*Applied Mathematics, Modeling and Computer Simulation*
*C.-H. Chen et al. (Eds.)*

*doi:10.3233/ATDE230951*

# Research on Rollover Threshold Value of Tank Truck Based on ADAMS CAR, SIMULINK and FLUENT Co-Simulation

Xiaodong XU[1], Guide DENG, Heyi FENG, Linlin DUAN, Cenfan LIU, Zhirong YANG
*Key Laboratory of Special Equipment Safety and Energy-saving for State Market Regulation, China Special Equipment Inspection and Research Institute, Beijing, 100029, China*

**Abstract.** This paper overcomes the traditional simulation method which does not consider the coupling effect between tank truck movement and liquid sloshing in the rollover process, simulates the rollover process of tank truck more truly, and calculates the critical value of tank truck rollover more accurately. The data interaction between ADAMS CAR and FLUENT is realized indirectly by using SIMULINK as the intermediate transfer software. Through the secondary development of UDF and S function, data exchange between FLUENT and SIMULINK is realized by means of socket communication. ADAMS CAR transmits the translation velocity and angular velocity of the tank truck to FLUENT, and FLUENT then transmits the resultant force and moment of liquid sloshing to ADSMS CAR, so as to realize the co-simulation of the rollover process of the tank truck by using ADAMS CAR, SIMULINK and FLUENT. The critical acceleration of tank truck rollover was calculated by step steer simulation, and the influence data of liquid sloashing were obtained.  The research results can be applied to the safety warning and accident recovery of tank truck. In this paper, the accident recovery of the "June 13" tank truck explosion accident in Wenling section of Shenyang-Haikou Expressway in 2020 is carried out. The calculated results are consistent with the facts, which proves that the results of the co-simulation method are reliable.

**Keywords.**Tank truck, rollover, FLUENT, SIMULINK, ADAMS CAR, collaborative simulation

## 1. Introduction

The tank truck plays an important role in the transportation of hazardous chemicals. Once the rollover accident occurs, it is easy to cause a major explosion accident, resulting in huge loss of personnel and property, or serious environmental pollution. So it is necessary to study the rollover of tank truck [1][2].

ADAMS CAR is a professional software used for vehicle multi-body dynamics analysis. It can simulate the operation stability and ride comfort of the entire vehicle and obtain the motion characteristic curve and mechanical characteristic curve [3]. Therefore, it is feasible to use ADAMS CAR to simulate the rollover of tank truck. The

[1]Corresponding Author, Xiaodong XU, Key Laboratory of Special Equipment Safety and Energy-saving for State Market Regulation, China Special Equipment Inspection and Research Institute, Beijing, China; E-mail: xuxiaodong105@163.com.

disadvantage is that the coupling effect between liquid sloshing and tank truck movement is not considered.

FLUENT is an internationally popular general fluid mechanics computing software, which is capable of solving various fluid mechanics problems with powerful front and rear processors and rich physical models [4]. FLUENT can use multiphase flow technology to simulate liquid sloshing and dynamic mesh technology to simulate the rigid motion of fluid domain boundary, so it can be used to simulate the liquid sloshing of tank truck. If ADAMS CAR transfers the motion parameters of the tank truck to FLUENT, and FUENT transfers the resultant force of liquid sloshing to ADAMS CAR, the co-simulation of FLUENT and ADAMS CAR can more truly simulate the rollover process of the tank truck. The difficulty lies in that there is no interface between ADAMS CAR and FLUENT, so data interaction cannot be conducted directly.

SIMULINK is one of the important components of MATLAB, which provides a graphical environment. Users can combine several modules with certain functions by means of wire connection, so as to build a system capable of running simulation calculation [5]. ADAMS CAR and SIMULINK have interfaces that allow direct data interaction. This paper realizes data interaction between SIMULINK and FLUENT through secondary development. Therefore, ADAMS CAR and FLUENT can indirectly realize data interaction through intermediate software SIMULINK.

On the research of automobile rollover, domestic and foreign scholars have done a lot of work. Hegazy S[6] conducted multi-body dynamics analysis on the vehicle, and evaluated the vehicle rollover with vertical wheel load and lateral acceleration. Richardson[7] et al. in the United States monitored the status of vehicle rollover indicators through monitors and issued timely alarms. Jin Liqiang et al. [8] established a 3-degree-of-freedom vehicle model and introduced the zero moment point as the vehicle rollover index. Zhu Jun et al. [9] established kinematic and dynamic models of vehicle rollover and turnover, and deduced the range of lateral velocity ofvehicle rollover. Shen Ming et al. [10] applied ADAMS CAR to simulate the process of vehicle rollover accident to study its mechanism. Zhao Weiqiang et al. [11] adopted the equivalent pendulum model to simulate the dynamic process of liquid sloshing in the tank and established the dynamics model of the tank truck. Yu Guofei et al. [12] used ADAMS CAR simulation to analyze the relevant factors affecting the rollangle of a domestic passenger car body.Arslan M S et al. [13] developed an anti-rollover control algorithm for vehicles by using a nonlinear vehicle model with 11 degrees of freedom. Van Tan Vu et al. [14] integrated the active anti-roll bar into the heavy vehicle model to realize the active control design. Ahmad Rahmati-Alaei et al. [15] analyzed the effects of liquid filling ratio, wave plate and tank shape on lateral dynamics of tank semitrailer.

At present, there are few researches on tank truck rollover, especially those combining vehicle movement with liquid sloshing. Therefore, in this paper, the critical acceleration of tank truck rollover is studied by co-simulation of ADAMS CAR, SIMULINK and FLUENT, which overcomes the shortcoming that the traditional simulation method does not consider the coupling effect between vehicle movement and liquid sloshing. The research results can be applied not only to the accident recovery of the car tank car, but also to the safety warning.

## 2. Data Interaction Between ADAMS CAR and SIMULINK

A tank truck model is built in ADAMS CAR for dynamics simulation. Meanwhile, data such as translation velocity and angular velocity of the tank truck are transmitted to SIMULINK. SIMULINK then transmits data of liquid sloshing force and moment received from FLUENT to ADAMS CAR to realize data interaction.

### *2.1. Input/Output definition*

Data interaction between ADAMS CAR and SILULINK is realized through state variables. The data of position coordinate, displacement, speed and acceleration of tank truck can be output by state variable. At the same time, the data ADAMS CAR receives from SIMULINK is stored in state variables. The state variable is referenced by the VARVAL() function when applying force or torque in the tank truck model.

Force and torque are applied to tank truck components by actuators. The actuator will generate a Marker on the acting part and the reaction part respectively. The direction of the force and torque is determined by the Marker on the reaction part. The reaction part of the point torque actuatoris set as Ground, and the direction of the torque can be applied to the parts which does not change with the direction of the movement of the tank truck. When the Action Only option in thepoint torque actuator is turned on, a torque whose direction changes with the movement of the tank truck can be applied in the component.

The movement data of tank truck is output by running process function. If the Along Marker parameter in the displacement function DX() is set to the global coordinate system or not specified, the coordinates of the tank truck components relative to the global coordinate system can be output.

### *2.2. Interface files between ADAMS CAR and SIMULINK*

ADAMS CAR has professional menus that generate interface files between ADAMS CAR and SIMULINK. Open the dialog box of Plant Export through the menu "Controls>>Plant Export", and set it as shown in figure 1. The name entered in the text box of File Prefix must be consistent with the simulation name of the tank truck. Enter "file/command =FilePrefix_controls.acf" in the Initial Command text box.

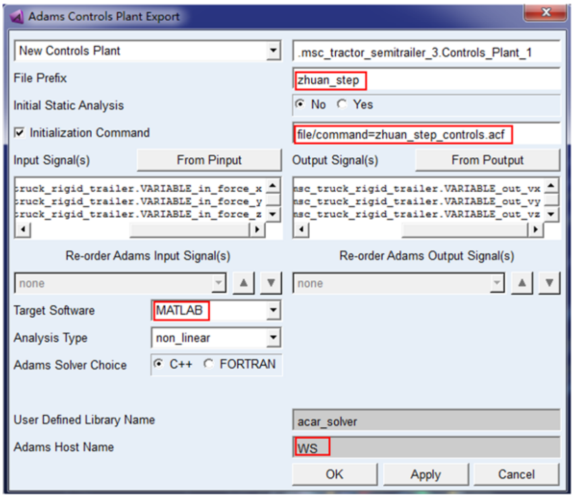


**Figure 1.**The dialog box of Plant Export

## 2.3. *ADAMS CAR interface module*

ADAMS CAR interface module is generated in SIMULINK using interface files.Open the ADAMS CAR interface module dialog box and set the settings as shown in figure 2. The Interprocess option is set to PIPE(DOE), the Animation mode is set to batch, and the Simulation mode is set to discrete. Discrete Computational Order is set to no, and the Comunicational interval setting must remain consistent with the setting of the SIMULINK computational step.

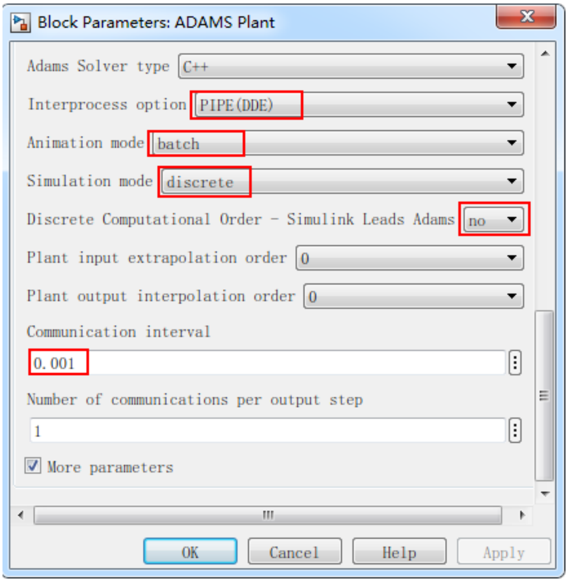


**Figure 2.** ADAMS CAR interface module Settings

## 3. Data Interaction Between SIMULINK and FLUENT

SIMULINK builds functional modules through S function, while FLUENT conducts secondary development through UDF. Therefore, FLUENT and SIMULINK can complete data interaction through UDF and S function.

### *3.1. Data interaction interface*

The data interaction process between FLUENT and SIMULINK is shown in figure 3. It can be seen from the figure that FLUENT execute macro function DEFINE_EXEXECUTE_AT_END() for each time step solution, and SIMULINK execute mdlOutputs() function for each time step solution. Therefore, data exchange can be completed through these two functions [16].

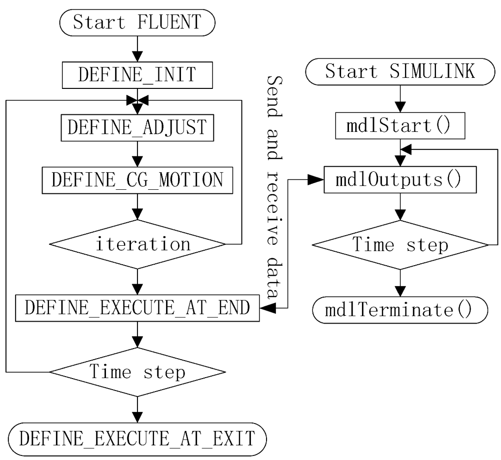


**Figure 3.**The data interaction between FLUENT and SIMULINK

### *3.2. Socket*

This paper realizes the communication between functions by socket. The server is SIMULINK, the client is FLUENT, and the communication protocol is UDP. Receiving data in blocking mode ensures synchronous communication between the server and the client because the receiver does not continue executing the code until the data is received.

### *3.3. Server programming*

In SIMULINK, C++ language is used to write S function to build continuous modules. For sockets, the socket initialization code is written in function mdlStart(), the sending and receiving data code is written in function mdlOutputs(), and the closing socket code is written in function mdlTerminiate().The socket uses function Sendto() and Recvfrom() to send and receive data, and function Closesocket() to close the socket.The header filesare shown below, the Winsock2.h file should be placed in front of the header files, otherwise the redefinition will occur.

*#define WIN32_LEAN_AND_MEAN*

```
#include <Winsock2.h>
#include <stdio.h>
#include <stdlib.h>
#pragma comment(lib, "ws2_32.lib")
using namespace std;
```

The program needs to convert the data format of the sent and received data. Before sending the data, the sprintf() function is used to convert the floating-point data to character data. Once the data is received, the character data is converted back to floating point data using the sscanf() function. The detailed code is as follows:

```
//real to char
int i, ValidateBuflen;
for(i=0;i<3;i++)
{ValidateBuflen=strlen(SendBuf);
sprintf(SendBuf+ValidateBuflen, "%f;", SendData[i]);}
//char to real
sscanf(recvBuffer, "%lf;%lf;%lf;", &fx, &fy, &fz);
printf("receved content:%lf %lf %lf \n", fx, fy, fz);
```

### 3.4. Client programming

In FLUENT, C++ language is used to write UDF (user-defined function) for secondary development. For sockets, the socket initialization code is written in the macro DEFINE_INIT(),, the sending and receiving data code is written in the macroDEFINE_EXECUTE_AT_END(), and the closing socket code is written in the macro DEFINE_EXECUTE_AT_EXIT(), The socket uses function Sendto() and Recvfrom() to send and receive data, and function Closesocket() to close the socket.The header filesare the same as the server.

The macro DEFINE_CG_MOTION()is mainly used to describe the motion of a rigid body, during which the geometry of the parts does not change, but the position of the center of mass does. FLUENT adopted the macro DEFINE_CG_MOTION()to transmit the motion data received from ADAMS CAR to the tank model to make it move, thus driving liquid slosh. Motion data mainly include translation velocity and angular velocity.

Set up the dynamic meshzones dialog, as shown in figure 4. The zone name item is set to the entire model region, the type item is set to rigid body, and the Motion UDF/Profile item is set to the function defined by the DFINE_CG_MOTION() macro. Set the center of motion coordinates in the center of gravity location item. The center of motion is the location in the ADAMS CAR tank truck ,whose motion data is output. The FLUENT tank model moves with the center of motion.

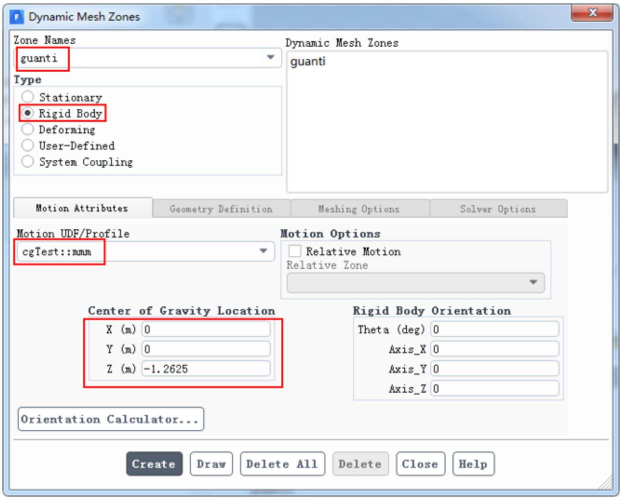


**Figure 4.** The dynamic mesh zones dialog

The latest version of FLUENT only supports parallel computing, so the code needs to do parallel processing [17]. Parallel computing consists of one master node and n compute nodes. The master node is responsible for passing commands from the user interface to compute node 0, which in turn passes commands to other compute nodes. Compute node 0 is also responsible for passing data from each compute node to the master node. Code that exchanges data with SIMULINK runs on the master node, and code that collects calculation data runs on the compute node. Since the calculated data is scattered among each compute node, this paper uses the global summation macro PRF_GRSUM1()to collect data from all compute nodes. The macro host_to_node_type_num() macro are used to pass data from the master node to the compute node, and the macro node_to_host_type_num() are used to pass data from the compute node to the primary node. The relevant code is shown below:

```
#if !RP_HOST  // Only compute node
#endif
#if RP_HOST   //Only master node
#endif
host_to_node_real_3(dx, dy, dz);
node_to_host_real_3(fx, fy, fz);
```

## 4. Co-simulation

It can be seen from the above that ADAMS CAR and SIMULINK have data interaction interface, and SIMULINK and FLUENT can realize data interaction through secondary development of UDF and S function. Therefore, ADAMS CAR and FLUENT can indirectly complete data interaction through the intermediate transfer of SIMULINK. At each time step, ADAMS CAR transmits the motion data of the tank truck to FULUENT to complete the simulation of liquid sloshing, and FLUENT sends the resultant force and moment of liquid sloshing on the tank back to ADAMS CAR as the input of the next time step of the dynamics simulation of the tank truck. Through continuous iterative calculation until the end of the simulation, the motion of the tank truck can be simulated more truly. The data interaction of ADAMS CAR, SIMULINK and FLUENT is shown in figure 5.

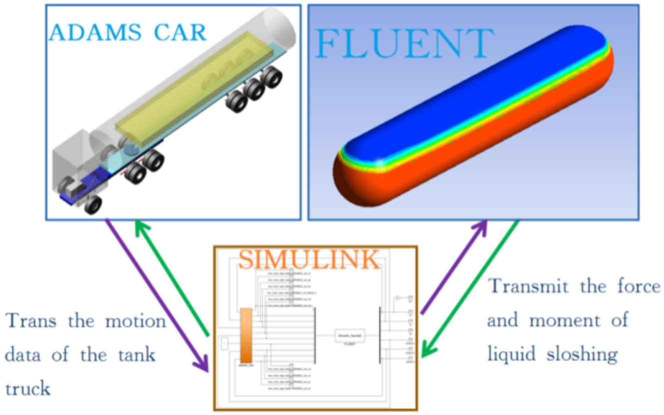


**Figure 5.** Collaborative simulation

## 5. An Example of Rollover Co-simulation

In this paper, the accident recovery of the "June 13" tanker explosion accident in Wenling section of Shenyang-Haikou Expressway in 2020 is conducted.

### *5.1. ADAMS CAR simulation*

ADAMS CAR was used to construct the multi-body dynamics model of tank truck for step steer simulation. The output parameters are the motion data (three translational velocities and three angular velocities)of the bottom center of the tank, and the input parameters are the three forces and three torques appliedtothe bottom center of the tank, which are used to apply the resultant force and torque of liquid sloshing on the tank. The input parameters and output parameters are based on the global coordinate system of the multi-body dynamic model of the tank truck. The position of bottom surface center of ADAMS CAR tank truck model corresponds to the position of motion center of FLUENT tank model, as shown in figure 6.

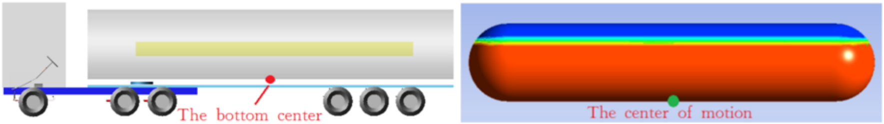


**Figure 6.** The bottom center of ADAMS CAR model and the center of motion of FLUENT model

### *5.2. FLUENT simulation*

The three resultant forces and three resultant torques of the liquid sloshing on the tank body relative to the bottom cemter of the tank are obtained by integrating the liquid surface pressure according to formula(1-6). The relevant codes are as follows:

$$F_X(t) = \sum_{\Omega}(P_i A_{xi}) \tag{1}$$

$$F_Y(t) = \sum_{\Omega}(P_i A_{yi}) \tag{2}$$

$$F_Z(t) = \sum_{\Omega}(P_i A_{zi}) \tag{3}$$

$$M_X(t) = \sum_{\Omega}(F_{zi} Y_i) - \sum_{\Omega}(F_{yi} Z_i) \tag{4}$$

$$M_Y(t) = \sum_{\Omega}(F_{xi} Z_i) - \sum_{\Omega}(F_{zi} X_i) \tag{5}$$

$$M_Z(t) = \sum_{\Omega}(F_{yi} Z_i) - \sum_{\Omega}(F_{xi} Y_i) \tag{6}$$

Where: $F_X$, $F_Y$, $F_Z$, The resultant forces in X ,Y and Z direction; $P_i$, The pressure on cell surface i; $A_i$, Area vector of cell surface i; $\Omega$, Wall surface; $M_x$, $M_y$, $M_z$, Resultant moments in X ,Y and Z direction; $F_{Xi}$, $F_{Yi}$, $F_{Zi}$, The forces in X ,Y and Z direction on cell surface i; $X_i$, $Y_i$, $Z_i$, The X, Y, Z coordinates of the cell surface i with respect to the bottom center of the tank.

```
begin_f_loop(f, tf)
{//Calculate three resultant forces
F_AREA(A, f, tf);
force_x += F_P(f,tf) * A[0];
force_y += F_P(f,tf) * A[1];
force_z += F_P(f,tf) * A[2];}
//Calculate three moments. tbc[] ,The coordinates bottom center of the tank
F_CENTROID(co,f,tf);
moment_x += F_P(f,tf) * A[2] * (co[1]-tbc[1]) - F_P(f,tf) * A[1] * (co[2]-tbc[2]);
moment_y += F_P(f,tf) * A[0] * (co[2]-tbc[2]) - F_P(f,tf) * A[2] * (co[0]-tbc[0]);
moment_z += F_P(f,tf) * A[1] * (co[0]-tbc[0]) - F_P(f,tf) * A[0] * (co[1]-tbc[1]);
}
end_f_loop(f, t)
```

Since the data exchange between ADAMS CAR and FLUENT takes place for the first time at the end of the first time step, the initial speed of ADAMS CAR and FLUENT must be consistent to avoid the violent shaking of liquid in the first time step. The initial liquid speed is set in FLUENT initialization interface. The initial speed of the tank is set in the macro DFINE_CG_MOTION().

### *5.3. SIMULINKcontrol flow*

The flow diagram of SIMULINK is shown in figure 7. ADAMS CAR outputs translational velocity and angular velocity to FLUENT, and FLUENT outputs liquid shaking force and moment to ADAMS CAR. ADAMS CAR, SIMULINK, and FLUENT must have the same time step and number of iterations. To run the calculation, start the SIMULINK side first and then the FLUENT side.

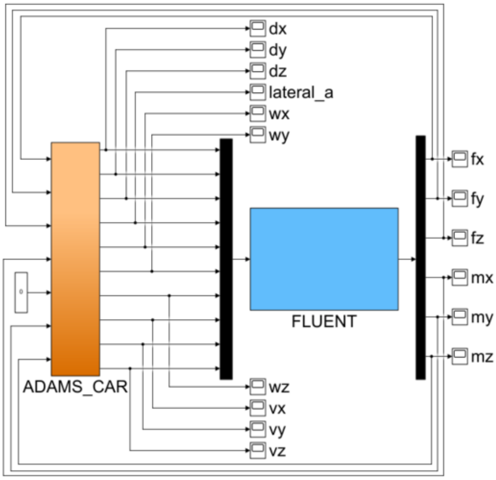


**Figure 7.** SIMULINK control flow

### *5.4. Critical lateral acceleration*

During turning, rollover will occur when lateral acceleration exceeds a certain value, which is the critical rollover acceleration of the tank truck. When the normal contact force between the innermost tire of the last row and the ground is 0, the lateral acceleration of the tank truck is determined to be the critical rollover acceleration of the tank truck. The moment when the tank truckroll over is shown in figure 8.

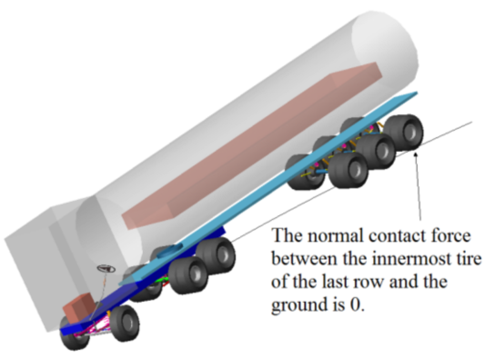


**Figure 8.** Moment of rollover

When calculating the critical acceleration, the input parameters of step steer simulation, speed and steering angle are adjusted continuously until the car tank car roll over. Open the multi-body dynamics model of the tank truck in ADAMS CAR software, import the simulation results of co-simulation calculation, and open the post-processor to view various data curves and simulation animations. Check the time curve of the normal contact force between the innermost tire of the last row of the tank truck and the ground in the post-processor, and confirm the moment when the normal contact force is 0, as shown in figure 9. Check the time curve of the lateral acceleration of the center of mass of the tank truck, and confirm the lateral acceleration at the moment when the normal contact force of the innermost tire in the last row of the tank truck is 0. The lateral acceleration is the critical rollover acceleration of the tank truck, and the value is 3.40m /s2, as shown in figure 10.

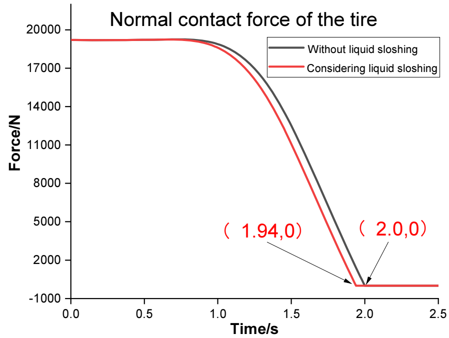


**Figure 9.** Normal contact force of the tire

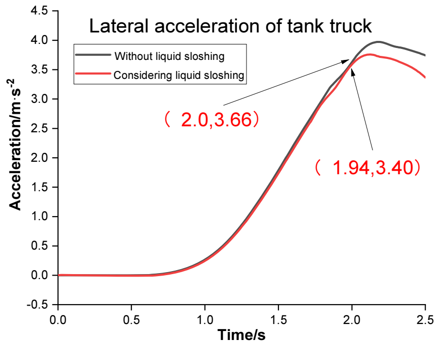


**Figure 10**. Lateral acceleration of the tank truck

As a contrast, the critical acceleration of tank truck rollover is calculated without considering the effect of liquid slosh. As shown in figure 9,the normal contact force of tire considering liquid sloshing reached 0 earlier than that considering liquid sloshing. As shown in figure 10, the critical acceleration of rollover without considering liquid sloshing is 3.66m/s2, and 3.40m/s2considering liquid sloshing. The critical acceleration without considering liquid sloshing is 7.10% larger than that considering liquid sloshing.

### *5.5. Accident recovery*

The turning motion of tank truck is simplified as circular motion, and its lateral acceleration is calculated according to formula 1. The turning radius of the accident site was measured to be about 60m, and the driving speed of the tank truck before rollover was 14.44 ~ 15.83m/s. According to formula 7, the lateral acceleration of the car tanker before rollover was 3.47 ~ 4.17m/s2, which exceeded the critical rollover acceleration of the tank truck. Therefore, the cause of the accident is determined to be overspeed in turning, which makes the lateral acceleration of the tank truck exceed the critical rollover acceleration, resulting in rollover accident.

$$a = \frac{v^2}{R} \tag{7}$$

Where: a, lateral acceleration; R, Turning radius; v, Running speed.

## 6. Conclusion

There is no interface between ADAMS CAR and FLUENT, so it is difficult to conduct secondary development to realize direct data interaction between them. The data interaction between ADAMS CAR and FLUENT is realized indirectly by using SIMULINK as the intermediate transfer software.The co-simulation of ADAMS CAR, SIMULINK and FLUENT was realized to simulate the rollover process of the tank truck and calculate the critical acceleration of rollover. The research results can be applied to the safety warning and accident recovery of tank truck.An accident recovery was carried out on the "June 13" tanker explosion accident in Wenling section of Shenyang-Haikou Expressway in 2020.

## Acknowledgments

This research was supported by Science and Technology Program of the State Administration for Market Regulation of China(2021MK177), and National Key Research and Development Program of China (2022YFB3306403).

## References

[1] ZHANG Weihua, WEI Tianyu, XU Chi, et al. GIS-T Based Method for Warning Rollover of Tank Truck[J]. China Safety Science Journal, 2019, 29(2):178-183.
[2] XIANG Li, XIE Qiyuan, ZHANG Jie, et al. Characteristic analysis on leakage-burning coupling of LNG tanker[J]. China Safety Science Journal, 2020, 30( 1):81-86.
[3] SHEN Hailong. Analysis and Research of Vehicle Rollover Simulation Based on ADAMS[D]. Dalian, Dalian Jiaotong University,2016.
[4] YANG Wei. Mechanism Analysis and Threshold Identification of Tank Semi-trailer Rollover[D]. Jilin: Jilin University,2019.
[5] CHEN Ziming, XUE Zhigang, ZHANG Song, et al. Closing Effort Analysis of Sliding Doors Based on Co-simulation of ADAMS and Simulink[J]. China Mechanical Engineering,2020, 31(8):924-930.
[6] Hegazy S,Rahnejat H,Hussain K. Multi-Body Dynamics in Full-Vehicle Handling Analysis under Transient Manoeuvre[J].Vehicle System Dynamics, 2000, 34(1):1-24.
[7] Richardson S A,Rechnitzer G,R H Grzebieta.An advanced methodology for estimating vehicle rollover propensity[J]. International Journal of Crashworthiness,2003, 8(1):63-72.
[8] JIN Liqiang, SHI Guannan, Kong Dejuan, et al. Vehicle Rollover Warning Based on Zero-moment PointIndicator and Time-to-rollover Algorithm[J], Automotive Engineering,2017, 39(3):281-287.
[9] ZHU Jun, LI Yibing. A Research on the Modeling for Vehicle Rollover and Tunrnover Accident[J]. Automotive Engineering, 2006, 28(3):254-258.
[10] SHEN Ming, WANG Yunsong, LI Zhigang, et al. A Reasearch on the Rollover Risk of Motor Vehicles Based on Simulation Analysis[J]. Automotive Engineering, 2009, 31(12):1173-1176.
[11] ZHAO Weiqiang, LING Jingpeng, ZONG Changfu. Development of Anti-rollover Control Strategy For Liquid Tank Semi-trailer[J]. Automotive Engineering,2009, 31(12):1173- 1176.
[12] YU Guofei, AI Weiquan, WANG Cheng, et al. Factor of Body Roll Angles Correspond to Vehicle Steady Steering Characteristics[J]. Journal of Tongji University(Natural Science), 2006,34(9):1237-1241.
[13] [A] Arslan M S, Sever M. Vehicle stability enhancement and rollover prevention by a nonlinear

predictive control method[J]. Transactions of the Institute of Measurement and Control, 2019, 41(8): 2135-2149.

[14] [B] Vu V T, Sename O, Dugard L, et al. Enhancing roll stability of heavy vehicle by LQR active anti-roll bar control using electronic servo-valve hydraulic actuators[J]. Vehicle system dynamics, 2017, 55(9): 1405-1429.

[15] [C] Ahmad Rahmati-Alaei, Sharavi Majid, Samadian Zakaria Masoud. Development of a coupled numerical model for the interaction between transient fluid slosh and tank wagon vibration[J]. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 2019, 233(3): 568-582.

[16] LIU Huiling. Collaborative Simulation Based on SIMULINK and FLUENT[J]. The Science Education Article Collects, 015(6):183-185.

[17] HU Kun. ANSYS Fluent Secondary Development Guide[M]. Beijing: Chemical Industry Press,2021:90-113.