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Research on the Calculation Method of Vehicle Compatibility Index Based on Stiffness Theory

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Abstract:

Background: By the end of 2022, the number of private cars in China had reached 277,920,000, along with 157,407 traffic accidents and 42,012 traffic accident fatalities. There were almost 149,650 injured people in these traffic accidents, with direct property losses amounting to 991,290,000 yuan. Therefore, in order to reduce casualties and property losses in traffic accidents, the passive safety of vehicles has always been a key focus for automakers.

Objective: This paper is aimed at proposing a simplified method for calculating the *OLC* (Occupant Load Criterion) in frontal 50% overlap mobile progressive deformable barrier impact tests (MPDB tests), according to the displacement-stiffness curve of the vehicle front end structure.

Method and Material: Based on the principles of energy conservation and momentum conservation during vehicle impact process, combining the simplified spring model theory of vehicle collision, this paper ultimately predicts the vehicle compatibility index based on the stiffness curve of vehicle front end structure, which is verified by test data,.

Results: The study firstly uses the displacement-stiffness curves of the front end structure of 10 vehicles, which are obtained from the *x*-direction acceleration sensor at left B-pillar in frontal full width rigid barrier impact tests (FWRB test), combined with the simplified spring model theory, to calculate the maximum acceleration and maximum displacement of the FWRB test, offset deformable barrier test (ODB test), and MPDB test. Secondly, the applicability of this calculation method is verified by the results of real vehicle crash tests , where the deviations are all within 10%. Thirdly, according to the maximum acceleration and maximum displacement of the moving deformable barrier in the MPDB test calculated above, and the dynamic response calculation method of simplified spring models, a method for calculating the MPDB test compatibility index *OLC* based on the displacement-stiffness curves of the front end structure of the vehicle obtained from the FWRB test is proposed.

Conclusions: Vehicle compatibility is of great importance for ensuring the safety, smoothness, and efficiency of the road traffic. It is significant to predict the compatibility index of the vehicle in the MPDB test by using the displacement-stiffness curve of the vehicle's front end structure, providing some reference for the improvement of vehicle compatibility.

Keywords: Vehicle compatibility, Front-end stiffness, Simplified spring model, Occupant load Criterion

1 Introduction

With the rapid growth of the national economy, the number of private cars has been steadily increasing year by year.By the end of 2022[1], the number of private cars in China had reached 277,920,000, along with 157,407 traffic accidents and 42,012 traffic accident fatalities. There were almost 149,650 injured people in these traffic accidents, with direct property losses amounting to 991,290,000 yuan. Therefore, in order to reduce casualties and property losses in traffic accidents, the passive safety of vehicles has always been a key focus for automakers.

In traffic accidents, multi-vehicle accident is the main accident type which would cause severe passenger injuries. The differences in weight, size, and stiffness of the vehicles involved in the accident may lead to different injury situations for vehicles and passengers. According to statistics[2], in all passenger car accidents, the fatality rate of car-to-car frontal impact accidents is the highest among all types, where small sedans are at a disadvantage when impact with other vehicles.

Therefore, in order to reduce the injury to people in a car accidents, the Experimental Safety Vehicle (ESV) program proposed the concept of vehicle compatibility in 1970. Vehicle compatibility refers to the ability of a vehicle to protect its occupants as well as the occupants of the other vehicle in vehicle impact. In 2010, the German crash testing agency Allgemeiner Deutscher Automobil-Club (ADAC) introduced frontal 50% overlap mobile progressive deformable barrier impact tests (MPDB tests) to evaluate vehicle compatibility; after 2020, Euro NCAP and C-NCAP also successively introduced MPDB tests in their test programs.

In order to improve the passive safety performance of vehicles, many inspection engineers have been consistently studying the vehicle's compatibility using various methods. In the aspect of theoretical research, Danqi Wang et al. [3] combined the dynamic response theory analysis of the BVO system (barrier-vehicle-occupant system) and the cooperative optimization method of genetic algorithms to obtain the vehicle’s impact pulse which can acquire the optimal compatibility index. Junyuan Zhang et al. [4] proposed a three-stage target decomposition method for calculating the front-end structure impact pulse design based on the energy management in vehicle impacts. Zhu Haitao et al. [5] compared offset deformable barrier test (ODB test), frontal full width rigid barrier impact test (FWRB test), and frontal 50% overlap mobile progressive deformable barrier impact test (MPDB test) in the aspect of occupant load criterion (*OLC*) and energy equivalent speed (*EES*), verifying the effectiveness of MPDB test in vehicle compatibility evaluation. In the experimental analysis aspect, Dario Vangi et al. [6] proposed a vehicle stiffness calculation method on account of the analysis of impact test videos. Wang Yue et al. [7] studied the key factors affecting the compatibility index of MPDB test through experimental statistical method, and summarized the relationship between the vehicle's curb weight and the occupant load criterion *OLC*, giving some design suggestions for the vehicle front-end structure. Zhu Haitao et al. [8] summarized and analyzed the deformation data of the honeycomb aluminum after MPDB tests, where a barrier energy absorption ratio evaluation index and corresponding implementation method related to the vehicle's overall stiffness was proposed. Wang Limin et al. [9] conducted an analysis of a considerable number of MPDB test compatibility results, presenting the vehicle compatibility levels of current mainstream vehicle models and some intrinsically significant practical laws. In the finite element method (CAE calculation) aspect, Taisuke Watanabe et al. [10] compared the vehicle compatibility results of large vehicles in MPDB tests and occupant injury results of small vehicles in the vehicle-to-vehicle impact tests using finite element simulation software. Xing Zhiyuan [11] proposed a vehicle compatibility index optimization method for medium SUV through finite element simulation and the method was verified in the paper. Song Heping et al. [12] proposed a vehicle compatibility index optimization scheme for MPDB tests through finite element simulation analysis and verified it. Li Lujiang et al. [13] through the comparison between the MPDB test and the finite element simulation of vehicle-to-vehicle collision, discovered that it is appropriate to evaluate vehicle compatibility using the MPDB tests. Guibing Li et al. [14] employed the MATLAB genetic algorithm and LS-DYNA finite element simulation for optimizing vehicle compatibility to protect the lower limbs of pedestrians.

In C-NCAP management regulation(2024 edition), the vehicle compatibility indexes mainly include: Standard deviation (*SD*) of barrier deformation, occupant load criterion (referred to as *OLC* in the following text), barrier penetration depth and barrier penetration height, of which the referred to as *OLC* in the following text is calculated by the impact pulse obtained from the *x*-direction acceleration sensor installed at the center of gravity of the moving progressive deformation barrier. Generally speaking, the vehicle compatibility indexes are mainly gained by finite element simulation and real car crash tests. Finite element simulation usually requires a lot of time to establish finite element models, and precise calculation always depends on high-performance computer hardware, consuming a large amount of computing resources. Real car crash tests require a considerable economic cost. Therefore, this paper attempts to calculate *OLC* through a combination of theoretical calculation and experimental data analysis, providing some guidance for the compatibility evaluation of vehicles in the design stage.

Firstly, this paper explains the principles of energy conservation and momentum conservation during vehicle impact process, and combines the calculation method of the stiffness for the simplified spring model, where the displacement - stiffness curve of vehicle's front-end structure is calculated by data acquired from the *x*-direction acceleration sensor installed at the B-pillar below in frontal full width rigid barrier impact tests (FWRB tests). Secondly, according to the displacement - stiffness curve of vehicle's front-end structure, the maximum acceleration and maximum displacement during impact tests are calculated using MATLAB software for FWRB tests, offset deformable barrier tests (ODB tests) and frontal 50% overlap mobile progressive deformable barrier impact tests (MPDB tests), which will be compared with the corresponding values gained in real car impact tests to verify the validity of the calculation method mentioned above. Finally, combining the calculated maximum acceleration and maximum displacement with the dynamic response calculation method of simplified spring model, a method of estimating the vehicle compatibility index *OLC* based on the displacement - stiffness curve of the vehicle's front-end structure obtained from FWRB test is proposed.

2 Conservation during vehicle impacts

2.1 Energy conservation in impact processes

Real vehicle impact tests encompassed in this paper mainly consist of the frontal full width rigid barrier impact test (hereinafter referred to as the FWRB test), the offset deformable barrier test (hereinafter referred to as the ODB test), and the frontal 50% overlap mobile progressive deformable barrier impact test (hereinafter referred to as the MPDB test), as depicted in Figure 1. In the FWRB test, where the barrier is fixed and rigid, the initial energy of the system is mainly transformed into the deformation energy of the vehicle, the rotational energy during the impact, and the residual energy after the impact. In the ODB test, with the barrier fixed and deformable, the initial energy of the system is mainly converted into the deformation energy of the vehicle, the vehicle's rotational energy during the impact process, the vehicle's residual energy after the impact, and the deformation energy of the barrier. In the MPDB test, where the barrier is movable and deformable, the initial energy of the MPDB test system is mainly transformed into the deformation energy, the rotational energy during the impact process, and the residual energy after the impact of the vehicle and the barrier.

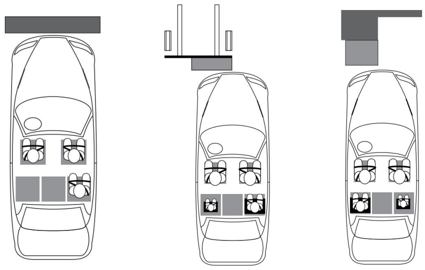

Figure 1. FWRB test, ODB test and MPDB test

During the process of real vehicle impact, the rotational amplitudes of both the vehicle and the barrier are often relatively small. Therefore, in this paper, the rotational energy is ignored. The energy transformation in the crash tests can be expressed as Equation (1).

$$E_{\mathrm{in}} = E_{\mathrm{D}} + E_{\mathrm{r}} \tag{1}$$

Where, E_{in} is the total energy of the impact system, E_{D} and E_{r} are the deformation energy and residual energy after the impact respectively.

The residual energy E_r after the impact is mainly divided into residual kinetic energy E_{rv} and residual rotational energy E_{rr}. Similarly, the residual rotational energy is disregarded, and the Equation (1) becomes:

$$E_{in} \approx E_D + E_{rv} \tag{2}$$

Then for the MPDB test:

$$E_{in} = \frac{1}{2}M_v v_0^2 + \frac{1}{2}M_B v_0^2 \tag{3}$$

$$E_{rv} \approx \frac{1}{2}M_v v_1^2 + \frac{1}{2}M_B v_2^2 \tag{4}$$

$$\begin{aligned} E_D &\approx E_{in} - E_{rv} \\ &\approx \frac{1}{2}M_v v_0^2 + \frac{1}{2}M_B v_0^2 - \frac{1}{2}M_v v_1^2 - \frac{1}{2}M_B v_2^2 \\ &= \frac{1}{2}M_v\left(v_0^2 - v_1^2\right) + \frac{1}{2}M_B\left(v_0^2 - v_2^2\right) \end{aligned} \tag{5}$$

Where, M_v and M_B represent the masses of the vehicle and the mobile progressive deformable barrier respectively, v_0 represents the initial velocity of the vehicle and the barrier, and v_1 and v_2 represent the velocities of the vehicle and the barrier at the end of the impact.

2.2 Momentum conservation during the MPDB test

In the MPDB test, the vehicle and the mobile progressive deformable barrier impact head-on with the same initial velocity v_0. After the impact, the speeds of the vehicle and the barrier are v_1 and v_2 at the moment of separation respectively. Assuming that the direction to which the vehicle moves with initial velocity v0 is positive, the momentum conservation during the MPDB test process is:

$$\left(M_v - M_B\right) \times v_0 = M_B \times v_2 - M_v \times v_1 \tag{6}$$

2.3 A Simple introduction to the energy transformation in side-impact test

In terms of vehicle side impact, the struck vehicle remains stationary, and the impacting vehicle strikes it with a certain initial velocity. As the impacting vehicle is fixed yet deformable, the initial energy of the side-impact test is transformed into the deformation energy, the rotational energy during the collision process, the residual energy after the collision of the impacting vehicle, and the deformation energy of the struck vehicle.

In side impact tests, the main factors influencing the distribution of impact energy and vehicle compatibility are the masses of the two vehicles, the stiffness characteristics and geometric features of the front end of the impacting vehicle and the side of the struck vehicle[15].

3 Simplified theoretical model and the calculation method

3.1 Spring model of vehicle impact

3.1.1 Introduction for the theoretical model

This paper adopts the simplified model for vehicle frontal impact proposed by BERNARD B. MUNYAZIKWIYE [16], which views the vehicle as a simplified spring model with stiffness K and mass M_v. For the MPDB test, the simplified model is shown in Figure 2, where a spring with stiffness K and mass M_v (representing the vehicle) and a spring with stiffness K_{MPDB} and mass M_B (representing the mobile progressive deformable barrier) impact against each other at the same initial velocity v_0.

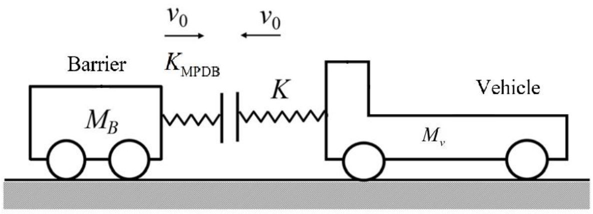

Figure 2. Simplified model for MPDB test

3.1.2 Dynamic response for the simplified spring model

In the simplified vehicle impact model, the vehicle and barrier can be considered as a two-stage vibration model. For the FWRB test, there is only one spring, while for the ODB test and the MPDB test, there are two springs. According to the principle of spring vibration, the vibration model can be simplified to the spring model shown in Figure 3.

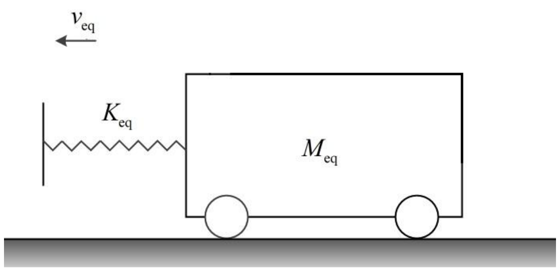

Figure 3. Simplified spring model for vehicle impact

The vibration response can be expressed as follows:

$$M_{eq}\ddot{f}(t) + K_{eq}f(t) = 0 \tag{7}$$

Herein, v_{eq} represents the equivalent initial velocity, while M_{eq} represents the equivalent mass, K_{eq} represents the equivalent stiffness, and f(t) represents the dynamic response of the vibration model.

For ODB test, v_{eq}, M_{eq}, and K_{eq} are respectively expressed as:

$$\begin{aligned} v_{eq} &= v_0 \\ M_{eq} &= M_v \\ K_{eq} &= \frac{K_{ODB} \cdot K}{K_{ODB} + K} \end{aligned} \tag{8}$$

For MPDB test, v_{eq}, M_{eq}, and K_{eq} are respectively expressed as:

$$\begin{aligned} v_{eq} &= 2v_0 \\ M_{eq} &= \frac{M_v \cdot M_B}{M_v + M_B} \\ K_{eq} &= \frac{K_{MPDB} \cdot K}{K_{MPDB} + K} \end{aligned} \tag{9}$$

Based on the vibration principle, the natural frequency of the spring model ω_{eq} is:

$$\omega_{eq} = \sqrt{\frac{K_{eq}}{M_{eq}}} \tag{10}$$

Then Equation (7) can be re-expressed as:

$$\ddot{f}(t) + \omega_{eq}^2 f(t) = 0 \tag{11}$$

By integrating theoretical equations of the spring vibration model and the practical physical significance of vehicle impacts, the dynamic response formula can be expressed as follows:

$$\begin{cases} d(t) = f(t) = C\cos\left(w_{\text{eq}}t - \varphi\right) \\ v(t) = \dot{f}(t) = -Cw_{\text{eq}}\sin\left(w_{\text{eq}}t - \varphi\right) \\ a(t) = \ddot{f}(t) = -Cw_{\text{eq}}^2\cos\left(w_{\text{eq}}t - \varphi\right) \end{cases} \tag{12}$$

Where, C represents the amplitude, φ represents the initial phase, $d(t)$ represents the time-displacement curve, $v(t)$ represents the time-velocity curve, and $a(t)$ represents the time-acceleration curve.

In the MPDB test, the initial conditions of the simplified spring model are as follows:

$$\begin{cases} d(0) = f(0) = 0 \\ v(0) = \dot{f}(0) = v_{\text{eq}} = 2v_0 \end{cases} \tag{13}$$

By substituting Equation (13) into Equation (12), the dynamic response of the MPDB spring system is obtained:

$$\begin{cases} d(t) = f(t) = \dfrac{2v_0}{w_{\text{eq}}}\sin\left(w_{\text{eq}}t\right) \\ v(t) = \dot{f}(t) = 2v_0\cos\left(w_{\text{eq}}t\right) \\ a(t) = \ddot{f}(t) = -2v_0 w_{\text{eq}}\sin\left(w_{\text{eq}}t\right) \end{cases} \tag{14}$$

Which FWRB test and ODB test are similar to. According to the simplified spring model, γ_1 and γ_2 represent the mass reduction factors of the vehicle and the mobile progressive deformable barrier, respectively:

$$\begin{cases} \gamma_1 = \dfrac{M_{\text{B}}}{M_{\text{v}} + M_{\text{B}}} \\ \gamma_2 = \dfrac{M_{\text{v}}}{M_{\text{v}} + M_{\text{B}}} \end{cases} \tag{15}$$

Then the dynamic response for the test vehicle can be expressed as:

$$\begin{cases} d_{\text{v}}(t) = \gamma_1 f(t) = \dfrac{M_{\text{B}}}{M_{\text{v}} + M_{\text{B}}}\cdot\dfrac{2v_0}{w_{\text{eq}}}\sin\left(w_{\text{eq}}t\right) \\ v_{\text{v}}(t) = \gamma_1 \dot{f}(t) = \dfrac{M_{\text{B}}}{M_{\text{v}} + M_{\text{B}}}\cdot 2v_0\cos\left(w_{\text{eq}}t\right) \\ a_{\text{v}}(t) = \gamma_1 \ddot{f}(t) = \dfrac{M_{\text{B}}}{M_{\text{v}} + M_{\text{B}}}\cdot -2v_0 w_{\text{eq}}\sin\left(w_{\text{eq}}t\right) \end{cases} \tag{16}$$

And the dynamic response for the mobile progressive deformable barrier is:

$$\begin{cases} d_{\text{B}}(t) = \gamma_2 f(t) = \dfrac{M_{\text{v}}}{M_{\text{v}} + M_{\text{B}}}\cdot\dfrac{2v_0}{w_{\text{eq}}}\sin\left(w_{\text{eq}}t\right) \\ v_{\text{B}}(t) = \gamma_2 \dot{f}(t) = \dfrac{M_{\text{v}}}{M_{\text{v}} + M_{\text{B}}}\cdot 2v_0\cos\left(w_{\text{eq}}t\right) \\ a_{\text{B}}(t) = \gamma_2 \ddot{f}(t) = \dfrac{M_{\text{v}}}{M_{\text{v}} + M_{\text{B}}}\cdot -2v_0 w_{\text{eq}}\sin\left(w_{\text{eq}}t\right) \end{cases} \tag{17}$$

Herein, $d_{\text{v}}(t)$, $v_{\text{v}}(t)$, and $a_{\text{v}}(t)$ respectively denote the displacement, velocity, and acceleration of the test vehicle; $d_{\text{B}}(t)$, $v_{\text{B}}(t)$, and $a_{\text{B}}(t)$ respectively denote the displacement, velocity, and acceleration of the barrier.

3.2 Stiffness calculation

In the simplified spring model dynamic response calculation, the front-end structure stiffness K, ODB honeycomb aluminum stiffness K_{ODB}, and MPDB honeycomb aluminum stiffness K_{MPDB} are used for the calculation.

3.2.1 Honeycomb aluminum stiffness calculation for ODB and MPDB test

For the stiffness calculation of ODB barrier, Yuanjie Liu et al. [17] developed a finite element model to study the deformation patterns and load responses of ODB honeycomb aluminum, and the crush force-displacement curve of ODB honeycomb aluminum was obtained, where the stiffness of ODB honeycomb aluminum can be determined as follows:

$$K_{\mathrm{ODB}} = 740\mathrm{kN/m} \tag{18}$$

For the stiffness calculation of the MPDB honeycomb aluminum, in terms of B.15 in the Appendix B of the C-NCAP management regulation (2024 edition), the stiffness of the MPDB honeycomb aluminum can be determined as:

$$K_{\mathrm{MPDB}} = 800\mathrm{kN/m} \tag{19}$$

3.2.2 Stiffness calculation for the test vehicle

In the FWRB test at the front-end structure of the vehicle, K is obtained by integrating the x-direction time-acceleration curve at the lower part of the left B-pillar to obtain the displacement-impact force curve. Thus, the stiffness of the test vehicle is a value that varies with the displacement, as shown in Figure 4, and the calculation formula is:

$$K(i) = \frac{F(i)}{d(i)} = \frac{M_{\mathrm{v}} \cdot a(i)}{d(i)} \tag{20}$$

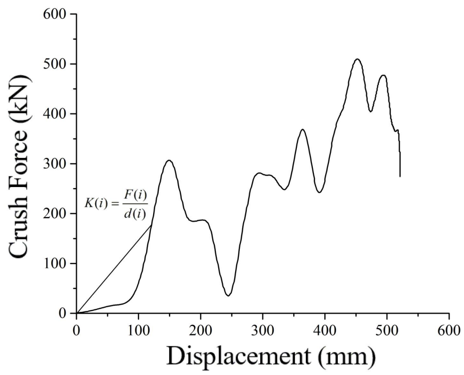

Figure 4. Stiffness calculation of the test vehicle

Thereby, the displacement-stiffness curve of the vehicle is acquired.

4 Validation of the simplified model

4.1 Calculation of FWRB test

In this subsection, by integrating the energy and momentum conservation presented in Section 2 and the stiffness calculation approach of the simplified spring model detailed in Section 3, the MATLAB software is employed, where the displacement-stiffness curve of the vehicle front-end structure derived from the FWRB test is inputted, and the maximum acceleration $a_{1\mathrm{max}}$ and the maximum displacement $d_{1\mathrm{max}}$ of the vehicle during the FWRB test are calculated eventually, which are compared with the maximum acceleration $a_1'_{\mathrm{max}}$ and the maximum displacement $d_1'_{\mathrm{max}}$ obtained through the integration of the x-direction time-acceleration curve beneath the left B-pillar of the vehicle in the impact test.

To verify the calculation method comprehensively, for the FWRB test, 10 types of vehicles with masses ranging from 1,100 kg to 3,000 kg are selected in this subsection, covering sedans, SUVs and MPVs, as shown in Table 1.

Firstly, the time-acceleration curves obtained from the x-direction acceleration sensor beneath the left B-pillar during the FWRB tests for these 10 groups of vehicles are integrated to calculate the displacement-acceleration curves of the vehicles during the impact process, thereby obtaining the displacement-stiffness curves of the front-end structures of these 10 groups of vehicles. Secondly, in combination with the principles of impact energy and momentum conservation and the simplified spring model, the maximum acceleration a_{1max} and the maximum displacement d_{1max} of the FWRB test are calculated using the MATLAB software, compared with the maximum values of the test acceleration $a_1'_{max}$ and the test displacement $d_1'_{max}$ obtained from the acceleration sensor during the test, and the deviation is calculated, as shown in Table 2.

Table 1. The vehicle circumstances utilized for calculating the FWRB test

No.	Vehicle type	Test mass/kg	Impact velocity/km/h
1	Sedan	1188	50.76
2	Sedan	1618	50.07
3	SUV	1956	49.86
4	SUV	2087	49.61
5	SUV	2101	49.57
6	SUV	2169	49.82
7	Sedan	2175	49.90
8	SUV	2594	50.80
9	MPV	2820	56.63
10	MPV	2917	56.30

Table 2. Comparison of FWRB test calculation results with test values

No.	$a_1'_{max}$/g	a_{1max}/g	E_{a1}/%	$d_1'_{max}$/mm	d_{1max}/mm	E_{d1}/%
1	43.793	43.750	-0.10	521.191	516.570	-0.89
2	45.244	47.838	5.73	549.078	541.859	-1.31
3	27.357	27.33	-0.10	655.78	656.729	0.14
4	40.262	40.222	-0.10	566.151	565.943	-0.04
5	27.578	26.352	-4.45	667.866	665.695	-0.33
6	39.717	39.676	-0.10	647.544	643.311	-0.65
7	39.066	39.025	-0.10	627.671	627.492	-0.03
8	34.091	34.056	-0.10	648.667	647.75	-0.14
9	31.338	32.189	2.72	770.324	767.994	-0.30
10	49.346	49.292	-0.11	740.195	740.004	-0.03

Where, Ea_1 and Ed_1 respectively represent the deviations of the maximum acceleration and the maximum displacement values between the calculation and the experiment in FWRB tests. The calculation formulas are as follows:

$$\begin{cases} E_{an} = \dfrac{a_{\mathrm{n\,max}} - a'_{\mathrm{n\,max}}}{a'_{\mathrm{n\,max}}} \times 100\% \\ E_{dn} = \dfrac{d_{\mathrm{n\,max}} - d'_{\mathrm{n\,max}}}{d'_{\mathrm{n\,max}}} \times 100\% \end{cases} \tag{21}$$

Herein, n represents the Arabic numerals 1, 2, 3, ... It can be observed from the calculation results that whether E_{a1} or E_{d1}, the values do not exceed 10%. Particularly, the deviation of the maximum displacement is all within 1%.

4.2 Calculation of ODB test

The calculation approach in this subsection is analogous to that in Subsection 4.1. However, as the barrier in the ODB test is a deformable one, the calculation of the ODB test employs the calculation method of equivalent stiffness Keq (Equation (8)).

In this subsection, 5 vehicles with different test masses are selected for calculation, as presented in Table 3.

Table 3. The vehicle circumstances utilized for calculating the ODB test

No.	Vehicle type	Test mass/kg	Impact Velocity/km/h
1	Sedan	1188	40.00
2	Sedan	1268	65.09
3	Sedan	1599	64.55
4	SUV	2166	56.41
5	MPV	2820	64.15

Firstly, based on the displacement-stiffness curves of the vehicle front-end structure calculated from FWRB tests, the displacement-stiffness curves corresponding to the simplified spring model are derived. Secondly, in combination with the principles of impact energy and momentum conservation and the simplified spring model, the maximum acceleration $a_{2\text{max}}$ and maximum displacement $d_{2\text{max}}$ of the ODB test are calculated using MATLAB software, and are compared with the maximum values of the test acceleration $a_2'_{\text{max}}$ and test displacement $d_2'_{\text{max}}$ obtained by integrating the x-direction acceleration sensor beneath the left B-pillar of the vehicle in ODB tests. The deviation calculation is then carried out, and the calculation results are presented in Table 4.

Table 4. Comparison of ODB test calculation results with test values

No.	$a_2'_{\text{max}}$/g	$a_{2\text{max}}$/g	E_{a2}/%	$d_2'_{\text{max}}$/mm	$d_{2\text{max}}$/mm	E_{d2}/%
1	21.298	21.862	2.65	630.477	607.553	-3.64
2	34.377	33.845	-1.55	998.475	1003.913	0.54
3	34.984	32.385	-7.38	1158.056	1049.545	-9.37
4	25.431	23.033	-9.43	1179.968	1118.404	-5.22
5	25.381	23.023	-9.27	1480.596	1410.278	-4.75

Among them, E_{a2} and E_{d2} respectively represent the deviations of the maximum acceleration and the maximum displacement between the calculation and the test results in ODB tests, whose calculation formula is Equation (21). It can be observed from Table 4 that for both E_{a2} and E_{d2}, the results do not exceed 10%. However, the calculation deviations for vehicles of No. 3 to 5 are slightly larger, all exceeding 5%. For a more intuitive comparison, the states of the honeycomb aluminum of all 5 tests after the impact are observed, as shown in Figures 5. to 9.

Figure 5. The state of the honeycomb aluminum after the ODB test (No. 1)

Figure 6. The state of the honeycomb aluminum after the ODB test (No. 2)

Figure 7. The state of the honeycomb aluminum after the ODB test (No. 3)

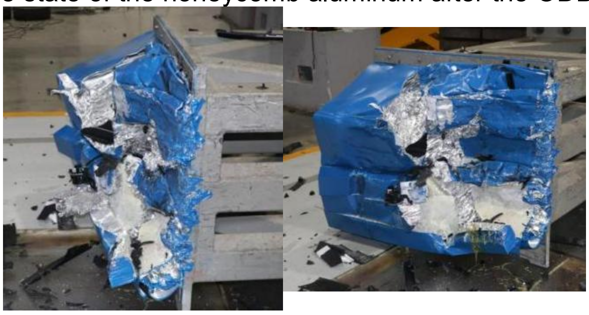

Figure 8. The state of the honeycomb aluminum after the ODB test (No. 4)

Figure 9. The state of the honeycomb aluminum after the ODB test (No. 5)

It can be observed that the crushing state of the honeycomb aluminum after the impact of No. 3 to 5 is more severe than that of No. 1 to 2, where the "bottoming out" phenomenon of the ODB honeycomb aluminum may have occurred in the tests of No. 3 to 5, which explains the slightly larger calculation deviations.

Meanwhile, through observing the high-speed cameras of the impact tests, it can be analyzed and concluded that the main vehicle components involved in deformation and energy absorption during the impact process are mainly the transverse anti-collision beam, the energy absorption box, the front longitudinal beam, the subframe, etc. Generally speaking, the energy absorption at the front end of the vehicle is mainly the extrusion of the anti-collision beam and the energy absorption box, and the extrusion and bending of the front longitudinal beam, which play a significant role in force transmission and energy absorption in frontal impacts, accounting for approximately 80% of the total collision energy[4].

4.3 Summary of the validation of the calculation method

In Subsections 4.1 and 4.2, the maximum acceleration and displacement of the FWRB test and the ODB test are calculated using the calculation method proposed in this paper, and their deviations from the maximum acceleration and displacement values obtained by the tests are all within 10%, validating the applicability of the calculation method presented in this paper.

5 Calculation of the dynamic response for MPDB test

In this section, the validated calculation methods in Section 4 will be initially employed to compute the maximum acceleration and displacement of the vehicle and barrier in the MPDB tests of 2 vehicle groups, compared with the test outcomes. Subsequently, based on the calculated maximum acceleration and displacement of the mobile progressive deformable barrier, the dynamic response equation of the simplified spring model (Equation (17)) will be utilized to obtain the $v_B(t)$ curve of the barrier, and ultimately the compatibility index *OLC* will be calculated.

5.1 Maximum acceleration and displacement calculation of MPDB tests

2 sets of vehicles are selected for calculation, which are presented in Table 5. The maximum acceleration and displacement of the vehicle and the barrier calculated by MATLAB, along with the deviations from the test results, are shown in Tables 6. to 7.

Table 5. The vehicle circumstances utilized for calculating the MPDB test

No.	Vehicle type	Test mass/kg	Impact velocity/km/h
1	Sedan	1251	50.40
2	Sedan	1267	50.58

Table 6. Comparison of MPDB test calculation results with test values (vehicle)

No.	$a_3'_{max}$/g	a_{3max}/g	E_{a3}/%	$d_3'_{max}$/mm	d_{3max}/mm	E_{d3}/%
1	47.689	45.212	-5.19	489.960	530.502	8.27
2	44.281	41.294	-6.75	494.769	530.311	7.18

Table 7. Comparison of MPDB test calculation results with test values (barrier)

No.	$a_4'_{max}$/g	a_{4max}/g	E_{a4}/%	$d_4'_{max}$/mm	d_{4max}/mm	E_{d4}/%
1	32.784	31.730	-3.21	598.493	622.544	4.02
2	30.128	31.880	5.82	683.035	625.494	-8.42

In Tables 6. to 7., $a_3'_{max}$ and a_{3max} denote the maximum acceleration values obtained from the impact test and the theoretical calculation of the vehicle, respectively, while $d_3'_{max}$ and d_{3max} represent the maximum displacement values obtained from the impact test and the theoretical calculation of the vehicle. E_{a3} and E_{d3} represent the deviations of the maximum acceleration and displacement calculated theoretically from the corresponding maximum values of the vehicle in the test. $a_4'_{max}$ and a_{4max} represent the maximum acceleration values obtained from the test and the calculated value of the barrier. $d_4'_{max}$ and d_{4max} represent the maximum displacement values obtained from the test and the calculated value of barrier. E_{a4} and E_{d4} represent the deviations of the maximum acceleration and displacement calculated for the barrier from the corresponding maximum values in the test. The calculation formulas for E_{a3} and E_{d3}, and E_{a4} and E_{d4} are as shown in Equation (21). It can be observed that the deviations are all within 10%.

5.2 Calculation of the compatibility index *OLC*

5.2.1 Compatibility index *OLC*

The compatibility index *OLC*, namely the occupant load criterion of the mobile progressive deformable barrier, pertains to the compatibility scoring content of the C-NCAP management regulation (2024 edition). *OLC* refers to the constant deceleration of the virtual dummy on the barrier when the relative displacement of the virtual dummy to the vehicle is 0.065m until the total relative displacement of the virtual dummy to the vehicle is 0.3m, whose calculation formula is presented as follows:

$$\begin{aligned} &\int_0^{t_1} v_{\mathrm{B}}(t)dt + 0.065 = v_0 \cdot t_1 \\ &\frac{(v_0 + v_{\mathrm{B}}(t_2) \cdot (t_2 - t_1)}{2} = \int_{t_1}^{t_2} v_{\mathrm{B}}(t)dt + 0.235 \\ &OLC = \frac{v_0 - v_{\mathrm{B}}(t_2)}{9.8 \times (t_2 - t_1)} \end{aligned} \tag{22}$$

Herein, t_1 corresponds to the instant when the virtual dummy freely moves forward by 0.065m, while t_2 corresponds to the instant when the virtual dummy starts to move forward under constraint by 0.235m. Within the period from t_1 to t_2, the deceleration of the virtual dummy under constraint is constant, namely *OLC*. A smaller *OLC* value indicates better vehicle compatibility.

5.2.2 Theoretical calculation of *OLC*

The maximum acceleration and displacement values of the mobile progressive deformable barrier calculated by the dynamic response equation of the simplified spring model (Equation (17)), the $v_{\mathrm{B}}(t)$ curve of the barrier are computed using MATLAB software. According to Equation (22), the final calculated *OLC* value is obtained. The calculation process is shown in Figure 10. and the calculation results are presented in Table 8.

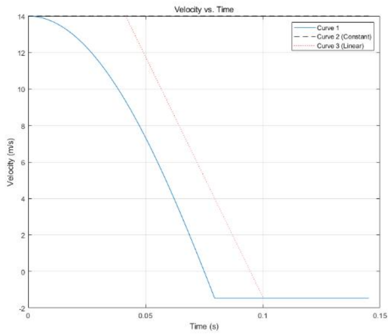

Figure 10. Calculation of *OLC* by MATLAB

Table 8. The comparison between the calculated results of OLC and the test values

No.	OLC/g （Calculation）	OLC/g （Test）	Deviations/%
1	26.747	24.47	9.31
2	26.903	25.16	6.93

It can be observed that the deviations between the calculated and test values of *OLC* for the 2 groups of vehicles are all within 10%.

5 Conclusions

In this paper, by applying the principles of energy conservation and momentum conservation in the vehicle impact process, in combination with the simplified spring model of vehicle impact and the actual impact tests (including FWRB test, ODB test, and MPDB test), a method for estimating the compatibility index *OLC* of the MPDB test in C-NCAP management regulation (2024 edition) is proposed, using the displacement-stiffness curve of the vehicle front-end structure obtained from the FWRB test.

Firstly, this paper explains the principles of energy conservation and momentum conservation in the vehicle impact process, and employs the stiffness calculation and dynamic response calculation of the simplified spring model for vehicle frontal impact.

Secondly, the acceleration-time curves collected by the *x*-direction acceleration sensor at the lower part of the vehicle's left B-pillar in FWRB tests of 10 vehicles are utilized, where the integrations is conducted to obtain the displacement-stiffness curves of the vehicle's front-end structure. Moreover, the conservation of energy and momentum in the impact is combined with the stiffness principle of the simplified spring model to calculate the maximum accelerations and displacements of the FWRB test, the ODB test, and the MPDB test. The results are compared with the test findings to validate the applicability of this calculation method, which uses the displacement-stiffness curves of the vehicle's front-end structure obtained from the FWRB test to estimate the maximum accelerations and displacements of the ODB test and the MPDB test.

Finally, based on the maximum acceleration and displacement values of the mobile progressive deformable barrier calculated in MPDB tests, in combination with the dynamic response formula of the simplified spring model, the value of the compatibility index *OLC* is computed and compared with the experimental results of the MPDB test. The deviations are all within 10%.

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