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RESEARCH ON MODULARIZED DESIGN AND PERFORMANCE ASSESSMENT BASED ON MULTI-DRIVER OFF-ROAD VEHICLE DRIVING-LINE

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ABSTRACT−The multi-driver off-road vehicle drive-line consists of many components, with close connections among them. In order to design and analyze the drive-line efficiently, a modular methodology should be taken. The aim of a modular approach to the modeling of complex systems is to support behavior analysis and simulation in an iterative and thus complex engineering process, by using encapsulated submodels of components and of their interfaces. Multi-driver off-road vehicles are comparatively complicated. The driving-line is an important core part to the vehicle, it has a significant contribution to the performance. Multi-driver off-road vehicles have complex driving-lines, so performance is heavily dependent on the driving-line. A typical off-road vehicle's driving-line system consists of a torque converter, transmission, transfer case and driving-axles, which transfers the power generated by the engine and distributes it effectively to the driving wheels according to the road condition. According to its main function, this paper proposes a modularized approach for design and evaluation of the vehicle's driving-line. It can be used to effectively estimate the performance of the driving-line during the concept design stage. Through an appropriate analysis and assessment method, an optimal design can be reached. This method has been applied to practical vehicle design, it can improve the design efficiency and is convenient to assess and validate the performance of a vehicle, especially of multi-driver off-road vehicles.

KEY WORDS : Multi-drivers off-road vehicle, Driving-line, Modular design, Performance assessment

1. INTRODUCTION

The multi-driver off-road vehicle drive-line consists of many components, with close connections existing among them. In order to design and analyze the drive-line efficiently, modular methodology should be taken. The aim of a modular approach to modeling of complex systems that is based on commercial CAD/CAE technology is to support behavior analysis and simulation in an iterative and thus complex engineering process, by using encapsulated submodels of components and of their interfaces. This way, we can check and evaluate the assembly/disassembly, matching performance deficiencies among the components of a product at the designing stage. This is very beneficial, especially for complex products.

A typical off-road vehicle's driving-line system consists of a torque converter, transmission, transfer case and driving-axles, which transfer the power generated by the engine and distribute it effectively to the driving wheels according to the road conditions. A main task during the concept design of a driving-line is to optimally match these parameters to fulfill the performance requirement of the vehicle.

Generally, it is very difficult to design a good driving-line for a certain vehicle using present design methods; the work needs to be done by experienced engineers. After the driving-line has been designed, a series of tests are required to verify the design, and redesigns are necessary. Although some optimal methods and software tools are developed to aid the design process, they are not very effective universally to all vehicles' driving-line systems, especially multi-driver off-road vehicles.

As an aid to conceptual developments of the driving-line system for multi-driver off-road vehicles, efficient, validated and physically based system models are necessary. The model should capture the basic features of the system and represent the most essential system behavior.

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The purpose of this paper was to develop a modular based computer model for driving-line systems. This model should be complete enough to predict the correct trend of behavior of a driving-line in a vehicle and be simple enough to study the influence of the main design factors, so as to optimally match these parameters in the driving-line system through performance assessment. The remainder of this paper is organized as follows. Some related works are briefly introduced in section 2. The modeling of each component of the drive-line is described in section 3. Conceptual design of the drive-line is explained in section 4. Performance assessment of drive-line is discussed in section 5. In section 6, a brief description of the performance assessment tools for off-road vehicle drive-lines is introduced. In section 7, a case study is given, to illustrate the method presented in the paper. Some conclusions and future works are drawn up in the final section.

2. RELATED WORKS

There are a lot of researchers who have researched dynamic simulation and modularized design methodology regarding Off-road vehicles. Andrew W. Phillips, etc. developed a personal computer-based vehicle powertrain simulation (VPS) to predict fuel economy and performance (Phillips and Assanis, 1996; Park *et al.*, 2004). VPS code can provide good predictions of vehicle fuel economy, and thus is a useful tool in designing and evaluating vehicle powertrains. H-S Jo, etc., presented the main algorithms of POTAS-MSM (POwer Transmission Analysis Software for MultiSlipping Mechanisms), which are based on the concept of subsystem assembly and the self-determination technique for system degrees of freedom (Lim *et al.*, 2000). Gumlnter H. Hohl and Alexander Corrieri put forward basic considerations for the Concepts of Wheeled off-Road Vehicles (Hohl and Corrieri, 2000). Lim, W. S., Jo, H. S., Jang, W. J. etc. developed a general purpose program based on the concept of subsystem assembly for the analysis of dynamic characteristics of a power-train system (Jo *et al.*). This paper puts forward the modularized methodology according to the component structural features of the driving-line of multi-driver off-road vehicles. Based on these, flexible tools to evaluate Driving-line Performance have been developed with Visual C++ and are able to be integrated into other CAD/CAE systems.

3. DRIVING-LINE MODELING

The main purpose of the driving-line system in a vehicle is to convert, transfer and distribute torque and rotation generated by the engine correctly and efficiently to the driving wheels to fulfill the kinematic requirements of the vehicle. From this point of view, the parts in the driving-line system can be abstracted as elements which input from the engine and finally outputs to driving. Because the torque and rotation are originally input from the engine and finally output to the driving wheels, models should also include them.

3.1. Engine

The main design parameters of an engine and their relationships are defined as follows (Liu *et al.*, 1991):

$$M=M_{e\max}-\frac{M_{e\max}-M_P}{(n_P-n_M)^2}(n_M-n)^2 \tag{1}$$

where: M--*Output torque*
n--Output rotate speed
M_{emax}--Maximal output torque
n_M--Rotate speed at maximal torque
M_P--Output torque at maximal power
N_P--Rotate speed at maximal power

3.2. Transmission (Reducer)

Similarly, the model of transmission or reducer is defined as:

Torque equation:

$$M_O=\eta i_0 M_I \tag{2}$$

Rotating speed equation:

$$n_O=n_I/I_0 \tag{3}$$

where: M_O--Output torque
M_I--Input torque
i_O--Ratio
n_O--Output rotate speed
n_I--Input rotate speed
η--*Efficiency*

3.3. Torque Converter

The difficult point of torque converter modeling lies in the fact that the torque coefficients and speed ratios are non-linear, otherwise it could simply be regarded as a reducer. The input and output relationships are (Shang *et al.*, 1999):

Torque equation:

$$M_O=k_C M_I \tag{4}$$

Rotating speed equation:

$$n_O=i_C n_I \tag{5}$$

Constraint equation:

$$k_C=\sum_{k=0}^{N_C} B_k i_C^k \tag{6}$$

where: M_O--*Output torque*
M_I--Input torque

k_C--Torque coefficient
n_O--Output rotate speed
n_I--Input rotate speed
i_C--Speed ratio
B_k--Polynomial coefficient
N_C--*Degree of the polynomial*

3.4. Transfer Case
The equations for the transfer case are defined as:
Torque equation:

$$M_{O1}=wM_{O2} \tag{7}$$

Rotating speed equation:

$$n_{O1}=n_{O2}=n_I/i \tag{8}$$

Constraint equation:

$$M_I \geq \frac{M_{O1}+M_{O2}}{\eta i} \tag{9}$$

where: M_{O1}--*Front output torque*
M_{O2}--Rear output torque
w--Torque bias ratio
M_I--Input torque
n_{O1}--Front rotating speed
n_{O2}--Rear rotating speed
n_I--Input rotating speed
i--Ratio
η--*Efficiency*

3.5. Differential
The equations for the differential are defined as:
Torque equation:

$$\max(M_{01}, M_{02})=k_D \min(M_{01}, M_{02}) \tag{10}$$

Rotating speed equation:

$$n_I=\frac{n_{O1}+n_{O2}}{2} \tag{11}$$

Constraint equations:

$$M_I \geq \frac{M_{O1}+M_{O2}}{\eta} \tag{12}$$

$$k_D=\sum_{k=0}^{N_K} D_k \Delta n_O^k \tag{13}$$

where: M_{O1}--*Left output torque*
M_{O2}--Right output torque
M_I--Input torque
k_D--Torque bias ratio
n_{O1}--Left rotating speed
n_{O2}--Right rotating speed
n_I--Input rotating speed
D_k--Polynomial coefficient
N_k--Degree of the polynomial
Δn_0--*Rotating speed difference*
η--*Efficiency*

3.6. Wheel
The equations for the wheel are defined as:
Force equations:

$$F_f=\mu F_P \tag{14}$$

$$F_t=\frac{M_I \eta}{R} \tag{15}$$

Speed equation:

$$v=\frac{\pi n_I(1-\delta)}{108} \tag{16}$$

Constraint equation:

$$F_f \leq F_t \leq \varphi F_P \tag{17}$$

where: F_f--Rolling resistance
F_P--Normal force
F_t--Circumferential force
M_I--Input torque
R--Rolling radius
v--Speed
n_I--Input rotating speed
μ--Coefficient of rolling resistance
δ--Slip rate
φ-- Coefficient of adhesion
η--Efficiency

3.7. Whole Driving-line Model
The whole driving-line is the combination of the above mentioned parts' models. According to the property of the model, it is convenient to represent it in a computer using the object-oriented programming method, making it very flexible to model the driving-line system accord-

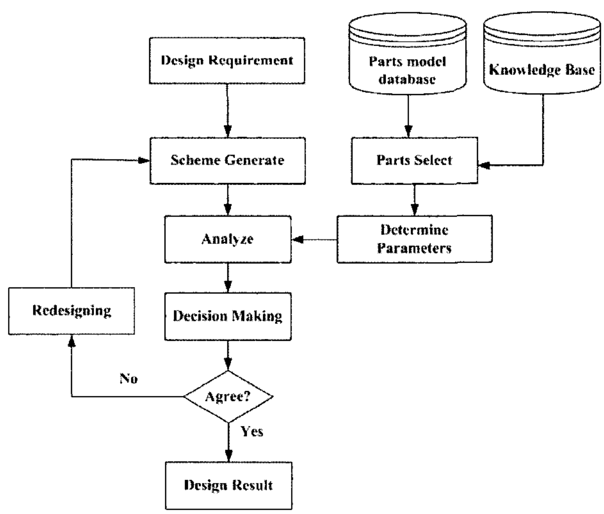

Figure 1. Conceptual design procedure.

ing to a certain design.

4. CONCEPT DESIGN OF DRIVING-LINE

The manner used to select parts according to the design requirements of the driving-line is the first step that must be considered during the concept design stage. Then, the design parameters of every part should be determined, and the design is considered finished after all these parameters are optimally matched.

Here, modular design methodology is used based on the driving-line model, and some heuristic rules are provided. The design procedure is divided into four steps, which is shown in Figure 1, they are driving-line scheme generation, performance analysis, decision making and redesign.

In this paper, only performances analysis is described in the following section.

5. PERFORMANCE ASSESSMENT

In order to optimally match the design parameters of a driving-line system during the design, performance assessment is essential.

5.1. Assessment Indices

Usually validity, safety, reliability and economy are four basic indices of off-road vehicles (Zhuang, 1997). Among them, the validity index is the most important measured performance of a ground vehicle.

According to the particularity of off-road vehicles, the following indices were chosen for assessment. They were tractive and velocity performances, turnability and ride stability.

Tractive and velocity performances define the ability of vehicles to move under the influence of circumferential wheel forces. Usually, tractive and velocity performances are considered, together with fuel economy. This is described by the transport efficiency η_x (Vantsevich, 1994):

$$\eta_x = \frac{\sum_{i=1}^{m} (F_{fi}' + F_{fi}'')}{\sum_{i=1}^{m} [F_{Pi}'/(1-\delta_i') + F_{Pi}'/(1-\delta_i'')]} \tag{18}$$

Circumferential force distribution influences the turnability of a vehicle. Turnability is the ability to change trajectory according to changes in construction and working conditions. The resistant torque (M_R) is used to estimate the turnability:

$$M_R = \sum_{i=1}^{m} (F_{ti}' - F_{ti}'') \times \frac{B}{2} \tag{19}$$

where B is the wheel-base of the vehicle.

5.2. Calculation of the Indices

According to equations (18) and (19), the circumferential force on each driving wheel should be calculated first before any of the indices can be gained. This is a very complex task for a multi-driver off-road vehicle driving-line. The following algorithm is used to automatically calculate circumferential force on each driving wheel under any running condition of the vehicle imposed on the driving-line model.

Step 1: Give working conditions, calculate rolling resistance and adhesive force on each driving wheel;

Step 2: Let the circumferential force be equal to the adhesive force, from wheels to engine, inversely calculate every parts' necessary output torque and rotating speed in the system which will provide the needed circumferetial force;

Step 3: To each part, know the output, seek the input; input torque is gained by the torque equation, input for rotating speed is gained by the rotating speed equation,

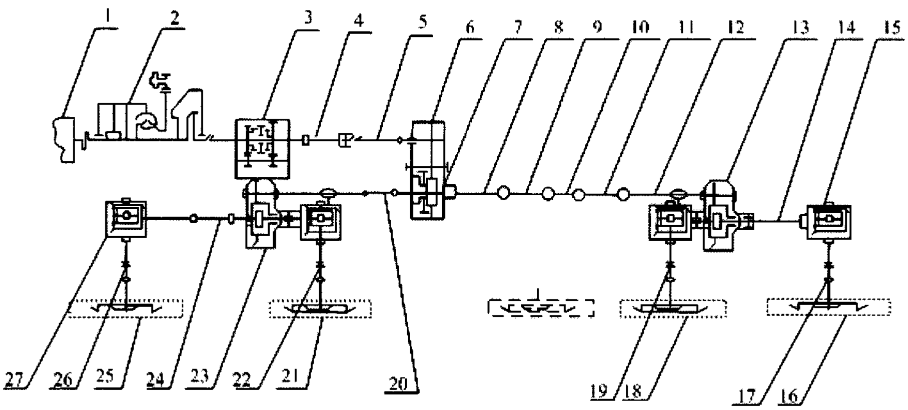

Figure 2. Example of a 10×8 heavy off-road vehicle's driving-line. 1. Engine & Torque Converter, 3. Transmission, 6. Transfer Case, 7. Grip Brake, 13,18,19. 4th Driving-axle, 15,16,17. 5th Driving-axle, 21,22,23. 2nd Driving-axle, 25,26,27. 1st Driving-axle, 2,4,5,8,9,10,11,12,14,20,24. Shafts & Bearings.

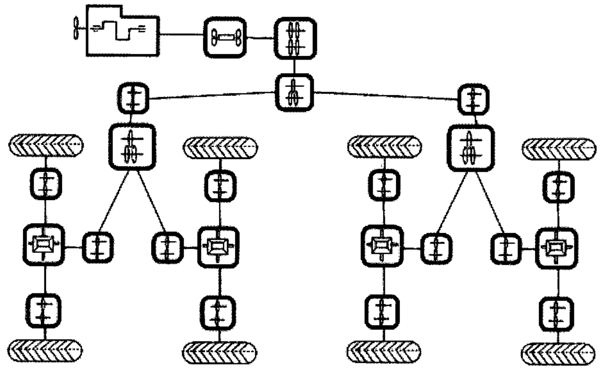

Figure 3. Model of the driving-line.

and the constraint equations should be satisfied as well;

Step 4: Repeat step 2 and step 3 until the engine is reached;

Step 5: If the part evaluated is the engine, judge whether the output torque or rotating speed is out of the range; if not, go to step 9; otherwise continue;

Step 6: Starting with the engine, moving from engine to wheels, the output torque and rotating speed of each part in the driving-line can be calculated;

Step 7: To each part, know the input, calculate the output; output torque is found using the torque equation, the output for rotating speed is gained by the rotating speed equation, all constraint equations should be satisfied;

Step 8: Compare the output torque with the torque obtained during the inverse seeking; choose a small one, and repeat steps 7 and 8;

Step 9: The algorithm has ended after all parts have been calculated, and the circumferential forces are gained.

6. INTRODUCTION FOR THE ASSESSMENT TOOL

Based on the above modeling methodology and the performance assessment for the drive-line, we developed performance assessment tools for off-road drive-line using Microsoft Visual C++. The main interface is illustrated in Figure 4. We take Object-oriented Programming (OOP) to implement the tools. For example, we define each component as a class which contains its position in screen, input, output, the last component ID, the next Component ID, etc.. All components are stored as a chained list. The following is some C++ source codes used to represent a component.

```
CTypedPtrList <CObList,CComp*>m_compList;//
```

The data structure of a single component is expressed as:

```
class CComp : public CObject
{
...
public:
INFCOMP m_comp;//component
information£®including layered codes£©
INFPHY      m_phy;//physical information
INFFUN      m_func;//functional information
INFPRO      m_proj;//processing information
INFCON      m_con;//connection information
INFCOMMONm_common;//public information
INFSYS      m_sys;//the required information in this
system
INPUT m_input; //the input of this component
OUTPUT m_output; //the output of this component
DWORD       m_parentNodeld; //it parent-node ID
UINT        m_nImageType; //type of image
int         m_number; //number
CPoint      m_GlobeLoc; // screen position information
of global view
CPoint      m_LocalLoc; // screen position information
of partial view
INFOTHER m_other;//other information
...
};
```

We can create an ICON to represent a component of the drive-line, and all ICONS are listed in the Toolbar. Then, we can connect each component according to the practical "input-output" relationship among them. Consequently, the entire model for the drive-line can be built. We can initialize the parameters of each component, the running conditions (e.g., road friction, coefficient of adhesion and so on) etc., and we can also modify them. After all parameters are defined, we can simulate and calculate the performance index of the drive-line according to the relevant algorithm. The tool facilitates the display of the calculated results. It is easy for us to check the running status of each component during the simulation.

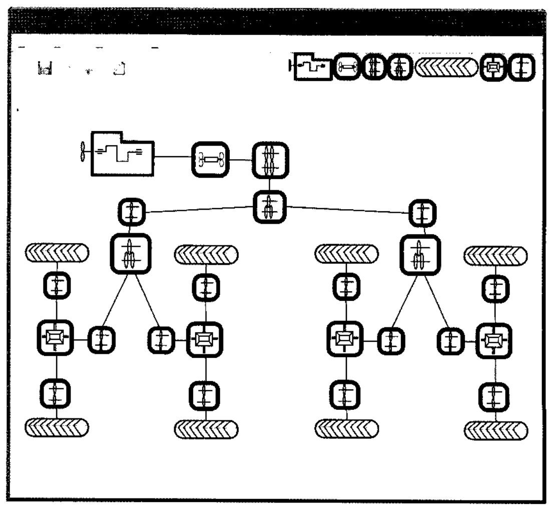

Figure 4 Performance assessment tools for off-road drive-line.

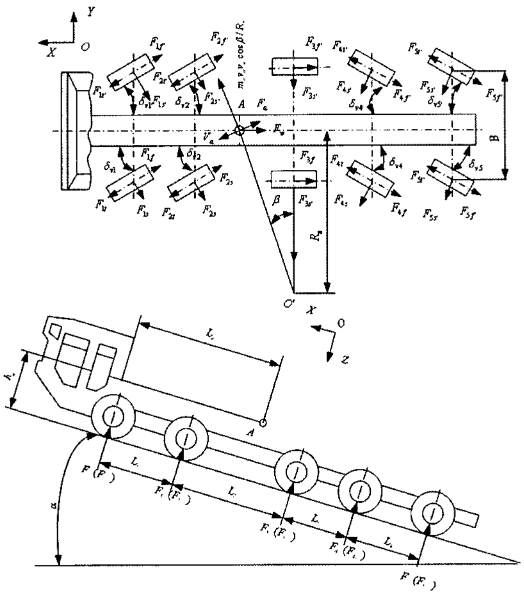

Figure 5. 10×8 vehicle's dynamic model diagram.

If the calculating result cannot meet the requirement, we can modify the parameters of one or more components in the drive-line until satisfactory results are achieved. From this viewpoint, the tool is very suitable for the conceptual design of multi-driver off-road vehicle drive-lines.

7. CASE STUDY

A 10×8 heavy off-road vehicle's driving-line system is chosen for an example (see Figure 2). Figure 3 is its model after concept generation.

7.1. Calculate the Rolling Resistance and Adhesive Force

As you can see from the previous section, the first step for performances assessment during the design stage is to calculate the rolling resistance and adhesive force using the given driving conditions and design requirements. These are gained from dynamic modeling of the vehicle.

Referring to the typical Ackerman steering geometry, the 10×8 vehicle's dynamic model is shown in figure 5. According to the figure, the following equations are defined.

CG (Center of Gravity) kinematic equation along the longitudinal direction:

$$
\begin{aligned}
& m_a\left(1+\delta_\varphi\right)\dot{v}_a \cos(\beta)-\frac{m_a v_a^2 \sin(\beta)}{R_n} \\
& -\sum_{i=1}^{4}\left[F_{it}^{'}\cos\left(\delta_{iv}^{'}\right)+F_{it}^{''}\cos\left(\delta_{iv}^{''}\right)\right] \\
& +\frac{C_D A v_a^2 \cos(\beta)}{21.15}+m_a g \sin(\alpha) \\
& +\sum_{j=1}^{5}\left[F_{jf}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\cos\left(\delta_{jv}^{''}\right)\right] \\
& +\sum_{j=1}^{5}\left[F_{js}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{js}^{''}\sin\left(\delta_{jv}^{''}\right)\right]=0
\end{aligned}
\tag{20}
$$

CG kinematic equation along lateral direction:

$$
\begin{aligned}
& m_a\left(1+\delta_\varphi\right)\dot{v}_a \sin(\beta)+\frac{m_a v_a^2 \cos(\beta)}{R_n} \\
& -\sum_{i=1}^{4}\left[F_{it}^{'}\sin\left(\delta_{iv}^{'}\right)+F_{it}^{''}\sin\left(\delta_{iv}^{''}\right)\right] \\
& +\frac{C_D A v_a^2 \sin(\beta)}{21.15} \\
& +\sum_{j=1}^{5}\left[F_{jf}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\sin\left(\delta_{jv}^{''}\right)\right] \\
& -\sum_{j=1}^{5}\left[F_{js}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{js}^{''}\cos\left(\delta_{jv}^{''}\right)\right]=0
\end{aligned}
\tag{21}
$$

CG kinematic equation along vertical direction:

$$
m_a \ddot{z}_A-m_a g \cos(\alpha)+\sum_{i=1}^{5}\left(F_{iP}^{'}+F_{iP}^{''}\right)=0 \tag{22}
$$

Yaw moment equation:

$$
\begin{aligned}
& \Theta_Z \ddot{\psi}_Z-\sum_{i=1}^{4}\left[F_{it}^{'}\cos\left(\delta_{iv}^{'}\right)+F_{it}^{''}\cos\left(\delta_{iv}^{''}\right)\right]\frac{B}{2} \\
& -\sum_{i=1}^{4}\left[F_{it}^{'}\sin\left(\delta_{iv}^{'}\right)+F_{it}^{''}\sin\left(\delta_{iv}^{''}\right)\right]d_i \\
& -\sum_{j=1}^{5}\left[F_{js}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{js}^{''}\sin\left(\delta_{jv}^{''}\right)\right]\frac{B}{2} \\
& -\sum_{j=1}^{5}\left[F_{jf}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\cos\left(\delta_{jv}^{''}\right)\right]\frac{B}{2} \\
& -\sum_{j=1}^{5}\left[F_{js}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{js}^{''}\cos\left(\delta_{jv}^{''}\right)\right]d_i \\
& -\sum_{j=1}^{5}\left[F_{jf}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\sin\left(\delta_{jv}^{''}\right)\right]d_i=0
\end{aligned}
\tag{23}
$$

Pitch moment equation:

$$
\begin{aligned}
& \Theta_Y \ddot{\psi}_Y-\sum_{j=1}^{5}\left[F_{jP}^{'}+F_{jP}^{''}\right]d_i \\
& +\sum_{j=1}^{5}\left[F_{js}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{js}^{''}\sin\left(\delta_{jv}^{''}\right)\right]h_A \\
& +\sum_{j=1}^{5}\left[F_{jf}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\cos\left(\delta_{jv}^{''}\right)\right]h_A \\
& +\sum_{i=1}^{4}\left\{\left[F_{it}^{'}\cos\left(\delta_{iv}^{'}\right)+F_{it}^{''}\cos\left(\delta_{iv}^{''}\right)\right]h_A\right\}=0
\end{aligned}
\tag{24}
$$

Roll moment equation:

$$
\begin{aligned}
& \Theta_X \ddot{\psi}_X-\sum_{j=1}^{5}\left[F_{jP}^{'}-F_{jP}^{''}\right]\frac{B}{2} \\
& -\sum_{j=1}^{5}\left[F_{js}^{'}\cos\left(\delta_{jv}^{'}\right)+F_{js}^{''}\cos\left(\delta_{jv}^{''}\right)\right]h_A
\end{aligned}
$$

Table 1. Parameters of three scenarios.

Parameters	No.1	No.2	No.3
i_0	4.55	3.36	3.97
K_c	2.16	2.37	2.21
i_{g1}	1.53	1.69	1.57
i_w	5.30	5.61	5.48
t_e (N.m)	1599	1599	1599
n_e (rpm)	2259	2259	2259

Note: i_0 is the main ratio of transmission; Kc is torque efficient of torque converter; i_{g1} is ratio of the first transfer case; i_w is ratio of wheel reducer; t_e is output torque of engine; n_e is output for engine rotating speed; and the other parameters are the same.

Table 2. Working conditions of vehicle.

Case	Conditions
1	Front two driving axles' coefficient of adhesion is smaller than the rears'
2	Front two driving axles' coefficient of adhesion is bigger than the rears'
3	On split road surface
4	Cornering on normal road surface
5	Cornering on split road surface

Table 3. Performance assessment result.

Condition	Indices	No. 1	No. 2	No. 3
Case 1	Transport efficiency	0.148	0.148	0.148
	Resistant torque (Nm)	0	0	0
Case 2	Transport efficiency	0.148	0.148	0.148
	Resistant torque (Nm)	0	0	0
Case 3	Transport efficiency	0.565	0.406	0.235
	Resistant torque (Nm)	2400	22200	73200
Case 4	Transport efficiency	0.059	0.059	0.092
	Resistant torque (Nm)	0	0	70611
Case 5	Transport efficiency	0.23	0.23	0.345
	Resistant torque (Nm)	3688	3688	804

$$
\begin{aligned}
&+\sum_{j=1}^{5}\left[F_{jf}^{'}\sin\left(\delta_{jv}^{'}\right)+F_{jf}^{''}\sin\left(\delta_{jv}^{''}\right)\right]h_A \\
&+\sum_{i=1}^{4}\left\{\left[F_{it}^{'}\sin\left(\delta_{iv}^{'}\right)+F_{it}^{''}\sin\left(\delta_{iv}^{''}\right)\right]h_A\right\}=0
\end{aligned} \tag{25}
$$

7.2. Performances Assessment

By using the above mentioned method, three scenarios of the driving-line's design concept have been compared within five typical working conditions of the vehicle. The parameters of these three scenarios are given in Table 1.

The working conditions are listed in Table 2. We use the tools which we developed for analyzing on a power flowchart of Multi-driver Off-road Vehicle Driving-lines based on Objected-oriented ideas (Hu *et al.*, 2000; Wang *et al.*, 2001). This analysis result is shown in Table 3. We assessed the three design schemes based on five working conditions. From Table 2, except for case 1 and case 2, the results are the same. But case 3, 4, 5, their differences are evident. Considering the comprehensive performance, the best scheme is No.1.

8. CONCLUSIONS

The models described in this paper have provided a convenient measure to aid the concept design and performance analysis for multi-driver off-road vehicle's driving-lines. This tool has been used in the practical development of products from the Special Vehicle Technical Center of China Sanjiang Space Group (Hu *et al.*, 2000; Wang *et al.*, 2001). Some related papers (Wang *et al.*, 2005, 2006) have shown experimental results in detail that are based on this project.

In this paper, multi-drivers Off-road Vehicle Driving-line is designed based on the modularized methodology; the object-oriented method is very suitable for analyzing its performance of torque, power and speed flow. Therefore, we use Visual C++ to develop the analyzing tools. Compared to the other similar tools (Phillips and Assanis, 1996; Lim *et al.*, 2000; Jo *et al.*, 2000), the drive-line model can be built easily with the components library. The components of the built model will be connected via their input/output interface, and their performance parameters can be displayed, checked or modified conveniently by users. Additionally, the tool can be integrated into an Intelligent CAD Expert System which is specially developed for multi-driver Off-road Vehicle Driving-line design, including scheme design, conceptual design, structural and topological design and so on. From its application in the Special Vehicle Technical Center of the Chinese Sanjiang Space Group in several recent years, it has been proven to be a useful, economical tool to facilitate the vehicle's driving-line system design, especially the conceptual design.

Moreover, it can be developed as a computer simulation tool to conserve testing needed during the design stage of vehicle development. It also can be used for traction control system design and evaluation for multi-driver off-road vehicles, which is the work currently underway.

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