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Investigation of train driver impact dynamics response during collision

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Abstract:

Background: In order to analyze train driver injury under secondary impact. For this purpose, the train cab's console - seat - dummy collision analysis model is established using MADYMO. The driver impact dynamic response and the driver injury results obtained from the collision model. The range analysis is conducted to determine the extent of the influence of each design variable (factor A: the longitudinal distance between the side of the console and the seat G-spot; factor B: the longitudinal distance between the side of the console and the knee bolster at the bottom of the console; factor C: the cross section thickness of the console) on each driver injury criterion.

Results: The driver injury results obtained from the collision model have shown that driver injury is considerably severe. Driver's head, neck, chest, and legs injuries are very serious, the corresponding injury criteria HIC, head acceleration, Nij, DC, and TI are beyond the maximum acceptable values. The work of range analysis has shown that the factor A greatly influences driver's HIC, DC, and FFC, the factor B mainly influences driver's head acceleration and TI, and the factor C greatly affects driver's Nij and TCFC.

Conclusions: This study mainly researches driver's secondary impact injury based on the multi-rigid-body dynamics. During the secondary impact, the results have shown that the driver's injury is extremely serious.

Keywords: Rail train; Secondary collision; Driver injuries

1. Introduction

Due to the development of the railway active safety technology, the train collision accidents rarely happen, train has higher security. But it cannot completely avoid the happening of the accidents. Once a train collision happens, it will cause significant casualties and property losses. From 1995 to 1997, 26 locomotive cab occupants were died and 289 were injured in train accidents in the United States [1]. In Europe, 362 fatal train collisions and derailments were identified in 1980–2009, of which 149 occurred in 1980–1989 and 213 in 1990–2009 [2]. Due to the sharp decelerations of train cab in primary collisions [3, 4, 5], fast relative motion is produced between the driver and the train cab. After the primary collision of the trains, the driver is subject to secondary collisions [6, 7] between himself (herself) and the console and seat [8, 9].

In recent years, much research on railway vehicle energy absorption structures and occupant secondary collisions has been developed rapidly. Main purpose of the research is to limit the deceleration imparted on driver due to the primary collision between the train and obstacles. The crashworthiness of vehicle energy absorption structures and passive safety protection measures of occupants were researched by the Volpe National Transportation System Centers [10, 11]. A detailed design of a coach car crash energy management system that could be applied to a modified existed passenger car and subjected to a full-scale collision test was developed by Mayville et al. [12]. Martinez et al. [13] designed a crush zone for an existed Budd M1 cab car to control both lateral and vertical vehicle motions that could promote lateral buckling of the train and override of the impacting equipment. A detailed computer finite element model was developed by Kirkpatrick and MacNeill [14] for predicting the rail passenger car response to collision conditions. The Volpe National Transportation Systems Center carried out numerous tests and numerical simulations on full-scale dummy secondary collisions in passenger compartments [15, 16]. European Union researched occupant secondary collisions by some coasting tests and numerical simulations with the Hybrid III dummy model [17]. Parent et al. [18] designed a workstation table with improved crashworthiness performance to reduce the injury risk to the occupants. Tyrell et al. [19] analyzed the occupant protection strategies, such as compartmentalization and occupant restraints, in train collisions. Severson et al. [20] designed, built, and tested a prototype 3-passenger commuter rail seat that could improve interior crashworthiness to manage and dissipate the energy during a secondary impact. Tyrell et al. [21] researched the influence of the lateral motions and vertical motions of the cars on the response of the test dummies, the results showed that the vertical motions of the cars had a greater influence on dummies response. Selecting central locking of doors and removing stairs into carriages were successful to reduce passenger fatalities in Finland [22]. However, at present, there is seldom research on the protection for train driver during secondary collision.

In this study, a train cab's console - seat - dummy collision analysis model is established to analyze train driver injury. The driver impact dynamic responses and the driver injury results obtained from the collision model.

2. Assessment of train driver impact injuries

2.1 Train cab model

The model for the train cab includes the console and seat. The dimension of console (see Figure 1) is designed according to the standard of International Union of Railways [23]. The longitudinal distance between the side of the console and the seat's G-spot is 450 mm, the longitudinal distance between the side of the console and the knee bolster at the bottom of the console is 370 mm, the cross section thickness of the console is 120 mm, and the pedal height is 250 mm. The seat is mainly composed of headrest, seat back, armrest, cushion, etc. The dimension of seat (see Figure 1) is designed according to the china railway industry standard [24]. The configuration of the console and seat is based on the standard of International Union of Railways [23].

2.2 Driver model

The driver model (see Figure 1) is the MADYMO's validated Hybrid III dummy model. The dummy model comprises head, neck, abdomen, chest, pelvis, spine, extremities, etc. Every part of the dummy body is connected by a hinge. The position of the dummy body and the relative position of parts of the dummy body can be determined by adjusting the hinge parameters.

2.3 Set up of collision model

Figure 1 shows the collision simulation dynamic model in MADYMO. The position of the dummy in the train cab is adjusted using an observation method and a pre-simulation method. In the pre-simulation, the dummy is placed close to the seat to avoid initial penetration. After the dummy is positioned in the train cab, the contact between driver and the console and seat is defined. The stiffness curves and contact characteristics of the console and seat are defined. Before analysis, two acceleration fields (one gravitational, the other horizontal) are applied to the model. The gravitational acceleration is -9.8 m/s^2. As shown in Figure 2, the horizontal impact acceleration [25] subjected to the driver is a rectangular impulse (upper limit curve) with a peak acceleration of 8 g and a pulse duration of 210 ms.

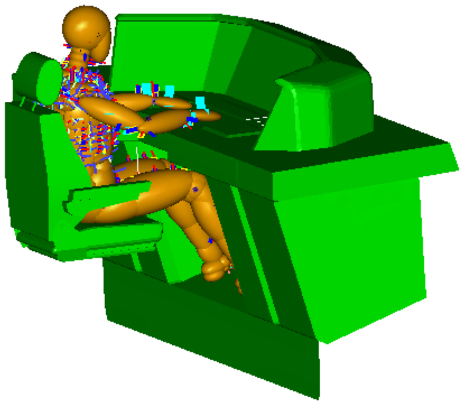


Figure 1. The collision simulation dynamic model in MADYMO

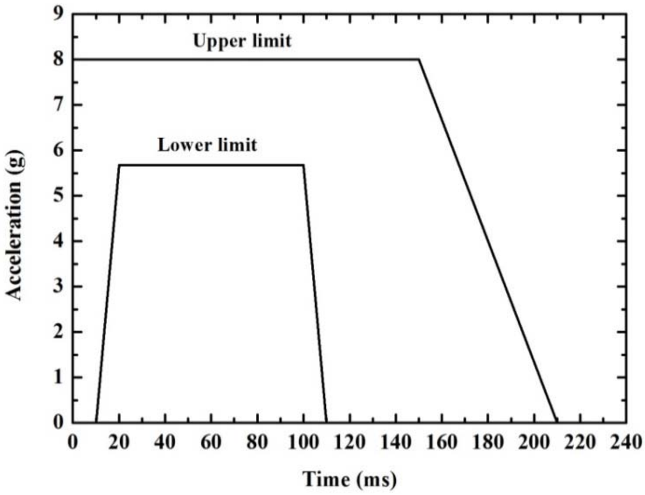


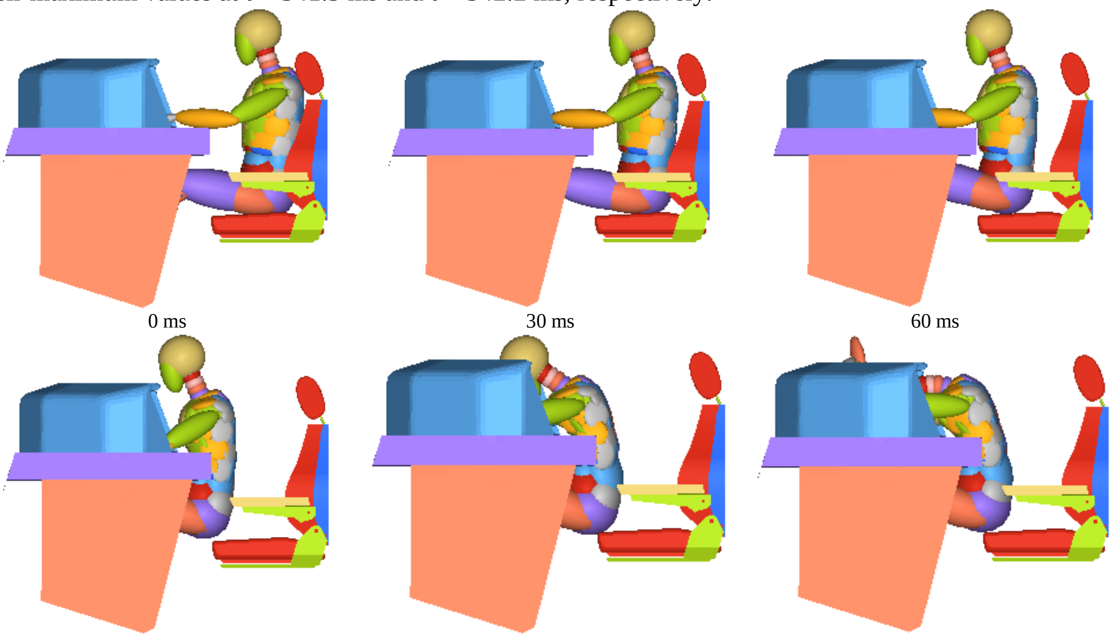
Figure 2. Definition of the horizontal impact acceleration

2.4 Evaluation criteria for the driver injury

The most vulnerable parts of an unrestrained driver's body in the driver workspace are the head, neck, thorax, and legs (injury proportion ⩾ 20 %) that could be attributed to console and seat [25]. Consequently, the injury parameters relevant to the Head Injury Criterion (HIC), head acceleration, Normalized neck injury criteria (Nij), Chest deflection limit for thoracic injury (D_C), Femur Force Criterion (FFC), Tibia Index (TI), and Tibia Compressive Force Criterion (TCFC) are mainly analyzed in this study to assess the risk of driver's injury. The HIC, head acceleration, Nij, D_C, FFC, TI, and TCFC should not exceed 500, 80 g, 1, 76 mm, -7560 N, 1.3, and -8000 N during the crash pulse [9, 26, 27].

2.5 Results

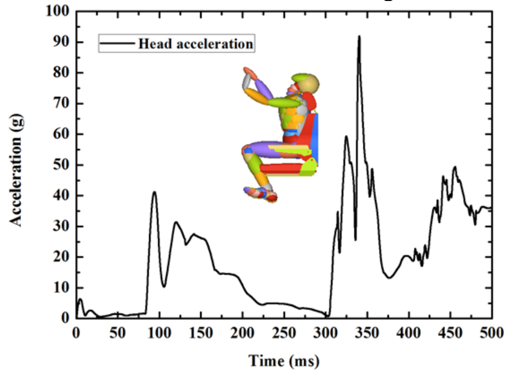
According to numerical analysis, the relative movement between the driver and the console and seat occurs and secondary impact ensues. Figure 3 shows the impact status between the driver and the console and seat. At t = 84 ms, the driver begins to strike the console, the corresponding head acceleration curve begins to rise until it reaches its local peak at t = 94.1 ms. The TI curve begins to fluctuate until it reaches its local peak at t = 95 ms. The Nij curve reaches its local peak at t = 95.8 ms. The corresponding femur force increases rapidly until it reaches its maximum value at t = 96.6 ms. The TCFC curve reaches its local peak at t = 98.3 ms. At t = 119.3ms, the chest compress deformation reaches its maximum value. Over time, the impact of the driver and the console finishes, to be followed by a rebound of the driver, resulting in an impact between the driver and the seat. At t = 295 ms, the driver begins to strike the seat, the corresponding TI curve rises rapidly until it reaches its maximum value at t = 339.9 ms. The head acceleration curve begins to fluctuate until it reaches its maximum value at t = 340.4 ms. The Nij curve and TCFC curve rise rapidly until they reach their maximum values at t = 341.3 ms and t = 342.2 ms, respectively.



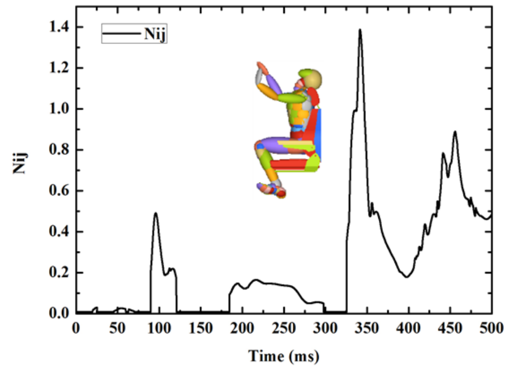
90 ms 120 ms 150 ms

220 ms 280 ms 350 ms

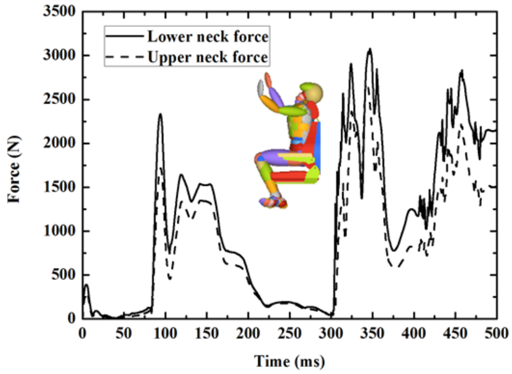
Figure 3. The driver's impact response



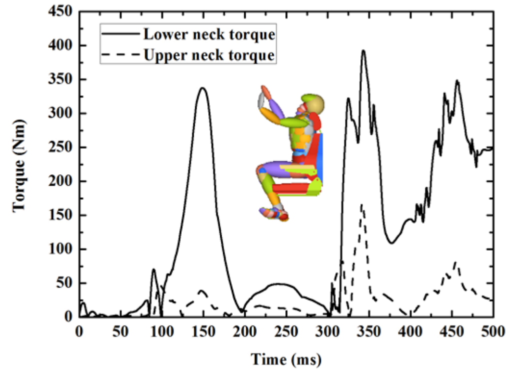
(a) The acceleration-time curve of head



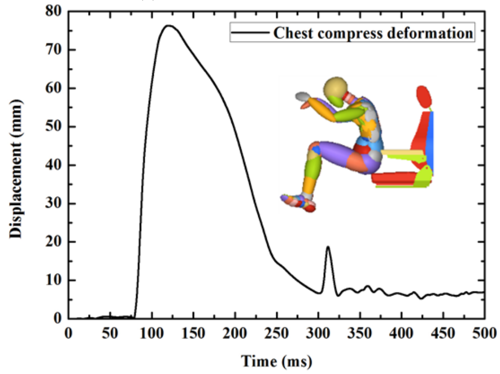
(b) The curve of Nij



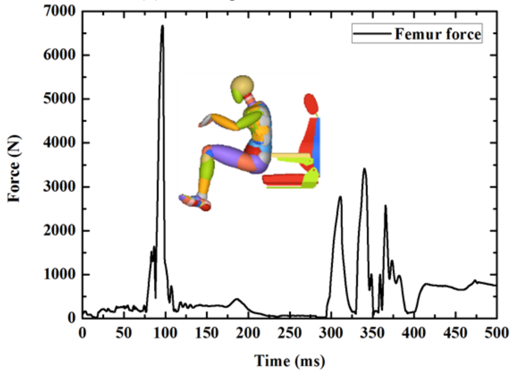
(c) The force-time curve of neck



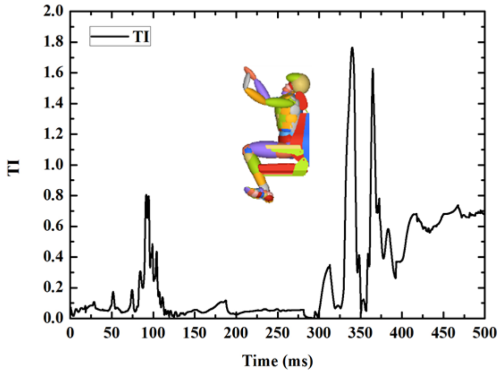
(d) The torque-time curve of neck



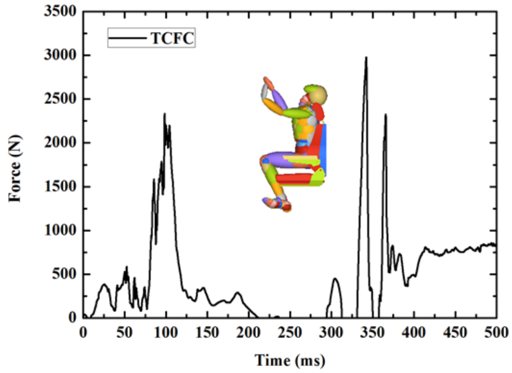
(e) The displacement-time curve of chest



(f) The force-time curve of femur



(g) The curve of Tibia Index



(h) The curve of TCFC

Figure 4. The curves of driver's injury results

Table 1. The driver injury results

Injury criteria	HIC	Head acceleration (g)	Nij	D_C (mm)	FFC (N)	TI	TCFC (N)
-	**782.6**	**92**	**1.3785**	**76.3**	-6674.2	**1.7642**	-2978.7

Figure 4 demonstrates the injury criteria curves of the driver. The peaks of all curves indicate that in the relative movement of the driver and the console and seat, the driver first strikes the console (the first peaks generate in all curves), then rebounds to strike the seat (the second peaks values thus generate). Moreover, as shown in Figure 4 and Table 1, during the impact with the console, the driver's chest and femur injuries are relatively severe, the corresponding D_C and FFC reach their maximum values 76.3 mm and -6674.2N, respectively. During the impact with the seat, the driver's head, neck, and tibia injuries are relatively severe, the corresponding HIC, head acceleration, Nij, TI, and TCFC reach their maximum values 782.6, 92 g, 1.3785, 1.7642, and -2978.7 N, respectively. As shown in Table 1, it is obvious that driver's head, neck, chest, and legs injuries are very serious, the corresponding five injury criteria HIC, head acceleration, Nij, D_C, and TI are beyond the maximum acceptable values.

3. Parameter sensitivity analysis

The parameters' sensitivity is conducted to determine the extent of the influence of each design variable on each driver injury criterion [28, 29, 30]. The design variables researched in this study are: the longitudinal distance between the side of the console and the seat G-spot (factor A), the longitudinal distance between the side of the console and the knee bolster at the bottom of the console (factor B), the cross section thickness of the console (factor C), and the pedal height (factor D). Figure 5 illustrates the meaning of each factor. The ranges of factor A, B, C, and D in this study are: 350 mm $\leqslant$ A $\leqslant$ 450 mm, 320 mm $\leqslant$ B $\leqslant$ 420 mm, 120 mm $\leqslant$ C $\leqslant$ 220 mm, and 150 mm $\leqslant$ D $\leqslant$ 250 mm, respectively. As shown in Table 2, some 9 samples based on a 4 – factor, 3 – level orthogonal experiment design are selected to analyze the influences of each factor on driver impact injury severity and extent. Table 3 contains the driver's injury results of the sample models.

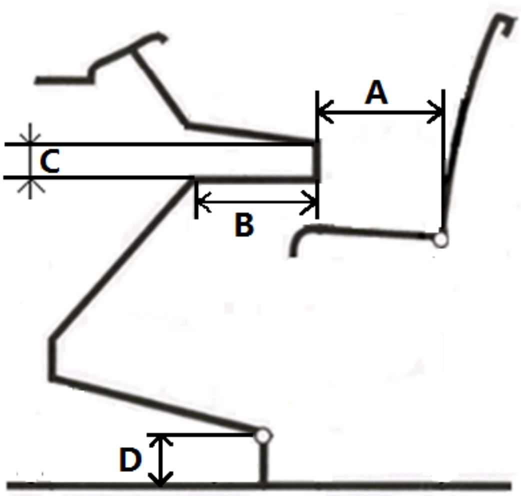


Figure 5. The schematic diagram of the dimension of each factor

Table 2. The table of the orthogonal experiment of the driver workspace parameters

Experiment number	A (mm)	B (mm)	C (mm)	D (mm)
1	350	320	120	150
2	350	370	170	200
3	350	420	220	250
4	400	320	170	250
5	400	370	220	150
6	400	420	120	200
7	450	320	220	200
8	450	370	120	250
9	450	420	170	150

Table 3. Injury results of the orthogonal experiment

Experiment number	HIC	Head acceleration (g)	Nij	D_C (mm)	FFC (N)	TI	TCFC (N)
1	338.9	**94.7**	0.8314	71.7	-4984.3	**1.6093**	-3159.5
2	302.2	70.9	0.5550	71.4	-6929	1.2707	-2142.9
3	304.8	62.8	0.5240	70.5	-3642.9	**2.2671**	-4459.7
4	417.6	**98.7**	0.7813	72.6	**-8504.9**	**1.7965**	-2295.7
5	298.2	**87.8**	0.6253	73.8	**-10423**	**1.8348**	-3075.7
6	312.8	**87.5**	0.6518	**79.1**	**-9636.4**	**1.6108**	-3489
7	403.2	**97.2**	0.5835	**77.6**	**-11226**	**1.8589**	-3069.8
8	**782.6**	**92**	**1.3785**	**76.3**	-6674.2	**1.7642**	-2978.7
9	403.7	60.7	0.9990	**81.3**	**-10139**	**2.3495**	-2701

The study researches range analysis for each driver injury criterion. K1, K2, and K3 are the mean values of the driver injury criteria corresponding to every level of each factor. The difference value of the maximum mean value and minimum mean value among the K1, K2, and K3 is R which reflects the extent of the influences of each factor on each driver injury criterion. Table 4 - 10 contain the results of range analyses for driver injury criteria.

As shown in Table 4 and Table 5, HIC increases with increasing factor A, head acceleration increases with decreasing factor B. As the factor A increases, the driver would strike the console at a higher velocity, and the upper body would pivot about the hips at a higher rate, both actions contributing to increasing the head injury as the factor A increases. As the factor B decreases, the driver's legs would contact the console before the driver's upper body, the range of motion of driver's head is bigger, so the driver's head injury is more serious. The sensitivity of the driver head injury criteria to factor A and B is stronger.

Table 4. Range analysis for HIC

Factors (mm)	A	B	C	D
K1	315.3	386.5	478.1	346.9
K2	342.8	461	374.5	339.4
K3	529.8	340.4	335.4	501.7
R	214.5	120.6	142.7	162.3

Table 5. Range analysis for head acceleration

Factors (mm)	A	B	C	D
K1 (g)	76.1	96.8	91.4	81
K2 (g)	91.3	83.6	76.7	85.2
K3 (g)	83.3	70.3	82.6	84.5
R (g)	15.2	26.5	14.7	4.2

As shown in Table 6, Nij presents an increasing trend with decreasing factor C. As the factor C decreases, the driver's chest would strike the console over a smaller area, the range of motion of driver's neck is bigger, so driver's neck injury is more severe. The sensitivity of the driver neck injury criterion to factor C is stronger.

Table 6. Range analysis for Nij

Factors (mm)	A	B	C	D
K1	0.6368	0.7321	0.9539	0.8186
K2	0.6861	0.8529	0.7784	0.5968
K3	0.9870	0.7249	0.5776	0.8946
R	0.3502	0.1280	0.3763	0.2978

As shown in Table 7, D_C increases with increasing factor A. The bigger factor A allows the driver to build up speed relative to the console, the driver's chest would contact the console with a higher force, the driver's chest compression deformation is bigger and chest injury is more serious. The sensitivity of the driver chest injury criterion to factor A is stronger.

Table 7. Range analysis for DC

Factors (mm)	A	B	C	D
K1 (mm)	71.2	74	75.7	75.6
K2 (mm)	75.2	73.8	75.1	76
K3 (mm)	78.4	77	74	73.1
R (mm)	7.2	3.2	1.7	2.9

As shown in Table 8, FFC generally increases with increasing factor A. As the factor A increases, the driver's legs would strike the console at a higher velocity, which resulting in a severe impact, the driver's femur injury is serious. The sensitivity of the driver femur injury criterion to factor A is stronger.

Table 8. Range analysis for FFC

Factors (mm)	A	B	C	D
K1 (N)	-5185.4	-8238.4	-7098.3	-8515.4
K2 (N)	-9521.4	-8008.7	-8524.3	-9263.8
K3 (N)	-9346.4	-7806.1	-8430.6	-6274
R (N)	4336	432.3	1426	2989.8

As shown in Table 9 and Table 10, TI generally increases with increasing factor B, TCFC firstly decreases and then subsequently increases as factor C increases. The bigger factor B allows the driver to build up speed relative to the console, the driver's legs would contact the console with a higher force. The sensitivity of the driver tibia injury criteria to factor B and C is stronger.

Table 9. Range analysis for TI

Factors (mm)	A	B	C	D
K1	1.7157	1.7549	1.6614	1.9312
K2	1.7474	1.6232	1.8056	1.5801
K3	1.9909	2.0758	1.9869	1.9426
R	0.2752	0.4526	0.3255	0.3625

Table 10. Range analysis for TCFC

Factors (mm)	A	B	C	D
K1 (N)	3254	2841.7	3209.1	2978.7
K2 (N)	2953.5	2732.4	2379.9	2900.6
K3 (N)	2916.5	3549.9	3535.1	3244.7
R (N)	337.5	817.5	1155.2	344.1

4. Discussion

This study establishes a console - seat - dummy collision analysis model and assesses the driver's injury during the secondary collision. Driver's head, neck, chest, and legs injuries of the collision model are especially serious, the corresponding injury criteria HIC, head acceleration, Nij, D_C, and TI are beyond the maximum acceptable values.

Factor A greatly influences HIC, D_C, and FFC. When the factor A is small, the driver contacts the console with a low impact velocity, thus minimizing injury. Factor B greatly influences head acceleration and TI. The greater the factor B is, the smaller the range of motion of driver's head is, the lower the head acceleration is. However, the greater the factor B, the bigger the impact velocity and contact force of legs, the higher the TI. The change trends of driver's head acceleration and TI with increasing factor B are opposite. Factor C greatly influences Nij and TCFC. The thicker the factor C, the bigger the contact areas of driver's chest, the smaller the range of motion of driver's neck is, the lower the

Nij. Besides factor B, the factor C is also an important factor greatly influences driver's TI. The thicker the factor C is, the higher the TI is. The change trends of driver's Nij and TI with increasing factor C are opposite.

5. Conclusion

This study mainly researches driver's secondary impact injury based on the multi-rigid-body dynamics. During the secondary impact, the results of the driver-console-seat coupling impact dynamics model have shown that the driver's injury is extremely serious. There are five injury criteria exceed the maximum injury tolerance levels. It is obvious that the driver's head, neck and chest injury is very severe. The work of range analysis has shown that the factor A greatly influences driver's HIC, D_C, and FFC, the factor B mainly influences driver's head acceleration and TI, and the factor C greatly affects driver's Nij and TCFC.

Acknowledgments

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