Model

3.3 Mode Model

Mode model is used to input the vehicle running speed into the simulation model. In the mode model, the Japanese 10-15 mode speed profile is used as shown Fig. 16. The Japanese 10-15 mode is the measurement of fuel consumption on the condition stipulated by the Ministry of Land Infrastructure Transport and Tourism. The fuel consumption is measured on not the actual load but chassis dynamometer at the following condition.

- Vehicle after braking-in over 3000km distance
- Fully warm-up condition (after 15 minutes warm-up operation at 60km/h)
- The vehicle weight including 2 passengers (110kg).
- Turn off the air conditioning and vehicle electrical equipment
- The test room temperature 25 deg. $\pm$ 5 deg., relative humidity is kept within the range of 75% from 30%

Fig. 16. Vehicle Speed (10-15mode)

4. Analysis Results

As a vehicle simulation model, four-cylinder engine and five speed manual transmissions vehicle was modeled. The representative parameters are listed on the table 2 from target vehicle catalog and specifications. The Simplorer by ANSYS, Inc. [8] was used as the multi-domain simulator supported the use of VHDL-AMS.

Table 2. Target Vehicle Specifications

	Parameter	
	Name	Value
Vehicle	Mass	1110kg
	Front projection area	1.83 m ²
	Air coefficient	0.29
	Air density	0.125 kgs ² /m ⁴
Tire	Radius	0.32 m
	Rolling coefficient	0.013
Trans mission	1 st gear ratio	3.545
	2 nd gear ratio	1.904
	3 rd gear ratio	1.233
	4 th gear ratio	0.885
	5 th gear ratio	0.725
	Final reduction gear ratio	4.312
Alternator	Efficiency	0.95%
	Figure 12	
Battery	Resistance r_i	0.01
	Resistance r_d	0.04
	Capacitance c_f	60
	Capacitance c_s	20000

At first, it is reported that the results of fuel consumption model does not take into account the slope and electrical equipment. This condition is quite similar to the 10-15 mode. When the vehicle running speed varied from 20km/h to 0km/h, the clutch is disengaged at 10km/h. Similarly, from 40km/h to 0km/h : at 20km/h, from 70km/h to 0km/h : at 30km/h. When the vehicle running speed is 0km/h or the clutch is disengaged, the engine rotational speed is 800r/min. The fuel consumption on decelerating condition and idling condition are 0.0g/s and 0.1g/s, respectively. The resulting fuel consumption was 17.8km/L as shown in Fig. 17. As the resulting value is almost similar to the catalog fuel consumption of 17.2km/L, this system model is useful for fuel consumption simulation.

Figure 18 shows the fuel consumption result when we consider the influence of the electrical equipment. The fuel consumption here was 16.4km/L which is evidently a decrease in 7.87%. Fuel consumption for the electrical equipment in current automobiles has been 5 to 10% of the total fuel consumption. Thus, the result was befitting in that range. The alternator current is also shown in Fig. 19.

Finally, Fig. 20 and 21 illustrates the results of fuel consumption in consideration of slope. It shows the inputted slope in the vehicle running resistance model in Fig. 19. In case of the required torque for a positive slope climbing in the interval is unobtainable, each shift position could be shifted down so that the required torque could be obtain. As the results, the fuel consumption was 14.7km/L. It indicates 10.4% deterioration in comparison with the electrical equipment.

Fig. 17. Fuel Consumption (no load and no slope) **Fig. 18.** Fuel Consumption (Add load) **Fig. 19.** Alternator current **Fig. 20.** Vehicle Speed And Slope **Fig. 21.** Fuel Consumption (Add load and slope)

5. Conclusion

This paper described the modeling method of the vehicle system and the fuel consumption calculation using standardized circuit description language VHDL-AMS. The modeling results showed that VHDL-AMS is useful for conducting a vehicle system simulation. As the results, this research can be applied to the energy management investigation using vehicle system for carbon dioxide reduction. In addition, on the design stage, our simulation method enables the development cost and time to be reduced.

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