Research on the Permitted Height of Combined Center of Gravity for Railroad Cars

Chao Chen[1, a], Ziji'an Wang[1, b, *] and Mei Han[1, c]
[1]School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China

Keywords: Railroad freight car, MBS, orthogonal experiment, combined center of gravity.

Abstract: Permitted height of combined center of gravity for railroad cars in China is studied. This study establishes a MBS model of the railroad freight car, and then validates the model. Orthogonal experiment method is used to find the worst operating condition. The factors' levels are determined and used for designing orthogonal experiment schemes. Extensive simulations are performed for the schemes. Statistics analysis is applied to simulation results. The worst operating conditions for Grade I and III railroad are derived from objective analysis. Based on the worst operating conditions, the permitted height of combined center of gravity for railroad cars can be increased to 2500mm. The influence degree of each factor is derived by variance analysis. Factor B is a significant factor for derailment coefficient, factor A and factor C have little effect on derailment coefficient. But the three factors are significant factors for wheel unloading rate.

1 INTRODUCTION

Permitted height of combined center of gravity for railroad cars is one of the basic technical standards in China's railroad. The height of combined center of gravity cannot over 2000mm in current Regulations on Loading and Securing of Railway Goods, else the car must be running with a speed limit to ensure safety, so the permitted height of combined center of gravity for railroad cars is 2000mm in China.

This standard originated from Manchuria railroad for several decades. Since the 1950s, (Wenpu Yang, 1957) has focused on studies of the height of combined center of gravity for railroad cars. He derived the safety factor related to the vertical force and unbalanced centrifugal force when the car was passing through a curve. The results of research have indicated that combined center of gravity can exceed 2000mm and keep safety.

(Yuanhan Wang, 1979) studied the overturning coefficient when the car is running on the curve and stop on the curve. (Xiaoqiang Ding et al, 1982) proposed models of overturning coefficient and height of combined center of gravity based on the vertical and lateral inertia force. (Renjun Wang et al, 1982) provided numbers of gondola car, flat car, box car and tank car that had combined center of gravity over 2000mm, but these cars were not running with speed limit.

(Hongnian Yan, 1991) investigated the wheel unloading rate when the combined center of gravity was over high. (Haibo He, 1996) analyzed the relationship between derailment coefficient, wheel unloading rate, overturning coefficient and combined center of gravity. It has been proposed that the permitted height of combined center of gravity for railroad cars should be over 2200mm.

(Mei Han et al, 2007) derived a derailment model under the effect of the lateral force. They found that the permitted height of combined center of gravity for C64K gondola car was 2207mm when the derailment coefficient was no more than 1.2.

(More recently Beijing Jiaotong University, 2007, 2008) devised and performed field tests specifically to identify the permitted height of combined center of gravity for tank car and double-deck container car. Experiments results showed that the permitted height of combined center of gravity for tank car is 2200mm and it is 2400mm for double-deck container car.

The permitted height of combined center of gravity for the car and load in North American Railroad must be at 98 in. (2489.2mm) or less above top of rail [10]. The permitted height in Russian Railroad is 2585mm when the load does not have lateral deviation (Н.Г.,Г.П., Lusheng Chen, 1965).

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They are much higher than 2000mm in China's railroad.

This paper describes work to analyze and identify the permitted height of combined center of gravity. A particular feature of the work is the use of orthogonal experimental design and the railroad car multibody system (MBS) modelling is conducted in the SIMPACK environment, after which the established model is validated using field test data. The orthogonal experiment factors are confirmed before designing of simulation schemes. The railroad car MBS model in SIMPACK provides a method to simulate all the schemes, the wheel unloading rate and derailment coefficient can be got from SIMPACK post processing. Aim at the permitted height of combined center of gravity, the most dangerous conditions are obtained by objective analysis and variance analysis. This paper further explores the significance level of each orthogonal experiment factors.

2 MBS MODELLING AND VALIDATION

2.1 MBS Model of the Railroad Car

The railroad cars used in China today mostly have the same structure, the car-rail coupling system is demonstrated in Fig.1.

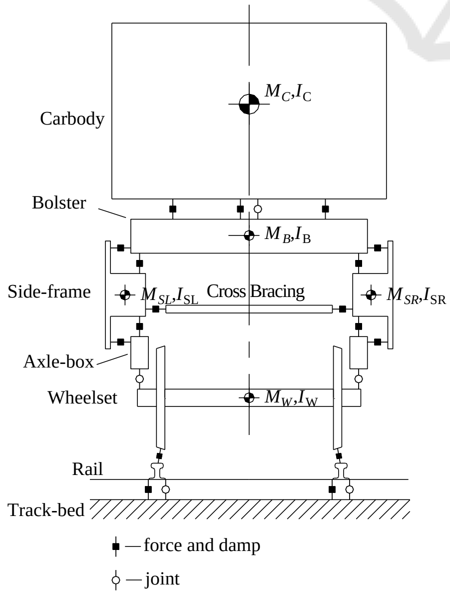

Figure 1. Physical model of railroad car system: side view.

The car has one carbody (a lading in it), two trucks and each truck has two wheelsets, two side-frames, one bolster, and two cross bracing poles (swing motion truck does not have). The suspension supplies stiffness and damping between side-frames and bolster in the longitudinal, lateral and vertical directions. The stiffness is supplied by spring group, and the damping is come from coil springs and friction. Furthermore, there are several clearance and block structures in the truck. First the force between two parts is friction, then the block will stop the movement of the parts after clearance disappeared. So the truck is a nonlinear dynamic system. The nonlinear force can be expressed as a spring that has two-stage stiffness.

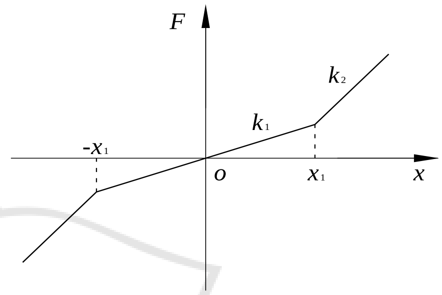

Figure 2. Force characteristic of two stage stiffness spring.

Figure.2 shows the two-stage stiffness spring model, and it can be described by

$$F = \begin{cases} k_1 x + [\max(x, x_1) - x_1](k_2 - k_1) & x \geq 0 \\ k_1 x + [\min(x, -x_1) + x_1](k_2 - k_1) & x < 0 \end{cases} \quad (1)$$

Where x is the relative displacement of two parts, k1, k2 are the two stage stiffness.

The total degrees of freedom (DOF) in the railroad car system are listed in Table 1.

A MBS model of the car-rail coupling system is established (Youm Y, 2005; Ahmed D. Shabana, Jalil R. Sany. 2001; Jenkins H.H. 1974) in SIMPACK environment based on the physical model (Fig.1) and the DOF of it.

Table 1. DOF of railroad car system.

	Number	**Longitudinal displacement**	**Lateral displacement**	**Vertical displacement**	**Roll angle**	**Pitch angle**	**Yaw angle**
Carbody	1	X_C	Y_C	Z_C	ϕ_C	θ_C	ψ_C
Lading	1	X_L	Y_L	Z_L	ϕ_L	θ_L	ψ_L
Bolster	2	X_B	Y_B	Z_B	ϕ_B	θ_B	ψ_B
Side-frame	4	X_S	Y_S	Z_S	ϕ_S	θ_S	ψ_S
Axle-box	8	X_A	Y_A	Z_A	ϕ_A	θ_A	ψ_A
Wheelset	4	X_W	Y_W	Z_W	ϕ_W	θ_W	ψ_W

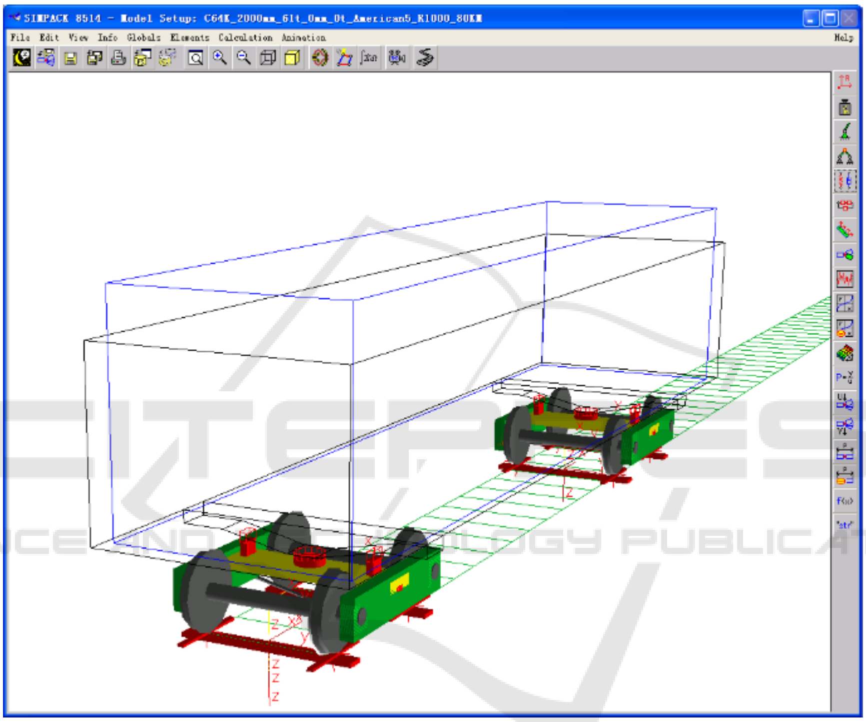

Figure 3. MBS model of car-rail coupling system in SIMPACK.

Fig.3 shows the final MBS car-rail coupling model in SIMPACK environment. The LM worn wheel tread and 60kg/m Chinese standard rail profile (TB/T 2341.3-93, 1993, TB/T 449-2003, 2003) are used in the wheel rail contact model.

2.2 MBS Model Validation

The MBS model in SIMPACK needs a validation before using it to analyze the permitted height of combined center of gravity.

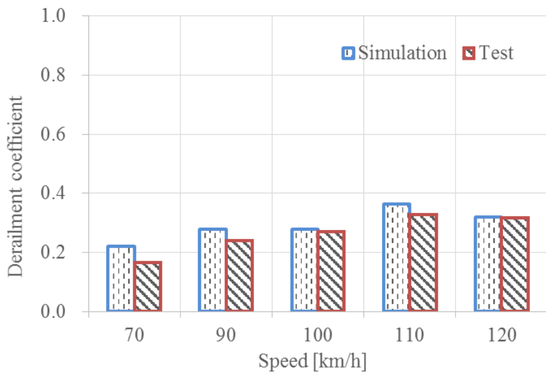

Figure 4. Derailment coefficient compare on tangent track.

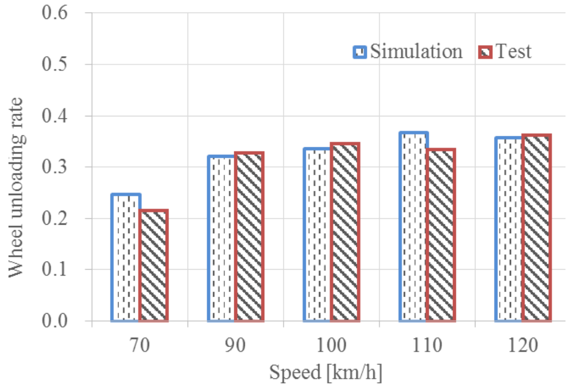

Figure 5. Wheel unloading rate compare on tangent track.

Figure.4 and Figure.5 show the derailment coefficient and wheel unloading rate of the No.1 wheelset while the C70H car operates on a tangent track at speed 70~120km/h. The data includes both of the field test results and the simulation results. The field test was conducted in the loop test line in Beijing, and the simulation model has the same type of car and loading status with the field test. Fig.4, Fig.5 demonstrate that both of the field test results and the simulation results have the same increasing trend when the car speeds up, and they have small difference. This difference may be come from the actual track irregularity is more intense than the AAR6 rail excitation that used in the simulation. The mean relative errors for the derailment coefficient and wheel unloading rate are 12.75% and 6.14%, respectively, indicating that the simulation results are accurate. A similar validation method is also performed for C70H running on curves of R350m and R600m, which show that the simulation model has a good accuracy. So, the MBS model in SIMPACK is validated accurate and effective for the next work.

3 SIMULATION RESEARCH

3.1 Method

The permitted height of combined center of gravity for railroad cars can be derived from the worst operating condition. Thus, many conditions should be simulated to find the worst operating condition. Orthogonal experiment method (Nagesh, S, Murthy, HNN, 2015) can be used to design simulation schemes, then the number of simulation schemes is decreased efficiently. Objective analysis and variance analysis (Sivam, SP, Michaelraj, AL, 2014; Saedon, JB, Jaafar, N, 2014) are carried out to get the worst operating condition based on the orthogonal experiment simulation results. Then, different height of combined center of gravity are set in the model and simulated to confirm the permitted height.

3.2 Orthogonal Experiment Factors

The railroad freight car operating safety is affected by height of combined center of gravity, lateral deviation of lading's center of gravity, track status, loading status, railroad car performance, and so on (Suarez, Berta, Felez, Jesus, 2013; Chen Chao; Han Mei, 2012). All the factors can be divided into two categories. One is the certain factors, includes the height of combined center of gravity and lateral deviation of lading's center of gravity. The other is the uncertain factors, includes the rest of factors. The level of uncertain factors need to be analyzed for orthogonal experiment schemes designing.

3.2.1 1st Factor-Railroad Car Level

The most general trucks used in Chinese railroad freight car are K2, K4, K5, K6. K2 and K6 are cross bracing trucks, but they have different axle-load. The axle-load of K2 is 21t, and the axle-load of K6 is 25t. K4 and K5 are swing motion truck, and the axle-load of K4 is 21t, and the axle-load of K5 is 25t. The four types of trucks have different axle-load and different structures, so each of them has unique dynamic performance.

At the same time, many types of railroad car put into operation, the general used mainly includes gondola car, flat car, box car, tank car. Box car and tank car have a maximum height of combined center of gravity as the top are closed. So this paper does not need to consider these two types of freight car. After that, we can pay attention to the length of truck centers. The freight cars equipped with the same truck which has the longer truck centers has a good dynamic performance (Taheri, Mehdi, Ahmadian, Mehdi, 2015). The gondola car has a worse dynamic performance than the flat car, as the length of truck centers of gondola car which equipped with K2 or K4 is 8700mm, and the length which equipped with K5 or K6 is 9210. But the length of truck centers of flat car which equipped with K2 or K4 is 9000mm, and the length which equipped with K5 or K6 is 10920mm. From the study above, gondola car equipped with four types of truck are the levels of the 1st factor. The simulation railroad freight cars are C64K, C64H, C70H and C70.

3.2.2 2nd Factor-Track Status and Speed Level

Track status not only contains the track irregularity, but also includes the curve radius and supper elevation. Some of the existing railroad line in China still keep the status as the Code for Design of Railway Line in 1999 (GB 50090-99, 1999). The railroad line in China is divided into three grades. In this paper, four curves are selected from real railroad line, two curves are from Grade I railroad in JingQin line and the other two are from Grade III railroad in JingCheng line. The four curves are R450m, R1200m in JingQin line and R350m, R600m in JingCheng line, the supper elevation for them are 80mm, 100mm, 120mm and 80mm.

The speed when running through a curve is connect to the radius and supper elevation as the centrifugal force. Balanced speed is the best, but passenger train and freight train operating together in the same line, so the supper elevation for different speed is less balanced or over balanced. With the curve radius, five levels for each railroad line are as follows,

Grade I railroad in JingQin line: (R450m, 20km/h), (R450m, 77km/h), (R1200m, 40km/h), (R1200m, 120km/h), (tangent track, 132km/h).

Grade III railroad in JingCheng line: (R350m, 20km/h), (R350m, 70km/h), (R600m, 20km/h), (R600m, 70km/h), (tangent track, 70km/h).

3.2.3 3rd Factor-Loading Status Level

Regulations on Loading and Securing of Railway Goods has a rule about the positon of lading's center of gravity on railroad freight car. In the longitudinal, the load difference of two trucks must not exceed 10t, and for each truck load must not exceed half of the car load limit. The average static load of the car is not the same based on different types of goods. The average static load of the car for timber is about the same as car load limit, the average static load of the car for cotton is 10t less than the car load limit and for industrial machinery is 20t less than the car load limit. So the loading status has three levels, includes load and the longitudinal position of lading's center of gravity, (car load limit, center), (10t less than car load limit, center), (10t less than car load limit, 10t difference truck load), (20t less than car load limit, center), (20t less than car load limit, 10t difference truck load).

3.3 Schemes and Simulation Results

The orthogonal experiment in this paper has three factors, railroad car has four levels, track status and speed has five levels for each railroad line grade, loading status has five levels. So this is an orthogonal experiment at different levels (Khajeh, MAZ; Shokrollahi, H, 2015). Quasi-level is presented to converse the 4-5-5 different levels to 5-5-5 equal-level (Bangxing Shen, Changjun Wen, 2005). The factors and levels are listed in Table 2.

Then we can use $L_{25}(5^6)$ orthogonal table to design simulation schemes, column 4, 5, 6 are left vacant as this orthogonal experiment only has three factors (Chengjun Zhang, 2009). All the schemes are defined in the MBS model and simulated in SIMPACK.

Table 2. Factor levels for orthogonal experiment.

Level No.	Factor						
	A	B				C	
	Car	Track status and speed				Loading status	
		Grade I Radius(m)	Grade I Speed(km/h)	Grade III Radius(m)	Grade III Speed(km/h)	Weight(t)	Truck load difference(t)
1	C_{64K}	450	20	350	20	P_L	0
2	C_{64H}	450	77	350	70	P_L-10	0
3	C_{70H}	1200	40	600	20	P_L-10	10
4	C_{70}	1200	120	600	70	P_L-20	0
5	C_{70}	Tangent	132	Tangent	70	P_L-20	10

Table 3. Simulation results.

No.	Factors			Grade I		Grade III	
	A	B	C	Derailment Coefficient	Wheel Unloading Rate	Derailment Coefficient	Wheel Unloading Rate
1	1	1	1	0.344	0.258	0.482	0.294
2	1	2	2	0.227	0.201	0.41	0.267
3	1	3	3	0.266	0.259	0.372	0.338
4	1	4	4	0.326	0.356	0.456	0.285
5	1	5	5	0.377	0.445	0.323	0.308
6	2	1	2	0.368	0.351	0.515	0.384
7	2	2	3	0.245	0.33	0.323	0.364
8	2	3	4	0.273	0.33	0.382	0.399
9	2	4	5	0.274	0.494	0.384	0.381
10	2	5	1	0.223	0.279	0.312	0.217
11	3	1	3	0.373	0.349	0.502	0.394
12	3	2	4	0.249	0.308	0.349	0.337
13	3	3	5	0.282	0.334	0.395	0.408
14	3	4	1	0.323	0.287	0.452	0.268
15	3	5	2	0.223	0.298	0.312	0.227
16	4	1	4	0.376	0.261	0.526	0.321
17	4	2	5	0.272	0.196	0.41	0.268
18	4	3	1	0.234	0.188	0.328	0.237
19	4	4	2	0.327	0.268	0.31	0.199
20	4	5	3	0.337	0.378	0.372	0.202
21	5	1	5	0.401	0.299	0.561	0.368
22	5	2	1	0.27	0.122	0.378	0.196
23	5	3	2	0.241	0.205	0.391	0.259
24	5	4	3	0.35	0.328	0.49	0.223
25	5	5	4	0.303	0.298	0.346	0.191

Table 3 lists the simulation results of derailment coefficient and wheel unloading rate for Grade I and Grade III railroad line.

3.4 Statistics Analysis

Derailment coefficient and wheel unloading rate are different kinds of indexes to evaluate railroad car operating safety. The correlation coefficient between these two indexes are calculated and the value are as follows, the correlation coefficient for Grade I and Grade III railroad line are 0.4021 and 0.3896. These two values show that the derailment Coefficient and wheel unloading rate have a poor correlation, which indicates that the worst operating condition should be confirmed based on derailment coefficient and wheel unloading rate separately.

Aimed at the worst operating condition, Table 4 shows the objective analysis.

t1~ t5 are the average value of each level No., they can demonstrate the influence of each factor level. R is the range, the first column's range is R=max{t1,t2,t3,t4}-min{t1,t2,t3,t4} and the 2nd and 3rd columns' range is R=max{t1,t2,t3,t4,t5}-min{t1,t2,t3,t4,t5}. The worst operating condition can be got for each grade of railroad line from objective analysis.

Objective analysis is a qualitative analysis method, but variance analysis is a quantitative analysis. The factors contribution rate can be calculated by quantitative analysis. Take the derailment coefficient of Grade I railroad line as an example, we can derive the contribution rate as follows.

Table 4. Objective analysis.

Index	Item	Grade I			Grade III		
		A	**B**	**C**	**A**	**B**	**C**
Derailment Coefficient	t_1	0.308	0.3724	0.2788	0.4086	0.5172	0.3904
	t_2	0.2766	0.2526	0.2772	0.3832	0.374	0.3876
	t_3	0.29	0.2592	0.3142	0.402	0.3736	0.4118
	t_4	0.3111	0.32	0.3054	0.4112	0.4184	0.4118
	t_5	—	0.2926	0.3212	—	0.333	0.4146
	R	0.0345	0.1198	0.044	0.028	0.1842	0.027
	worst scheme	A_4	B_1	C_5	A_4	B_1	C_5
Wheel Unloading Rate	t_1	0.3038	0.3036	0.2268	0.2984	0.3522	0.2424
	t_2	0.3568	0.2314	0.2646	0.349	0.2864	0.2672
	t_3	0.3152	0.2632	0.3288	0.3268	0.3282	0.3042
	t_4	0.2543	0.3466	0.3106	0.2464	0.2712	0.3066
	t_5	—	0.3396	0.3536	—	0.229	0.3466
	R	0.1025	0.1152	0.1268	0.1026	0.1232	0.1042
	worst scheme	A_2	B_4	C_5	A_2	B_1	C_5

(1) Derailment coefficient dispersion square sum

Total dispersion square sum:

$$SS_T = \sum_{r=1}^{25}(y_r - \bar{y})^2 = 0.074816 \qquad (2)$$

Factor dispersion square sum:

$$SS_A = 5\sum_{i=1}^{3}(t_i - \bar{y})^2 + 10(t_4 - \bar{y})^2 = 0.00478 \qquad (3)$$

$$SS_B = 5\sum_{i=1}^{5}(t_i - \bar{y})^2 = 0.048029 \qquad (4)$$

$$SS_C = 5\sum_{i=1}^{5}(t_i - \bar{y})^2 = 0.008237 \qquad (5)$$

Error dispersion square sum:

$$SS_e = SS_T - SS_A - SS_B - SS_C = 0.013769 \qquad (6)$$

(2) Degree of freedom

Total degree of freedom, factor A, B and C degree of freedom:

$$f_T = 25 - 1 = 24 \qquad (7)$$

$$f_A = 4 - 1 = 3 \qquad (8)$$

$$f_B = f_C = 5 - 1 = 4 \qquad (9)$$

Error degree of freedom:

$$f_e = f_T - f_A - f_B - f_C = 13 \qquad (10)$$

(3) Average dispersion square sum

The average dispersion square sum of factor A, B and C:

$$MS_A = \frac{SS_A}{f_A} = 0.001539 \qquad (11)$$

$$MS_B = \frac{SS_B}{f_B} = 0.012007 \qquad (12)$$

$$MS_C = \frac{SS_C}{f_C} = 0.002059 \qquad (13)$$

The average dispersion square sum of Error:

$$MS_e = \frac{SS_e}{f_e} = 0.001059 \qquad (14)$$

$MS_A < 2MS_e$, $MS_C < 2MS_e$ shows that the influence from factor A and factor C is less than factor B, so the average dispersion square sum and degree of freedom of factor A and factor C are added to error. The error's new parameters are as follows.

$$SS_e' = SS_e + SS_A + SS_C = 0.0267864 \qquad (15)$$

$$f_e' = f_e + f_A + f_C = 20 \qquad (16)$$

$$MS_e' = \frac{SS_e'}{f_e'} = 0.001339 \qquad (17)$$

(4) F-test

$$F_B = \frac{MS_B}{MS_e'} = 8.697 \qquad (18)$$

From F critical value table, $F_{0.01}(4,20) = 4.43069$, $F_{0.05}(4,20) = 2.866081$, obviously, $F_B > F_{0.01}$, so factor B is a very significant factor for derailment coefficient based on the significance level$\alpha = 0.01$. Factor A and factor C only have little effect on derailment coefficient.

(5)Contribution rate

The sum of squares of factors B is$PS_B = SS_B - f_B \cdot MS_e' = 0.42673$, so the contribution rate of factor B is,

$$\rho_B = \frac{PS_B}{SS_T} = 57.04\% \tag{19}$$

The rest contribution rate is come from factor A, factor C and error.

Similar statistic method is performed for wheel unloading rate and Grade III railroad line. No matter the railroad line grade is, factor B is a very significant factor for derailment coefficient, factor A and factor C only have little effect on derailment coefficient. But the three factors are very significant factors for wheel unloading rate.

From the objective analysis, the worst operating conditions for Grade I railroad are as follows,

(1) When use derailment coefficient, C70 gondola car, loaded 50t and 10t difference between two trucks, R450m curve with an 80mm supper elevation, the speed is 20km/h.

(2) When use wheel unloading rate, C64H gondola car, loaded 41t and 10t difference between two trucks, R1200m curve with a 90mm supper elevation, the speed is 120km/h.

The worst operating conditions for Grade III railroad are as follows,

(3) When use derailment coefficient, C70 gondola car, loaded 50t and 10t difference between two trucks, R350m curve with a 120mm supper elevation, the speed is 20km/h.

(4) When use wheel unloading rate, C64H gondola car, loaded 41t and 10t difference between two trucks, R350m curve with a 120mm supper elevation, the speed is 20km/h.

3.5 The Permitted Height of Combined Center of Gravity

The limit of derailment coefficient and wheel unloading rate in China are 1.2 and 0.65 (GB 5599-85, 1985). To confirm the permitted height of combined center of gravity for railroad car, the operating safety indexes must both under the limit. In all the orthogonal experiment schemes, the height of combined center of gravity is 2000mm. For the convenience of work on site, the height of combined center of gravity of the worst operating conditions are set as 2100mm, 2200mm, 2300mm, 2400mm, 2500mm, 2600mm.

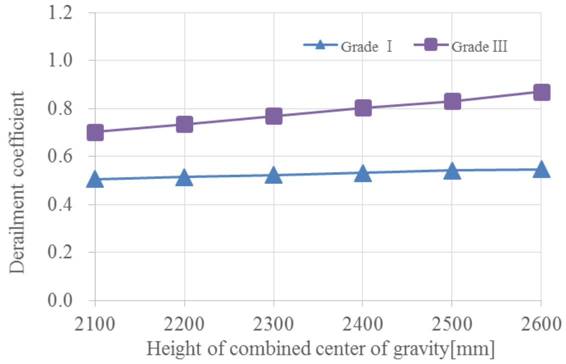

Figure 6. Derailment coefficient trend.

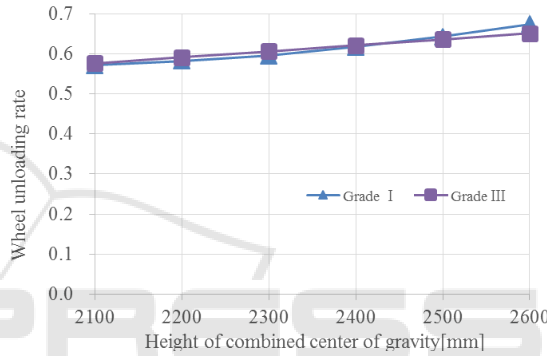

Figure 7. Wheel unloading rate trend.

Figure.6 and Figure.7 demonstrate the derailment coefficient and wheel unloading rate of each height of combined center of gravity for Grade I and Grade III railroad line. Figure.6 shows that the derailment coefficient does not exceed 1.2 even the height of combined center of gravity is 2600mm. Figure.7 shows that the wheel unloading rate is over 0.65 based on the worst operating condition of Grade I railroad line. But when the height of combined center of gravity is 2500mm, they all under the limit. So, the permitted height of combined center of gravity for railroad cars is 2500mm in China.

4 CONCLUSION

A review of the literature in the field of the height of combined center of gravity for railroad cars revealed that the concepts of increase the permitted height is possible. And this study can enhance the railroad freight transportation capacity.

The factors that affect railroad car operating safety can be divide into two categories, the certain factors and the uncertain factors. The orthogonal experiment method was used for analyzing the uncertain factors. So the three uncertain factors are studied and the levels of each factor are determined for orthogonal experiment.

MBS model was used to simulate the railroad freight car dynamic performance. The model was validated by simulation and field test result comparison. The operating condition are include tangent track, R350m and R600m curves, they all showed that the simulation model has a good accuracy.

The worst operating conditions for Grade I railroad and Grade III railroad were derived from objective analysis. The variance analysis showed the factors' influence degree. Factor B is a very significant factor for derailment coefficient, factor A and factor C only have little effect on derailment coefficient. But the three factors are very significant factors for wheel unloading rate.

Based on the worst operating conditions and the limit of derailment coefficient and wheel unloading rate in China, we can simulate the different height of combined center of gravity and get the permitted height of combined center of gravity for railroad cars can be increased to 2500mm in China.

Further work is underway to extend the MBS modelling approach to deal with train simulation and the braking and accelerating during operating. The field test will be conducted to confirm the permitted height of combined center of gravity for railroad cars at last.

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