AN INVESTIGATION OF COMPATIBILITY FOR THE PASSENGER CAR FLEET IN HEAD-ON FRONTAL COLLISIONS

ÖNDEN KAFA KAFAYA ÇARPIŞMALARDA BİNEK ARAÇ FİLOSUNUN UYUMLULUĞUNUN ARAŞTIRILMASI

GÜNCE ŞAHİN

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Submitted to
Graduate School of Science and Engineering of Hacettepe University
as a Partial Fulfillment to the Requirements
for the Award of the Degree of Master of Sciences
in Mechanical Engineering.

2022

ABSTRACT

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September 2022, 60 pages

Vehicle crash safety is an important field in vehicle design. There are customer-oriented or regulatory vehicle crash tests made to measure the crash safety of vehicles. In the frontal crash tests conducted by the US National Highway Traffic Safety Administration (NHTSA), vehicles hit the full-width rigid barrier (FWRB) at constant speed (56 km/h) and the safety levels of the vehicles are measured with the data obtained with the help of sensors. Although these tests give an idea about vehicle safety, they cannot fully test real-world collisions due to the problem called incompatibility. For this reason, in this thesis, the incompatibility problem is investigated by modeling head-on frontal collisions. For this purpose, 52 vehicles with different characteristics produced between 2011 and 2018 are selected among the vehicle crash test data available on NHTSA's website. The loading and unloading stiffnesses of the front structural elements of these vehicles are estimated with a linear approximation, then a lumped-mass model is constructed for frontal head-on collisions and all possible collisions of the selected vehicles are simulated with the help of a computer software. By comparing these data with the full-width rigid barrier (FWRB) frontal impact tests, it is aimed to have an idea about the level of the incompatibility problem between vehicles. Thanks to the model used in this study, the necessary data for the initial design of vehicle safety systems can be easily obtained with a cheaper solution than real crash tests, and different test conditions can be easily tested in the computer environment.

Keywords: full-width rigid barrier test, head-on frontal collisions, lumped-mass vehicle model, vehicle incompatibility, crash safety

ÖZET

ÖNDEN KAFA KAFAYA ÇARPIŞMALARDA BİNEK ARAÇ FİLOSUNUN UYUMLULUĞUNUN ARAŞTIRILMASI

Günce ŞAHİN

Yüksek Lisans, Makine Mühendisliği Bölümü

Tez Danışmanı: Dr. Öğr. Üyesi Selçuk HİMMETOĞLU

Eylül 2022, 60 sayfa

Araç çarpışma güvenliği araç tasarımında önemli bir alandır. Araçların çarpışma güvenliğini ölçmek için müşteri odaklı ya da yasal zorunluluklar nedeniyle yapılan araç çarpışma testleri vardır. ABD Ulusal Otoyol Trafik Güvenliği Dairesi (NHTSA) tarafından yapılan önden çarpışma testlerinde araçlar sabit hızla tam genişlikte sert bariyere çarpmakta ve sensörler yardımıyla elde edilen verilerle araçların güvenlik seviyeleri ölçülmektedir. Bu testler araç güvenliği hakkında bir fikir verse de gerçek dünyada yapılan kazaları uyumsuzluk sorunu olarak adlandırılan sorun nedeniyle tam olarak test edememektedir. Bu nedenle bu tezde kafa kafaya önden çarpmaların modellenerek uyumsuzluk sorunu incelenmiştir. Bunun için NHTSA'nın internet sitesi üzerinden erişme açık olan araç çarpışma verileri arasından 2011-2018 yılları arasında üretilmiş farklı özelliklere sahip 52 araç seçilmiştir. Bu araçların ön yapısal elemanlarının yükleme ve boşalma sertlikleri doğrusal yaklaşımla tahmin edilmiş, daha sonra ise önden kafa kafaya çarpma için toplu-kütle modeli oluşturulup seçilen araçların olası tüm çarpışmaları bilgisayar programı yardımıyla simüle edilmiştir. Bu veriler FWRB testleriyle karşılaştırılarak araçların uyumsuzluk sorununun seviyesi hakkında fikir sahibi olmak amaçlanmıştır. Bu çalışmada kullanılan model sayesinde, gerçek çarpışma testlerinden daha ucuz bir çözümle araç güvenlik sistemlerinin başlangıç tasarımı için gerekli veriler kolayca elde edilebilecek ve farklı test koşulları bilgisayar ortamında kolayca test edilebilecektir.

Anahtar Kelimeler: tam genişlikte sert bariyer testi, kafa-kafaya önden çarpışmalar, toplu kütleli araç modeli, araç uyumsuzluğu, çarpışma güvenliği

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere thanks to my supervisor Dr. Selçuk Himmetoğlu for his continuous support and guidance during my graduate education.

I would also like to thank my dear friend Umay Sara Gürsoy, who always motivates me and is always there for me with her moral support.

Finally, I thank my mother Rahile Şahin and my father Ülkü Şahin for the never-ending support they have given to me.

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Abbreviations

NHTSA	The National Highway Traffic Safety Administration
NCAP	New Car Assessment Program
FMVSS	Federal Motor Vehicle Safety Standards
FWRB	Full-width rigid barrier

1. INTRODUCTION

Vehicle collisions have become quite common today. Vehicle manufacturers do a lot of development to improve vehicle crash safety. Studies on vehicle collision safety are carried out especially for ensuring passenger and pedestrian safety. To determine the crash safety of vehicles, some non-profit publicly funded independent organizations such as The European New Car Assessment Program (Euro NCAP) and some government agencies such as The National Highway Traffic Safety Administration (NHTSA) implement crash test programs (car safety performance assessment program) with different procedures. NHTSA, one of these organizations, has been evaluating the crash safety of vehicles with a program named United States New Car Assessment Program (US NCAP) since 1979 [1]. In the US NCAP there are three crash tests, frontal-impact crashes, side crashes and rollover crashes.

In the frontal-impact crash tests, vehicles impact a full-width fixed rigid barrier (FWRB), with a constant speed of 56 km/h with 100% overlap. Key parameters of vehicles such as acceleration and deformation are measured with the aid of the sensors. Load cells are attached to the rigid barrier to measure crush forces and moments, accelerometers are attached to the car to measure the deformation. In addition, through the sensors on the human models used in the driver and passenger seat, the damage suffered by the driver and passenger is calculated. With these data a star rating is evaluated with a system that calculates the vehicle crash safety over five stars. These ratings are published on the NHTSA website, along with a detailed test report with all the data [2].

Figure 1.1. Pre-Test Left View of Test Vehicle [3]

Figure 1.2. Post-Test Left Rear ¾ View [3]

Although the frontal crash tests in the US NCAP give an idea about the safety of the vehicles, they do not fully reflect the situations that can be encountered in the real world. Vehicles that get high scores from this program may not be as successful in real-world head-on collisions due to an issue named vehicle incompatibility. Differences in mass and stiffness of the colliding vehicles are defined as load incompatibility, and misalignment of the structural elements is defined as geometric incompatibility.

In the report published by NHTSA it is seen that 10.6% of fatal accidents in the US in 2019 are head-on collisions [4]. This type of collision is the second most fatal involving multiple vehicles. For this reason, head-on collisions should be considered in the crash safety design of vehicles. Although some head-on collision tests have been made, there is not enough data since very few vehicles have been tested. It will not be enough to carry out these tests with more vehicles [5]. To examine the incompatibility problem between vehicles, a vehicle needs to be crash tested with all other vehicles. Since the tests to be performed in this way will be extremely expensive, it is useful to create mathematical models to simulate head-on collision. It is also useful for easy prediction of the results of different test conditions, such as different speeds.

In this thesis, the compatibility of vehicles was investigated by modeling the head-on collision of vehicles. For this study, 52 vehicles with different specifications which were manufactured between 2011 and 2018 are selected from the US NCAP database.
Test data is used to derive the stiffness of the vehicles which is an important parameter to create a model since acceleration of the vehicle is directly related to the stiffness of the vehicle. FWRB frontal impact test data of selected vehicles which is available on NHTSA web site for researchers are used to obtain stiffness of vehicles. A lumped-mass model is constructed for head-on frontal collisions and all possible collisions of the selected vehicles are quickly simulated using computer software support. Also, due to incompatibility between the vehicles, the stiffnesses will not be the same as obtained from FWRB test data. For this reason, the simulations are repeated with different stiffnesses to estimate real-world response.

In the simulations, especially considering the mean acceleration and maximum deformation values, it was examined which vehicles are safer or less safe when it collides with other vehicles compared with US NCAP test data. In addition, the vehicles are grouped according to their segments which are widely used among the public and defined by the Commission of The European Communities [6]. Head-on collision performances are also examined based on vehicle segments and statistical data that evaluating segment-based performances are created. The "Overall Front Star Rating" values of the vehicles given in terms of driver and front passenger safety by the US NCAP are also shown to compare with simulated head-on collision test results.

The main objective of this study is to investigate how compatible passenger cars manufactured in the last years (2011-2018). Recent studies on fleet safety [7,8] do not include vehicles from the last decade. Thus, the level of compatibility of the current vehicle fleet for passengers was examined and some recommendation has been made to make improvements in vehicle designs.

The make and models of the vehicles are not shared in the thesis, the vehicles are defined by the numbers in Table 1.1 along with the segment, mass, and overall front star ratings of vehicles.

Table 1.1. Vehicle specifications

Vehicle Number	Mass (kg)	Segment	Overall Front Star Rating	Model Year
Car 1	2073.3	E	4	2011
Car 2	1996.4	E	4	2012
Car 3	1764.9	D	4	2012
Car 4	1599	C	4	2012
Car 5	1907	D	3	2012
Car 6	1876.6	E	3	2012
Car 7	1442.5	B	4	2012
Car 8	1624.3	C	4	2012
Car 9	2101.3	D	5	2012
Car 10	1488.9	B	5	2013
Car 11	1521.4	C	4	2013
Car 12	2006.4	D	5	2013
Car 13	1781.8	S	4	2013
Car 14	1487.4	C	4	2013
Car 15	1159.9	A	4	2013
Car 16	1536.9	C	4	2013
Car 17	2096.4	E	5	2014
Car 18	2154.7	D	5	2014
Car 19	1205.5	A	4	2014
Car 20	1737.9	D	4	2014
Car 21	1489.3	C	4	2014
Car 22	1889.7	D	4	2014
Car 23	1431.3	B	4	2014
Car 24	2279.8	S	5	2014
Car 25	1775.6	D	5	2015
Car 26	1771.8	S	5	2015
Car 27	1430.5	B	4	2015
Car 28	1960.3	D	4	2015
Car 29	1475.5	C	5	2015
Car 30	1120.6	B	4	2015
Car 31	1573.3	C	4	2015
Car 32	1642.3	C	4	2015
Car 33	1866.5	D	5	2016
Car 34	2101.5	E	4	2016
Car 35	1337.4	B	5	2016
Car 36	1423.5	C	4	2016
Car 37	1840.8	E	4	2016
Car 38	1652	D	5	2016
Car 39	1284.8	B	4	2016
Car 40	1432.5	S	4	2016
Car 41	1857.8	D	5	2016
Car 42	1607.9	C	4	2016
Car 43	1265.8	B	4	2016
Car 44	1563.6	C	4	2017
Car 45	1889.6	E	5	2017
Car 46	1925.6	E	5	2017
Car 47	1485.8	C	4	2017
Car 48	1681.3	D	5	2017
Car 49	1640.8	C	5	2017
Car 50	1670.5	D	4	2017
Car 51	1879.3	D	4	2017
Car 52	1543.8	C	5	2018

2. THEORY

2.1. Modelling of Full-Width Rigid Body (FWRB) Frontal Impact Tests

Stiffness is an important parameter in vehicle crash safety design as it is a value that directly affects mean acceleration. The mean acceleration of the passenger compartment, restraint system, impact pattern, and amount of passenger compartment intrusion determine the risk of injury for an occupant involved in a crash [9–12].

There are different methods to obtain stiffness of vehicles such as finite element methods (FEM) and lumped-mass model.

Finite element methods provide very detailed information, but it is complex and difficult to construct. Lumped-mass models do not provide detailed information as much as FEM does, but it is a simple and fast method.

Munyazikwiye et al. study [13] indicates, simple lumped-mass models cannot replace the complex finite element models, but it can be useful to speed-up. Determining the simulation parameters of FEM needs several iterations because of the complexity. Therefore, lumped-mass model is a reasonable choice for preliminary design of vehicle design.

2.1.1. Lumped-Mass Model

In legally required frontal crash tests (such as Federal Motor Vehicle Safety Standards, FMVSS) and customer-oriented frontal crash tests (such as EuroNCAP), vehicles impact to a full-width fixed rigid barrier (FWRB) with a constant impact velocity V_0 as shown in Figure 2.1.

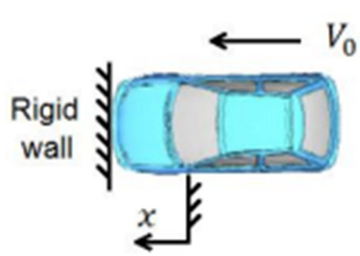

Figure 2.1. FWRB frontal impact test model [5,12]

Figure 2.2. Lumped-mass model of FWRB frontal test [5]

For example, in the FMVSS208 frontal crash test, vehicles impact the fixed rigid barrier at 56 km/h [1]. In these tests, the force on the wall is measured via load cells on the barrier and the amount of crushing of the vehicle is measured with accelerometers in the passenger compartment. With processing these data crushing force and deformation can be obtained.

If crushing force vs deformation plotted using obtained data from sensors. a behavior like the gray curve in Figure 2.2 is observed. The total force acting on the wall is F and displacement of the vehicle is specified as x. In this frontal impact test, the crushing of the vehicle is limited to the front of the vehicle therefore the passenger cabin is designed to maintain its pre-collision shape [2].

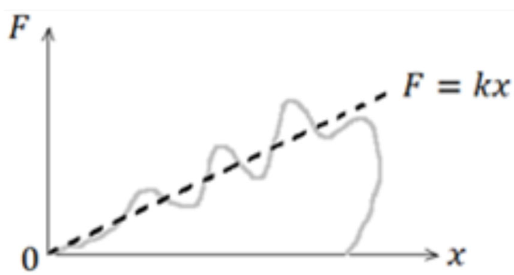

Figure 2.3. Crush force vs. deformation [5,14]

There are different studies for modelling FWRB frontal impact tests. In Pawlus's et al. study [15], it is stated that basic spring-mass model can give reliable results for loading phase while it suggests three different approaches for unloading phase:

- Elastic unloading: perfectly elastic, no energy losses ($k_L = k_U$)
- Plastic unloading: perfectly plastic, all energy absorbed, no rebound ($k_L = \infty$)
- Elasto-plastic unloading: rebound occurs with energy dissipation

The study shows that basic spring-mass model with elasto-plastic unloading gives reasonable results.

Also, in Himmetoglu's study [5] energy based linear modelling with unloading phase with rebound is proposed for FWRB impact test.

Figure 2.4 is an approximation of the vehicle behavior on Figure 2.3 using energy equations. The loading phase and unloading phase is modelled in Figure 2.4. During the loading phase, the structural elements of the vehicle are loaded and therefore the slope of the black line is defined as the loading stiffness.

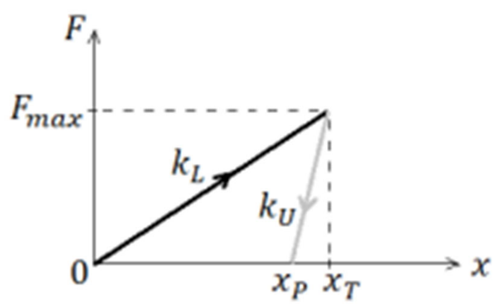

Figure 2.4. Crush force vs. deformation [5,14]

After the vehicle reaches the maximum deformation (x_T), the unloading phase is initiated as the structural elements tend to return to their original state until the forces on them are zero. When the car completely rebounds from the barrier the loading phase ends and the car reaches permanent deformation x_P. The unloading phase is modelled with the gray line and the slope of the line is defined as the unloading stiffness k_U. The energy absorbed by structural elements is equal to the area under the black line between $x = 0$ and $x = x_t$. Elastic energy returned by the structural elements can be calculated as area under the gray line between $x = x_p$ and $x = x_t$.

Maximum force can be represented with the equation below.

$$F_{max} = k_L x_T = k_U x_e \tag{1}$$

Where x_e is elastic rebound displacement ($x_T - x_P$).

Below equations can represent FWRB tests [5,11,14]:

$$k_L = (mV_0^2)/x_t^2 \tag{2}$$

$$W_T = mV_0^2/2 = k_L x_T^2/2 = F_{max} x_T^2/2 = F_{max}^2/2k_L \tag{3}$$

$$W_R = m(V'\,)^2/2 = (F_{max} x_e)/2 = (k_U x_e^2)/2 \tag{4}$$

$$e = (V_w' - V')/\,(V_0 - V_w) \tag{5}$$

$$W_R/W_T = (V'/V_0)^2 = (k_U x_e^2)/(k_L x_T^2) = e^2 \tag{6}$$

$$e^2 = k_L/k_U \tag{7}$$

$$e = \sqrt{x_e/x_T} \tag{8}$$

$m = Mass$

$F_{max} = \ Maximum\ force$

$x_P =$ Permanent deformation

$x_T =$ Maximum (total) deformation, dynamic crush

$x_e =$ Elastic rebound displacement

$k_L =$ Loading stiffness

$k_U =$ Unloading stiffness

$V_0 =$ Impact speed

$V' =$ Rebound velocity

$V_w =$ Velocity of the wall at the start of impact

$V_w' =$ Velocity of the wall at the end of impact

$e =$ Coefficient of restitution

$W_T =$ Total crush energy absorbed by the vehicle structure

$W_R =$ Elastic energy returned by the vehicle structure

Coefficient of restitution is around 0.12 for FWRB frontal impacts. It is 0 for perfect plastic impact ($k_U = \infty$) and 1 for perfect elastic impact ($k_U = k_L$) [14].

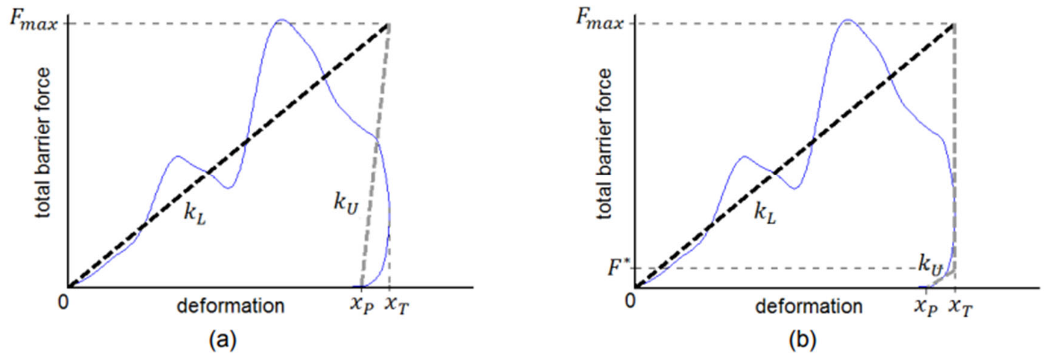

Figure 2.5. Modelling unloading phase [5]

2.3 Lumped-Mass Model of Head-On Frontal Collision Tests

Lumped-mass models can inexpensively provide key parameters needed for preliminary design of vehicle safety systems, accident reconstruction, and load compatibility analysis of vehicles [5,11,12,16].

In Himmetoglu’s study [5], a lumped-mass model is proposed for head-on frontal collision tests.

Linear approximation is used to models for both FWRB tests and head-on frontal collision tests with 100% overlap. Estimating a single stiffness is realistic for most of the cars for 56 km/h and below impact speed, as impact forces are less sensitive to the rate of deformation at this speed range, it is supported by the studies where deformation behaviors against crush force of different car compared [14,16–18].

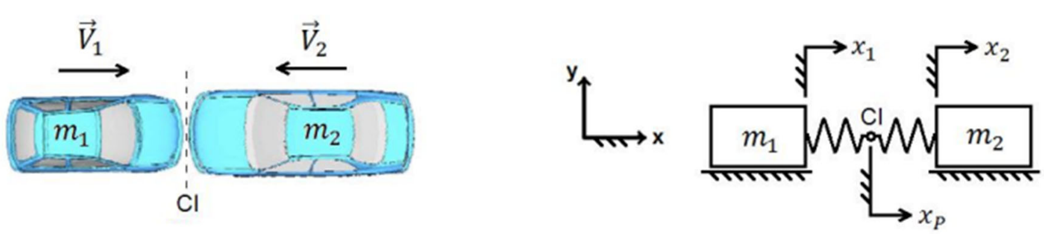

Figure 2.6. Lumped-mass model of head-on frontal collision [5]

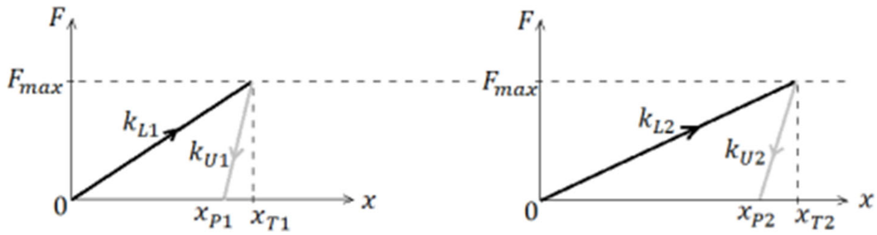

Figure 2.7. Crush-force vs deformation in head-on collision model [5]

It is modelled with the equations from Himmetoglu's study [5]:

$$\vec{F}_{s1} = k_{L1}(x_P - x_1)\,\vec{\imath}\ \ ,\ \ \vec{F}_{s2} = k_{L2}(x_2 - x_p)\,\vec{\imath}$$

Applying work-energy formula to the loading phase for each system, it is written as

$$\int \vec{F}_{s1}\,(dx_1)\vec{\imath} = \int k_{L1}(x_P - x_1)dx_1 = m_1V_c^2 - m_1V_1^2/2$$

$$\int \vec{F}_{s2}\,(dx_2)\vec{\imath} = \int k_{L2}(x_2 - x_P)dx_2 = m_2V_c^2 - m_2V_2^2/2$$

$$s_1 = x_p - x_1$$

$$s_2 = x_2 - x_P$$

$$ds_1 = dx_P - dx_1$$

$$ds_2 = dx_2 - dx_P$$

$$-\int k_{l1}s_1ds_1 - \int k_{l2}s_2ds_2 = (m_1 + m_2\,)V_c^2/2 - (m_1V_1^2/2 + m_2\,V_2^2)/2$$

At the start of the impact, there $x_1 = x_2 = x_P = s_1 = s_2 = 0$. At the end of the loading phase, there $s_1 = -x_{T1}$ and $s_2 = -x_{T2}$.

$$-\int_0^{-x_{T1}} k_{l1}s_1ds_1 - \int_0^{-X_{T2}} k_{L2}s_2ds_2 = (m_1 + m_2)V_c^2/2 = (m_1V_1^2/2\ + m_2V_2^2/2\,)$$

$$m_1V_1^2/2\ + m_2V_2^2/2 = (m_1 + m_2)V_c^2/2 + k_{L1}x_{T1}^2/2 + k_{l2}x_{T2}^2/2$$

$$F_{max} = k_{L1}x_{T1} = k_{L2}x_{T2}$$

$$W_T = k_{L1}x_{T1}^2/2 + k_{L2}x_{T2}^2/2 = F_{max}x_{T1}/2 + F_{max}x_{T2}/2$$

$$W_{T1} = F_{max}x_{T1}/2$$

$W_{T2} = F_{max}x_{T2}/2$

$m_1V_1 + m_2V_2 = (m_1 + m_2)V_c$

With a similar work-energy analysis, returned crush energy in the unloading phase, W_R can be shown with these equations:

$W_R = k_{U1}\left(x_{T1} - x_{p1}\right)^2/2 + k_{U2}\left(x_{T2} - x_{p2}\right)^2/2$

$W_R = m_1(V_1')^2/2 + m_2(V_2')^2/2 - (m_1 + m_2)V_c^2/2$

$e = (V_2' - V_1')/(V_1 - V_2)$

$\vec{V}_1 = V_1\vec{\imath}$, $\vec{V}_2 = V_2\vec{\imath}$: Velocities of vehicles 1 and 2, at the start of the impact

$\vec{V}_1' = V_1'\vec{\imath}$, $\vec{V}_2' = V_2'\vec{\imath}$: Velocities of vehicles 1 and 2, at the end of the impact

$\vec{V}_c = V_c\vec{\imath}$: Common velocity of vehicles at the end of the loading phase

$\vec{V}_P = V_P\vec{\imath}$: Velocity of the pin at the start of impact

x_P, x_1, x_2 : Displacements of the pin, vehicles 1 and2

m_p, m_1, m_2 : Masses of the pin, vehicles 1 and 2

k_{L1}, k_{L2} : Loading stiffnesses of vehicles 1 and 2

k_{U1}, k_{U2} : Unloading stiffnesses of vehicles 1 and 2

x_{T1}, x_{T2} : Maximum deformations of vehicles 1 and 2

x_{P1}, x_{P2} : Permanent deformations of vehicles 1 and 2

$\vec{F}_{s1}, \vec{F}_{s2}$: Total forces on vehicles 1 and 2

F_{max} : Magnitude of the crush force acting on both vehicles at maximum deformation

In the Himmetoglu's study [16], the model in Figure 2.6 is validated by comparing actual crash test results.

	m [kg]	V [kph]	V_c [kph]	t_{zv} [ms]	a_m [g]	x_T [m]	x_P [m]	ΔV [kph]	e
Car1: Model	2004.4	101.2	55.71	81.14	-15.88	0.659	0.429	-53.22	0.170
Car1: Actual	2004.4	101.2	54.79	81.10	-16.20	0.676	0.430	-53.59	0.126
Car2: Model	1636.8	0	55.71	81.14	19.44	0.793	0.519	65.17	0.170
Car2: Actual	1636.8	0	54.79	81.10	19.13	0.804	0.511	60.35	0.126

Figure 2.8. Lumped-mass model vs actual results – head-on collision test [16]

This model is also validated using finite element methods (FEM) in Himmetoglu et al. [19] study.

2.3. Vehicle Incompatibility

Incompatibility is defined as "energy mismanagement during a crash that produces an uneven distribution of injury risk across the 2 vehicles involved" in the Monfort et al. study [20].

Incompatibility types are defined as [21]

- Mass incompatibility
- Stiffness incompatibility
- Geometric incompatibility

Mass incompatibility is a disadvantage of smaller vehicles because conservation of momentum leads to a higher velocity change in smaller cars. In the Joksch et al. study [22] it is estimated that when a vehicle collides with a car twice its own mass, the smaller one has ten times more fatality risk than the heavier vehicle.

Although frontal stiffness of vehicles is mostly mass dependent [23], the same stiffness may not be seen in vehicles with the same mass as shown in Figure 2.7 [21].

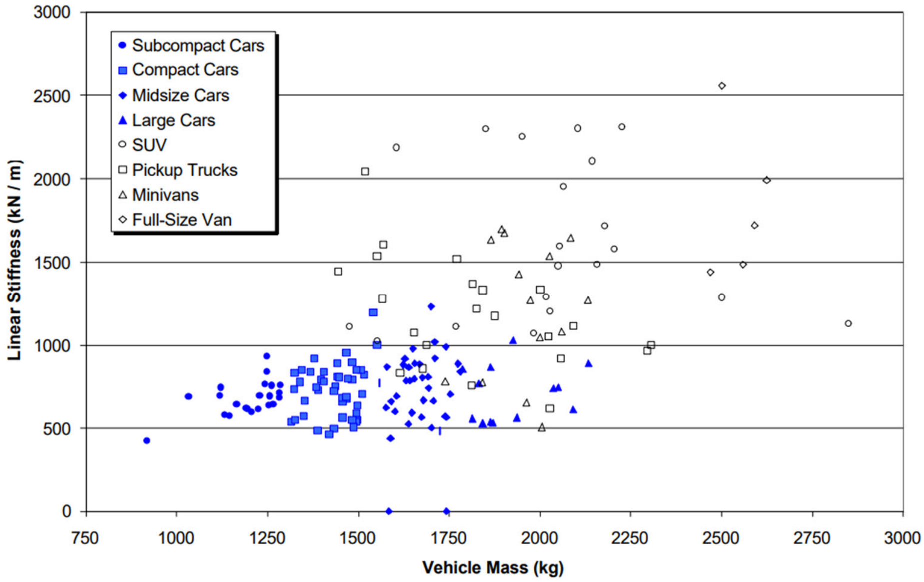

Figure 2.9. Vehicle mass vs. linear stiffness [21]

In a frontal collision between two vehicles has stiffness incompatibility with the same mass, most of the collision energy will be absorbed by the less stiff vehicle, resulting in greater deformation of the less stiff vehicle.

It is more difficult to measure geometric incompatibilities between vehicles than mass and stiffness incompatibilities. Geometric incompatibility between vehicles due to the misalignment of energy-absorbing system [18]. Geometric incompatibility is sometimes defined as, but not limited to; one vehicle applies force at a height above the other vehicle's structures designed to withstand force [24]. Override/underride crashes, oblique impacts, side impacts and offset crashes are also typical examples of incompatibility [5,18].

As a result of the misalignment of the structural elements, energy absorbing structures do not absorb energy as desired therefore the loading and unloading stiffnesses of the vehicles are lower than the FWRB crash tests. In Himmetoglu’s study [16] it is seen that the loading and unloading stiffnesses are 0.71/0.37 times lower than the FWRB frontal crash test.

2.4. Closing Speed

Closing speed is the relative speed between crashing vehicles. It is used to express the total energy of the collision. Calculated as $V_1 - V_2$.

V_1, V_2 : Velocities of the vehicles 1 and 2

The amount of energy a vehicle absorbs in a head-on collision can be different than the amount it absorbs in the FWRB frontal crash test due to stiffness and mass incompatibility of the vehicles. For example if $k_{L1}m_1 > k_{L2}m_2$ then $EEBS_2 > EEBS_1$ Therefore, $EEBS_2$ can be at most the barrier impact speed which is $V_B = 56$ km/h. Hence $EEBS_2 = V_B$ at the limit so that the crush energies absorbed by each car in head-on collision do not exceed the crush energy in the FWRB test [14].

$$W_{T2} = (1/2)m_2V_B^2 \quad , \quad W_{T1}/W_{T2} = k_{L1}/k_{L1} \quad , \quad W_T = W_{T1} + W_{T2}$$

$$W_T = \left(\frac{1}{2}\right) m_2 V_B^2 \left(\frac{k_{L1} + k_{L2}}{k_{L1}}\right) = \left(\frac{1}{2}\right) \frac{m_1 m_2}{m_1 + m_2} V_{CL}^2$$

$$V_{CL}^2 = V_B^2 \left(1 + \frac{k_{L2}}{k_{L1}}\right)\left(1 + \frac{m_2}{m_1}\right)$$

$EEBS$: Closing speed

V_{CL} : Closing speed

W_{T1}, W_{T2} : Total crush energy absorbed by vehicles 1 and 2

V_B : Barrier impact speed

m_1, m_2 : Mass of vehicles 1 and 2

k_{L1}, k_{L2} : Stiffnes of vehicles 1 and 2

In head-on collisions, in order for the absorbed energy by each car not to exceed the crush energy in the FWRB test, the closing speed V_{CL} must satisfy the formula:

$$V_{CL} \leq V_B \sqrt{\left(1 + \frac{k_{L2}}{k_{L1}}\right)\left(1 + \frac{m_2}{m_1}\right)}$$

3. METHOD

3.1. Modelling and Simulating FWRB Crash Tests

First, total barrier force vs deformation graph is plotted (Figure 3.1) by using the FWRB frontal crash test data of the vehicles to obtain the stiffnesses using spring-mass model in Figure 2.2.

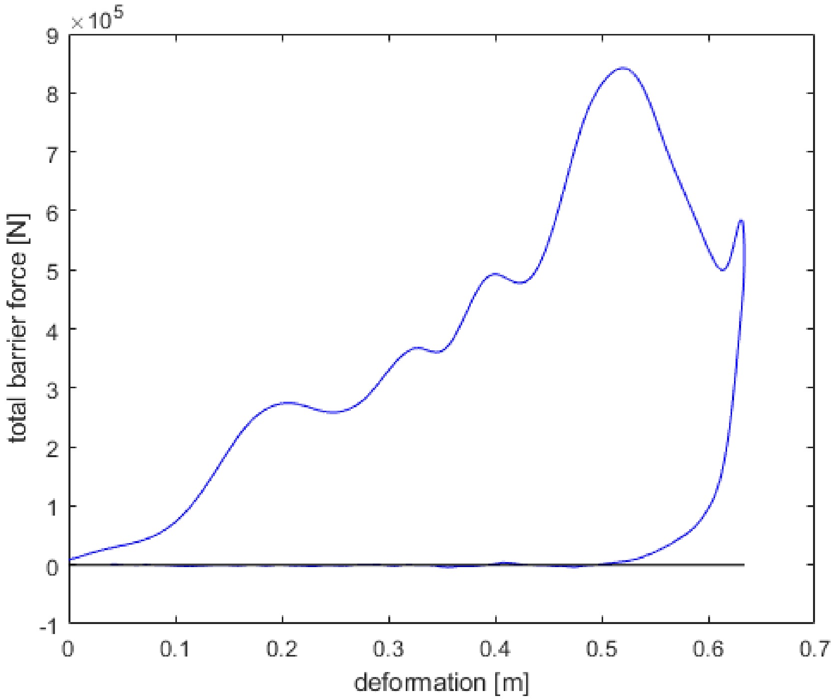

Figure 3.1. Total barrier force vs deformation – Car 48

Then, permanent deformation, x_P is found from Figure 3.1 which is the point where the force line cuts the x-axis.

Rebound velocity, V' and permanent deformation, x_T were found in the crash test report and elastic rebound displacement, x_e is found using permanent deformation with this formula:

$$x_e = x_T - x_P$$

Using elastic deformation and rebound velocity, the separation force, F^* is calculated with this formula:

$F^* = m(V')^2/x_e$

By equating the area under the graph in the loading phase to spring energy, the barrier force work-based loading stiffness is estimated by linear approximation.

The unloading stiffness is found by equating the area under the crush force-deformation curve at the unloading stage to the area under the inclined straight line in Figure 3.2. In doing so, the separation force F^* is found. Finally, the F_{max}/F^* value is found as the force drop ratio, c.

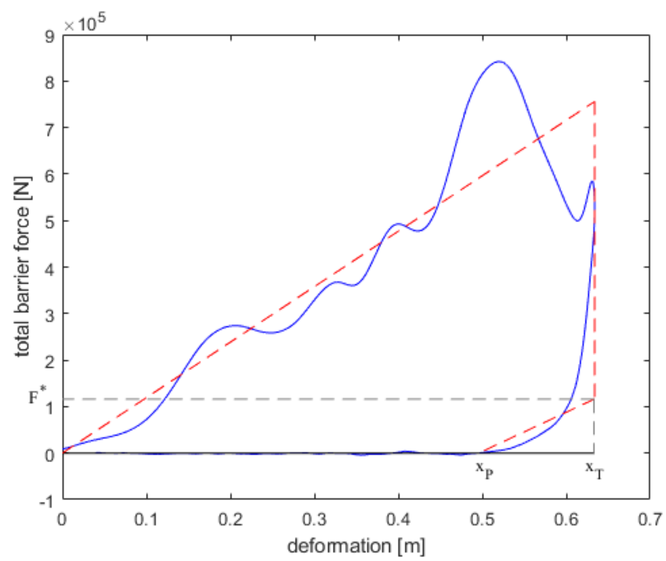

Figure 3.2. Barrier-force-work based linear approximation – Car 22

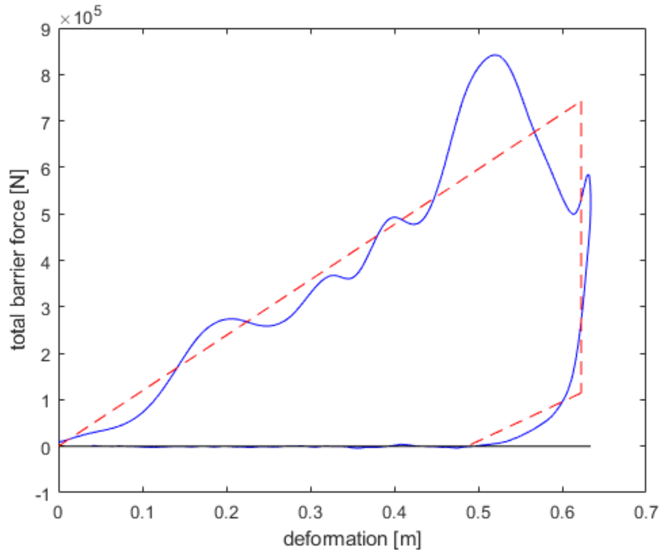

Figure 3.3. Model solution vs actual data – Car 22

Table 3.1. Estimated key parameters from model

Vehicle Number	Loading Stiffness (N/m)	Unloading Stiffness (N/m)	Force-Drop Ratio
Car 1	1680657.7	2049281.84	5.19
Car 2	1143377.85	806511.08	12.88
Car 3	925692.72	1763837.45	4.7
Car 4	1193175.89	709741.67	8.11
Car 5	1035047.41	426930.44	8.7
Car 6	952828.17	1101004.7	7.27
Car 7	1043216	1151178.28	6.94
Car 8	1320436.74	517337.33	11.89
Car 9	1229628.25	997258.86	8.08
Car 10	1264738.77	305900.47	22.14
Car 11	853306.63	375306.68	11.67
Car 12	1093381.94	1631511.05	7.33
Car 13	1040270.82	337398.83	10.72
Car 14	1109374.76	1389478.36	7.48
Car 15	1444688.22	3034637.15	4.15
Car 16	1128487.73	967515.73	7.84
Car 17	1192870.2	862590.4	9.06
Car 18	1212736.81	1548558.5	6.68
Car 19	1134053.58	581495.67	14.8
Car 20	984759.34	977391.54	5.81
Car 21	826514.96	1215588.34	3.86
Car 22	1192671.03	844510.6	6.49
Car 23	1563850.48	805354.41	12.97
Car 24	1458635.9	2655119.81	5.85
Car 25	1112884.84	2575674.22	2.48
Car 26	939221.66	1005710.89	6.29
Car 27	748433.2	86527.78	10.13
Car 28	1440745.07	564729.59	11.3
Car 29	729731.8	395859.82	9.06
Car 30	998816.39	253463.3	20.56
Car 31	1279937.26	1672462.84	7.36
Car 32	1215690.1	735405.31	12.68
Car 33	1033972.36	221605.15	15.13
Car 34	1037701.07	818634.56	5.93
Car 35	776858.19	712922.01	6.86

Car 36	830572.89	269330.88	14.33
Car 37	1088319.88	775763.66	7.65
Car 38	914855.92	2008450.42	3.9
Car 39	706520.23	429060.56	6.14
Car 40	900248.46	1478778.81	5.91
Car 41	1124223.79	1029269.03	8.24
Car 42	1537344.3	1018421.57	12.36
Car 43	914491.22	508722.37	7.28
Car 44	1291677.3	612246.22	9.16
Car 45	1072967.69	960179.06	6.16
Car 46	1127666.87	2372178.66	4.39
Car 47	961360.14	1389328.61	5.62
Car 48	1060970.6	1243192.45	5.94
Car 49	1051426.06	559901.3	11.91
Car 50	1143410.89	559019.69	15.33
Car 51	1159586.39	1388482.56	7.83
Car 52	836470.39	345968.44	9.71
Maximum	1680657.70	3034637.15	22.14
Minimum	706520.23	86527.78	2.48
Average	1097317.43	1020129.40	8.85
Std.	216124.18	671680.82	4.04

After the model was created, the loading and unloading stiffnesses and force-drop ratios of fifty-two vehicles were estimated with the MATLAB program.

3.2. Validation of FWRB Crash Test Model

To validate the model, key parameters estimated using the model were compared with the actual FWRB test data.

One of the key parameters to determine injury risk [9–12], mean acceleration, a_{mean} is found by dividing the impact velocity, V_0 by the loading phase duration, t_L because velocity is zero at the end of the loading phase.

$a_{mean} = -V_0/t_L$

Table 3.2. Estimated parameters vs actual FWRB test data

	a_{mean} (g)		x_p (m)	
Vehicle	**Actual**	**Model**	**Actual**	**Model**
Car 1	-26.16	-28.70	0.456	0.459
Car 2	-21.11	-24.33	0.637	0.583
Car 3	-22.36	-23.33	0.635	0.609
Car 4	-24.79	-27.75	0.477	0.454
Car 5	-21.02	-23.66	0.523	0.485
Car 6	-20.58	-22.95	0.653	0.614
Car 7	-25.60	-27.24	0.530	0.505
Car 8	-27.73	-28.78	0.404	0.428
Car 9	-23.03	-24.65	0.557	0.550
Car 10	-26.43	-29.53	0.422	0.436
Car 11	-22.14	-24.14	0.566	0.532
Car 12	-20.17	-23.73	0.658	0.610
Car 13	-21.49	-24.57	0.460	0.462
Car 14	-24.25	-27.72	0.548	0.512

Car 15	-34.66	-35.77	0.380	0.392
Car 16	-25.25	-27.40	0.507	0.490
Car 17	-20.83	-24.12	0.585	0.554
Car 18	-21.69	-23.99	0.609	0.580
Car 19	-25.85	-31.48	0.479	0.448
Car 20	-22.51	-24.30	0.563	0.546
Car 21	-21.98	-23.87	0.592	0.546
Car 22	-25.25	-25.50	0.496	0.487
Car 23	-28.45	-33.21	0.416	0.398
Car 24	-23.64	-25.64	0.571	0.559
Car 25	-22.03	-25.36	0.595	0.596
Car 26	-20.76	-23.24	0.602	0.575
Car 27	-21.90	-23.21	0.595	0.553
Car 28	-24.93	-27.46	0.483	0.446
Car 29	-21.27	-22.61	0.553	0.561
Car 30	-28.89	-26.45	0.420	0.487
Car 31	-26.26	-28.95	0.529	0.491
Car 32	-24.12	-27.61	0.516	0.500
Car 33	-21.29	-23.97	0.483	0.462
Car 34	-21.41	-22.55	0.590	0.553
Car 35	-22.35	-24.57	0.584	0.548
Car 36	-25.44	-24.58	0.448	0.509
Car 37	-22.45	-24.68	0.561	0.525
Car 38	-21.64	-23.93	0.626	0.588
Car 39	-23.89	-23.91	0.516	0.490
Car 40	-23.57	-25.44	0.588	0.560
Car 41	-21.75	-24.99	0.591	0.552
Car 42	-28.25	-31.44	0.460	0.445
Car 43	-27.89	-27.18	0.440	0.436
Car 44	-28.74	-29.07	0.422	0.417
Car 45	-20.68	-24.18	0.600	0.537
Car 46	-22.75	-24.65	0.599	0.578
Car 47	-24.58	-25.75	0.562	0.538
Car 48	-23.46	-25.62	0.562	0.536
Car 49	-23.79	-25.77	0.542	0.522
Car 50	-23.18	-26.75	0.569	0.522
Car 51	-24.81	-25.26	0.598	0.564
Car 52	-22.49	-21.54	0.534	0.560

The comparison of the actual data and data obtained from model can be seen in Figure 3.4 and Figure 3.5.

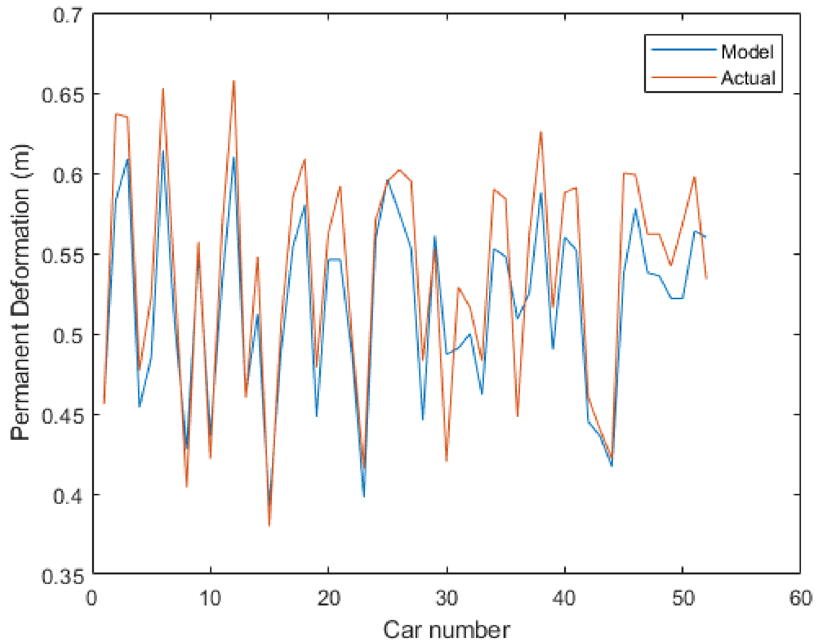

Figure 3.4. Permanent deformation - model vs actual

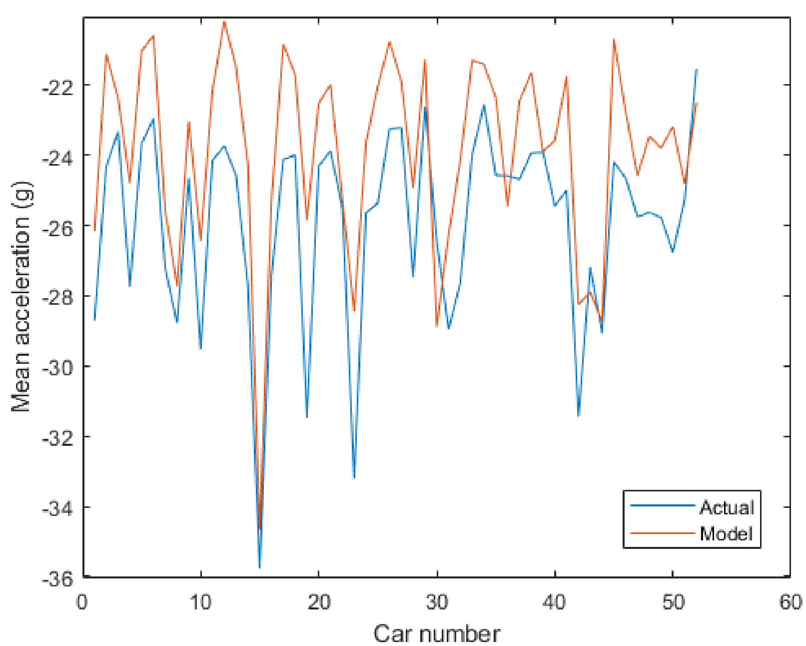

Figure 3.5. Mean acceleration - model vs actual

Average error in the permanent deformations (x_p) is 3 cm and in the mean accelerations (α_{mean}) is 10%.

Distribution of stiffness, unloading stiffness and force-drop ratio and mass values of vehicles can be seen in Figure 3.6, Figure 3.7, Figure 3.8, and Figure 3.9

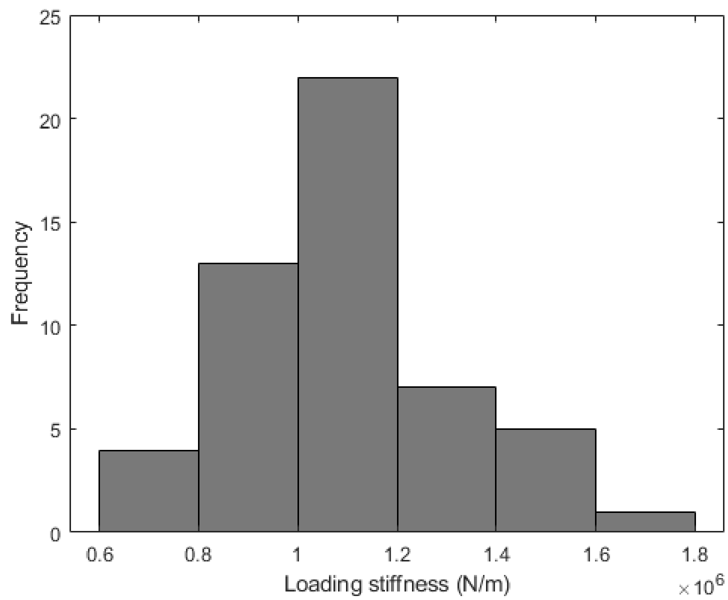

Figure 3.6. Loading stiffness distribution

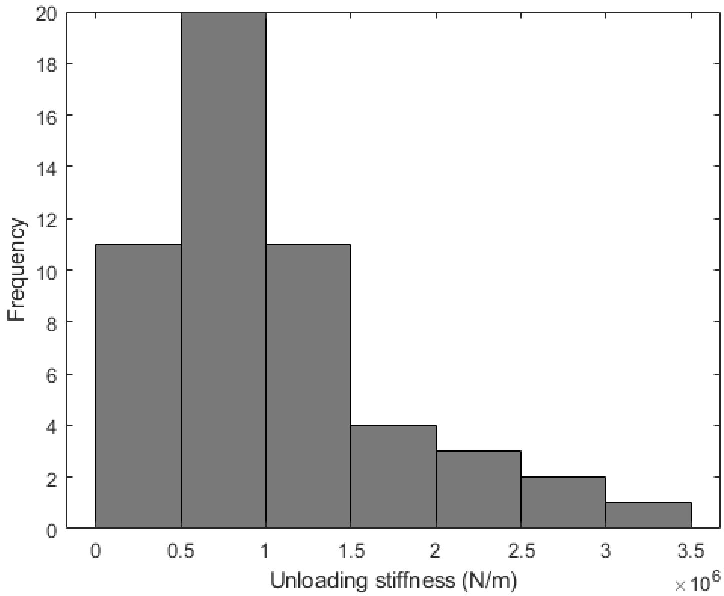

Figure 3.7. Unloading stiffness distribution

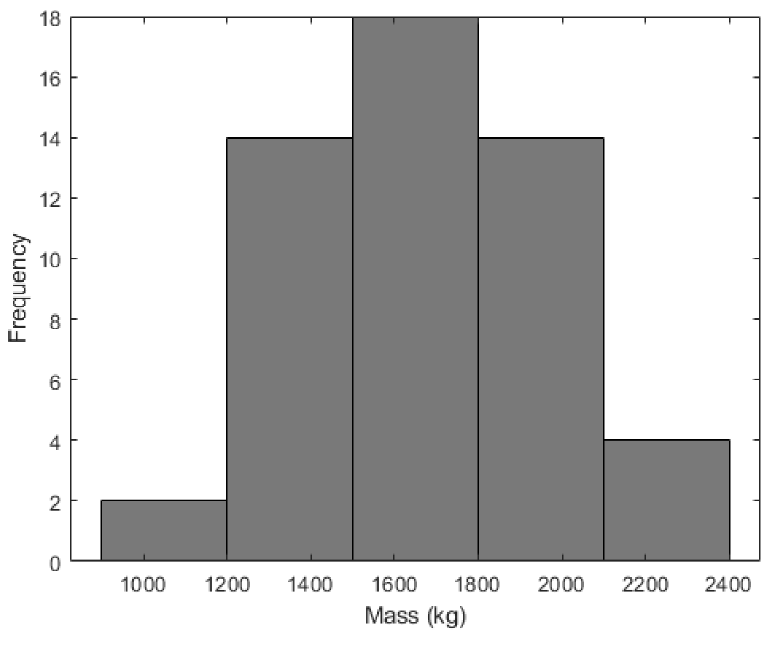

Figure 3.8. Mass distribution

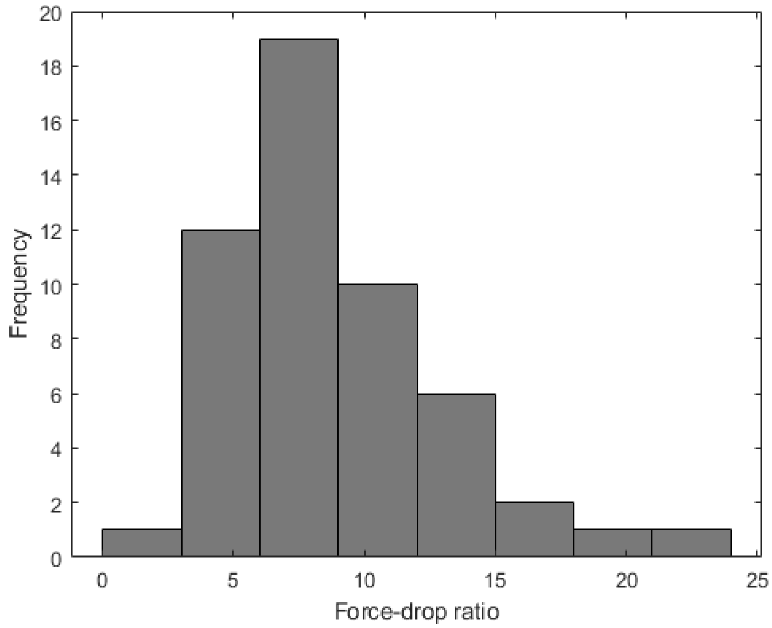

Figure 3.9. Force-drop ratio distribution

3.3. Modelling and Simulating Head-On Collision

In this model, the maximum crushing force is modeled using Figure 2.5(b). The basic inputs used in this model are vehicle mass with loading stiffness, unloading stiffness and force-drop ratio that are obtained from FWRB frontal crash test models.

The data to be used for this model is obtained from the datasets created over the FWRB model using certain queries and a 52x52 matrix was created for each value.

3.3.1. Stiffness Reduction

As mentioned in the theory section there is a stiffness reduction due to incompatibility issue between cars which is difficult to estimate. Therefore, it is assumed that the loading stiffness and unloading stiffness reduced by 0.7 and 0.4 as shown by Himmetoglu's study [5, 17].

As it is difficult to estimate incompatibility simulations were repeated with loading stiffness values reduced by 0.85 and unloading stiffness values reduced by 0.7.

3.3.2. Determination of Maximum Safe Closing Speed

The maximum closing speed was calculated as 85 km/h to ensure that the energy absorbed between the cars for each collision is less than that in the FWRB test. It is named as maximum safe closing speed.

3.3.3 Obtaining Results

Head-on simulations were repeated with maximum safe closing speed without reducing stiffness values.

The following simulations have been made:

- With closing speed 112 km/h
    - Loading/unloading stiffness values reduced by 0.7/0.4
    - Loading/unloading stiffness values reduced by 0.85/0.7
- With maximum safe closing speed (85 km/h) without reducing stiffness values

As a result of each simulation, maximum acceleration, mean acceleration, maximum deformation, permanent deformation, elastic deformation, velocity changes, coefficient of restitution, rebound velocity values are obtained for all collisions (52x52 matrix for each value). Then, tables of mean acceleration and max deformation values are created to evaluate the data statistically. It was examined which vehicles are safer or more unsafe when they collided with them.

All calculations and data analysis were carried out with codes written in MATLAB. The results of the head-on collision simulation were examined through mean acceleration and max deformation, summary results are given in the result section.

4. RESULTS

4.1. Results of Head-on Collision Simulations

The results obtained from the collision of all vehicles were analyzed separately as mean acceleration based and maximum deformation based.

4.1.1. Acceleration Based Results

The highest and lowest mean acceleration of cars when collided with each other is given in Table 4.1.

Table 4.1. Mean acceleration values that occur when each vehicle collides with other vehicles – Stiffness reduced by 0.7/0.4.

Vehicle	Highest (g)	Lowest (g)	Average (g)	Standard Deviation
Car 1	24.05	16.18	20.03	1.76
Car 2	22.26	15.63	18.94	1.50
Car 3	22.83	16.52	19.71	1.44
Car 4	26.51	18.78	22.65	1.74
Car 5	22.34	15.90	19.14	1.47
Car 6	22.03	15.83	18.96	1.42
Car 7	27.40	19.81	23.64	1.71
Car 8	26.99	18.90	22.92	1.81
Car 9	21.88	15.20	18.53	1.51
Car 10	28.37	20.06	24.20	1.86
Car 11	24.74	18.22	21.54	1.47
Car 12	21.88	15.44	18.66	1.53
Car 13	23.52	16.80	20.18	1.74
Car 14	27.32	19.59	23.47	2.26
Car 15	35.01	24.77	29.85	1.72
Car 16	26.83	19.16	23.01	1.49
Car 17	21.73	15.15	18.43	1.48
Car 18	21.39	14.86	18.11	1.95
Car 19	31.84	23.06	27.47	1.50
Car 20	23.55	16.94	20.28	1.47
Car 21	24.85	18.38	21.69	2.10
Car 22	23.47	16.47	19.96	1.56
Car 23	30.91	21.42	26.10	1.58
Car 24	21.58	14.65	18.06	1.45
Car 25	24.07	17.07	20.58	1.42
Car 26	22.87	16.52	19.73	1.70
Car 27	24.72	18.52	21.70	1.38
Car 28	24.09	16.53	20.26	1.81
Car 29	23.98	17.98	21.06	1.73
Car 30	32.18	23.72	28.01	1.48
Car 31	27.37	19.26	23.30	1.39
Car 32	26.15	18.46	22.30	1.50
Car 33	22.69	16.17	19.45	1.51
Car 34	20.80	14.72	17.77	1.53
Car 35	26.25	19.67	23.04	1.48
Car 36	25.70	19.05	22.45	1.44

Car 37	23.29	16.52	19.92	1.58
Car 38	23.86	17.36	20.65	1.55
Car 39	26.12	19.81	23.06	1.69
Car 40	26.28	19.31	22.85	1.83
Car 41	23.36	16.51	19.94	1.50
Car 42	28.33	19.53	23.87	1.52
Car 43	28.79	21.27	25.10	1.61
Car 44	27.56	19.39	23.46	1.59
Car 45	22.75	16.14	19.45	1.60
Car 46	22.77	16.05	19.41	1.66
Car 47	26.16	19.04	22.64	1.49
Car 48	24.69	17.66	21.19	1.58
Car 49	25.06	17.96	21.53	1.57
Car 50	25.37	18.01	21.69	1.96
Car 51	23.38	16.45	19.91	1.88
Car 52	24.32	17.93	21.19	1.46
Maximum	35.01	24.77	29.85	2.26
Minimum	20.80	14.65	17.77	1.38
Mean	25.12	17.97	21.56	1.62
Standard Deviation	3.00	2.27	2.63	0.19

All maximum values are obtained when cars collided with Car 1 and all minimum values are obtained from when cars collided with Car 39.

The maximum value of mean acceleration, 35.01g, occurs on Car 15 when it collides with Car 1.

The minimum value of mean acceleration, 14.65g, occurs on Car 24 when it collides with Car 36.

In Table 4.2 it can be seen how the mean acceleration has changed compared to the FWRB test data.

Table 4.2. Change of mean acceleration compared to the FWRB test data – Stiffness reduced by 0.7/0.4.

Vehicle	Average	Maximum	Minimum
Car 1	-30%	-16%	-44%
Car 2	-22%	-9%	-36%
Car 3	-16%	-2%	-29%
Car 4	-18%	-5%	-32%
Car 5	-19%	-6%	-33%
Car 6	-17%	-4%	-31%
Car 7	-13%	1%	-27%

Car 8	-20%	-6%	-34%
Car 9	-25%	-11%	-38%
Car 10	-18%	-4%	-32%
Car 11	-9%	4%	-23%
Car 12	-24%	-11%	-37%
Car 13	-27%	-15%	-39%
Car 14	-34%	-24%	-45%
Car 15	10%	29%	-9%
Car 16	-5%	11%	-21%
Car 17	-23%	-9%	-37%
Car 18	-43%	-32%	-53%
Car 19	13%	31%	-5%
Car 20	-15%	-1%	-29%
Car 21	-35%	-25%	-45%
Car 22	-22%	-8%	-36%
Car 23	3%	22%	-16%
Car 24	-22%	-7%	-37%
Car 25	-11%	4%	-26%
Car 26	-28%	-17%	-40%
Car 27	-4%	9%	-18%
Car 28	-30%	-17%	-43%
Car 29	-24%	-13%	-35%
Car 30	17%	34%	-1%
Car 31	3%	21%	-15%
Car 32	-9%	6%	-25%
Car 33	-21%	-8%	-34%
Car 34	-28%	-16%	-40%
Car 35	-4%	10%	-18%
Car 36	-6%	8%	-20%
Car 37	-22%	-9%	-35%
Car 38	-17%	-5%	-31%
Car 39	-15%	-4%	-27%
Car 40	-21%	-10%	-34%
Car 41	-18%	-3%	-32%
Car 42	-3%	15%	-21%
Car 43	-3%	12%	-17%
Car 44	-8%	8%	-24%
Car 45	-25%	-12%	-37%
Car 46	-27%	-15%	-40%
Car 47	-6%	8%	-21%
Car 48	-17%	-3%	-31%
Car 49	-15%	-1%	-29%
Car 50	-31%	-19%	-43%
Car 51	-25%	-12%	-38%
Car 52	-2%	13%	-17%
Maximum	17%	34%	-1%

Minimum	-43%	-32%	-53%
Average	-16%	-2%	-30%

Negative values in Table 4.2 indicate a decrease in acceleration value compared with FWRB data. So maximum value is showing how much more or less the collision with the most acceleration is compared to FWRB.

There is an average of 16% decrease in mean accelerations and maximum of 34% increase compared to FWRB data. In addition, since the stiffness values of vehicles are reduced, it is observed that the vehicles have a mean acceleration to 15% less than FWRB data when they collide with themselves.

Based on the mean acceleration values obtained from the head-on collision simulation of the vehicles, the vehicles that are more unsafe than the FWRB frontal crash test result and how many vehicles they are more unsafe when they collide are shown in Table 4.3

Table 4.3. The vehicles that are more unsafe than the FWRB frontal crash test result and number of vehicles they are more unsafe when they collide – based on acceleration – Stiffness reduced by 0.7/0.4.

Vehicle	Number of Vehicles
Car 7	1
Car 11	3
Car 15	44
Car 16	13
Car 19	48
Car 23	36
Car 25	2
Car 27	13
Car 30	51
Car 31	37
Car 32	3
Car 35	13
Car 36	7
Car 42	19
Car 43	21
Car 44	5
Car 47	7
Car 52	25

Histograms showing the acceleration change distribution of Car 1, Car 30, and Car 52 as examples when colliding with other vehicles can be seen in Figure 4.1, Figure 4.2, and Figure 4.3.

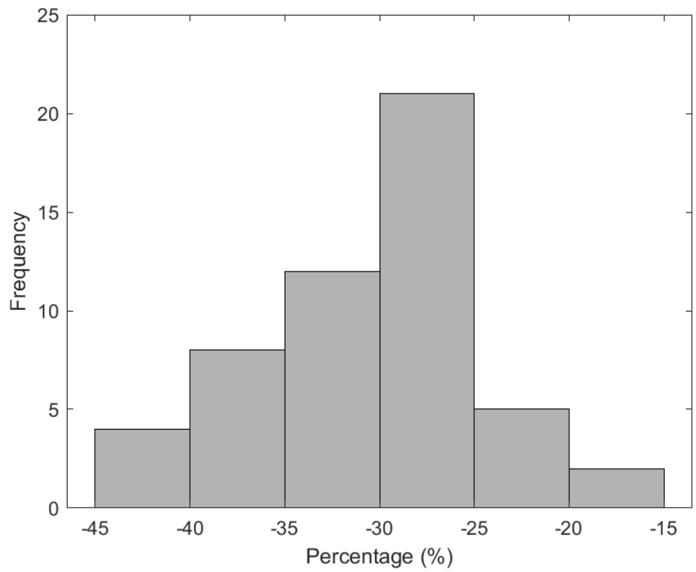

Figure 4.1. Changes of acceleration values compared with FWRB frontal crash test data – Car 1 – Stiffness reduced by 0.7/0.4.

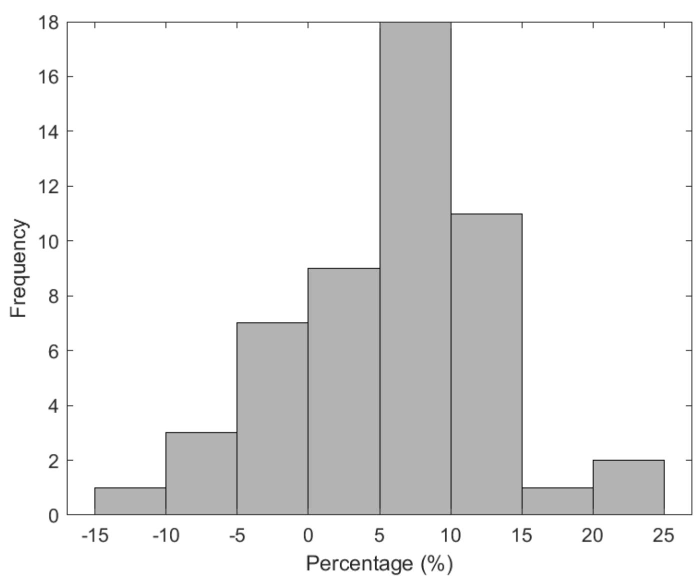

Figure 4.2. Changes of acceleration values compared with FWRB frontal crash test data – Car 30 – Stiffness reduced by 0.7/0.4.

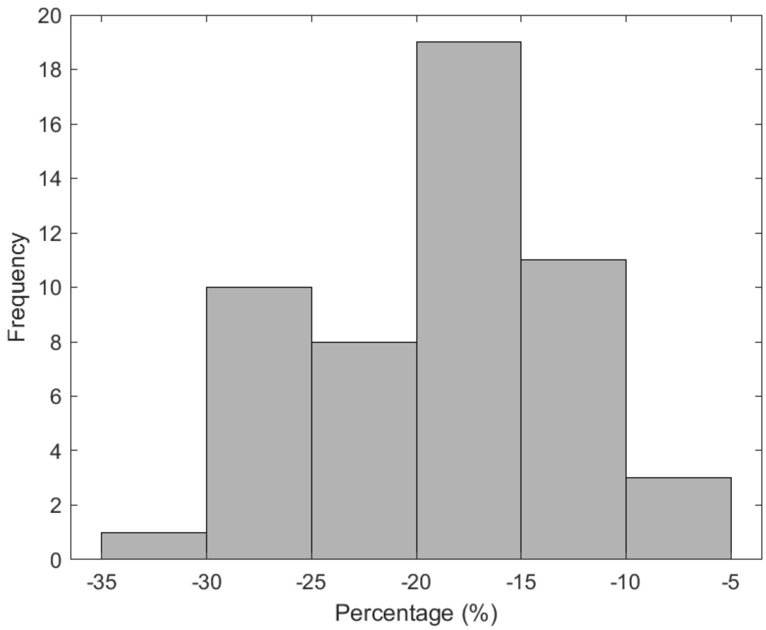

Figure 4.3. Changes of acceleration values compared with FWRB frontal crash test data – Car 52 – Stiffness reduced by 0.7/0.4.

4.1.2. Deformation Based Results

The highest and lowest max. deformation values of cars when cars collided with each other is given in Table 4.4.

Table 4.4. Max. deformation values that occur when each vehicle collides with other vehicles – Stiffness reduced by 0.7/0.4.

Vehicle	Maximum (m)	Minimum (m)	Average (m)	Std.
Car 1	0.653	0.439	0.544	0.047
Car2	0.856	0.601	0.728	0.057
Car 3	0.958	0.693	0.827	0.059
Car 4	0.782	0.554	0.668	0.050
Car 5	0.906	0.645	0.776	0.058
Car 6	0.955	0.686	0.822	0.060
Car 7	0.834	0.603	0.720	0.051
Car 8	0.731	0.512	0.621	0.048
Car 9	0.823	0.572	0.697	0.056
Car 10	0.735	0.520	0.627	0.047
Car 11	0.971	0.715	0.845	0.057
Car 12	0.884	0.624	0.754	0.058
Car 13	0.887	0.634	0.761	0.056
Car 14	0.806	0.578	0.693	0.050

Car 15	0.619	0.438	0.528	0.039
Car 16	0.804	0.575	0.690	0.051
Car 17	0.841	0.586	0.713	0.057
Car 18	0.837	0.581	0.708	0.057
Car 19	0.745	0.540	0.643	0.045
Car 20	0.915	0.658	0.788	0.057
Car 21	0.986	0.729	0.860	0.057
Car 22	0.819	0.574	0.696	0.054
Car 23	0.623	0.432	0.526	0.041
Car 24	0.742	0.504	0.621	0.053
Car 25	0.846	0.600	0.723	0.054
Car 26	0.950	0.686	0.819	0.059
Car 27	1.040	0.779	0.913	0.059
Car 28	0.722	0.495	0.607	0.050
Car 29	1.067	0.800	0.937	0.060
Car 30	0.795	0.586	0.692	0.046
Car 31	0.741	0.521	0.631	0.048
Car 32	0.778	0.549	0.663	0.050
Car 33	0.902	0.643	0.773	0.058
Car 34	0.927	0.656	0.792	0.061
Car 35	0.995	0.745	0.873	0.056
Car 36	0.970	0.719	0.847	0.056
Car 37	0.867	0.615	0.742	0.056
Car 38	0.949	0.690	0.821	0.058
Car 39	1.045	0.793	0.923	0.057
Car 40	0.920	0.676	0.800	0.054
Car 41	0.850	0.600	0.725	0.055
Car 42	0.652	0.450	0.550	0.044
Car 43	0.877	0.648	0.765	0.050
Car 44	0.735	0.517	0.625	0.048
Car 45	0.882	0.626	0.754	0.057
Car 46	0.856	0.603	0.730	0.056
Car 47	0.890	0.648	0.770	0.054
Car 48	0.861	0.616	0.739	0.054
Car 49	0.861	0.617	0.740	0.054
Car 50	0.816	0.579	0.698	0.052
Car 51	0.834	0.587	0.710	0.055
Car 52	0.988	0.729	0.861	0.058
Maximum	1.067	0.800	0.937	0.061
Minimum	0.619	0.432	0.526	0.039
Mean	0.852	0.611	0.732	0.054
Std.	0.105	0.088	0.098	0.005

All maximum values are obtained when cars collided with Car 1 and all minimum values are obtained from when cars collided with Car 39.

Maximum value of max. deformation, 1.067 m, occurs on Car 15 when it collides with Car 1.

Minimum value of max. deformation, 0.432m, on Car 24 when it collides with Car 36. In Table 4.5 it can be seen how the mean acceleration has changed compared to the FWRB test data.

Table 4.5. Change of max. deformation compared to the FWRB test data – Stiffness reduced by 0.7/0.4.

Vehicle	Maximum	Minimum	Average
Car 1	20%	-20%	0%
Car 2	31%	-8%	11%
Car 3	40%	1%	21%
Car 4	37%	-3%	17%
Car 5	35%	-4%	16%
Car 6	37%	-2%	18%
Car 7	44%	4%	24%
Car 8	34%	-6%	14%
Car 9	27%	-12%	7%
Car 10	37%	-3%	17%
Car 11	47%	8%	28%
Car 12	32%	-7%	12%
Car 13	37%	-2%	17%
Car 14	41%	1%	21%
Car 15	40%	-1%	19%
Car 16	40%	0%	20%
Car 17	29%	-10%	9%
Car 18	27%	-12%	8%
Car 19	44%	5%	25%
Car 20	38%	0%	19%
Car 21	49%	10%	30%
Car 22	31%	-8%	12%
Car 23	33%	-8%	12%
Car 24	20%	-18%	1%
Car 25	36%	-4%	16%
Car 26	41%	2%	21%
Car 27	52%	14%	34%
Car 28	25%	-14%	5%

Car 29	52%	14%	33%
Car 30	32%	-3%	15%
Car 31	35%	-5%	15%
Car 32	35%	-5%	15%
Car 33	35%	-4%	16%
Car 34	32%	-7%	13%
Car 35	53%	14%	34%
Car 36	49%	11%	31%
Car 37	35%	-4%	15%
Car 38	42%	4%	23%
Car 39	56%	18%	38%
Car 40	48%	8%	28%
Car 41	34%	-6%	14%
Car 42	29%	-11%	8%
Car 43	51%	12%	32%
Car 44	36%	-5%	15%
Car 45	34%	-5%	15%
Car 46	32%	-7%	12%
Car 47	45%	6%	26%
Car 48	38%	-2%	18%
Car 49	39%	-1%	19%
Car 50	36%	-4%	16%
Car 51	32%	-7%	13%
Car 52	33%	-2%	15%
Maximum	56%	18%	38%
Minimum	20%	-20%	0%
Average	37%	-2%	18%

There is an average of 18% increase in max. deformation and maximum of 56% increase compared to FWRB data.

Car 39 is the vehicle that has increased max. deformation the most compared to the average of all its collisions.

Based on the max. deformation values obtained from the head-on collision simulation of the vehicles, number of crash-partners which the vehicle is more unsafe when they collide are shown in Table 4.6

Table 4.6. The vehicles that are more unsafe than the FWRB frontal crash test result and number of vehicles they are more unsafe when they collide – based on deformation – Stiffness reduced by 0.7/0.4.

Vehicle	Number of Vehicles	Percentage
Car 1	28	54%
Car 2	45	87%
Car 3	52	100%
Car 4	51	98%
Car 5	50	96%
Car 6	51	98%
Car 7	52	100%
Car 8	48	92%
Car 9	40	77%
Car 10	51	98%
Car 11	52	100%
Car 12	46	88%
Car 13	51	98%
Car 14	52	100%
Car 15	51	98%
Car 16	51	98%
Car 17	41	79%
Car 18	40	77%
Car 19	52	100%
Car 20	51	98%
Car 21	52	100%
Car 22	45	87%
Car 23	46	88%
Car 24	30	58%
Car 25	51	98%
Car 26	52	100%
Car 27	52	100%
Car 28	39	75%
Car 29	52	100%
Car 30	51	98%
Car 31	48	92%
Car 32	50	96%
Car 33	51	98%
Car 34	46	88%
Car 35	52	100%
Car 36	52	100%
Car 37	50	96%
Car 38	52	100%
Car 39	52	100%
Car 40	52	100%
Car 41	47	90%
Car 42	41	79%
Car 43	52	100%
Car 44	48	92%
Car 45	50	96%
Car 46	46	88%
Car 47	52	100%
Car 48	51	98%
Car 49	51	98%
Car 50	51	98%
Car 51	46	88%
Car 52	51	98%

Based on deformation Car 1 is the safest vehicle as it has more deformation of only 28 collisions of its, while Car 39, Car 3, Car 7, Car 11, Car 14, Car 19, Car 21, Car 26, Car 27, Car 29, Car 35, Car 36, Car 38, Car 39, Car 40, Car 43, and Car 47 have more deformation of all collisions compared with FWRB test data. Deformation increases in 93% of all collisions.

Histograms showing the max. deformation change distribution of Car 1, Car 30, and Car 52 as examples when colliding with other vehicles can be seen in Figure 4.1, Figure 4.2, and Figure 4.3.

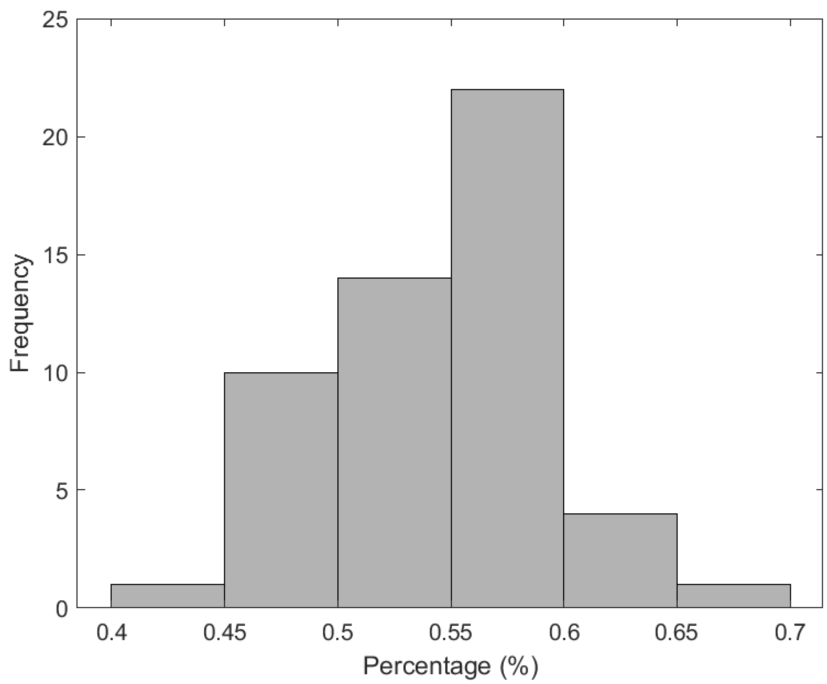

Figure 4.4. Changes of max. deformation values compared with FWRB frontal crash test data – Car 1 – Stiffness reduced by 0.7/0.4.

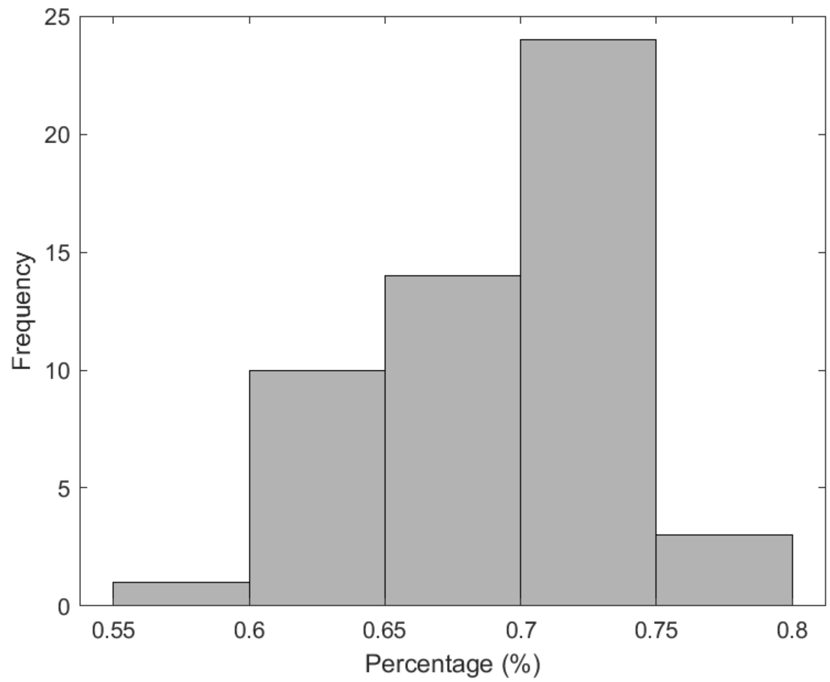

Figure 4.5. Changes of max. deformation values compared with FWRB frontal crash test data – Car 30 – Stiffness reduced by 0.7/0.4.

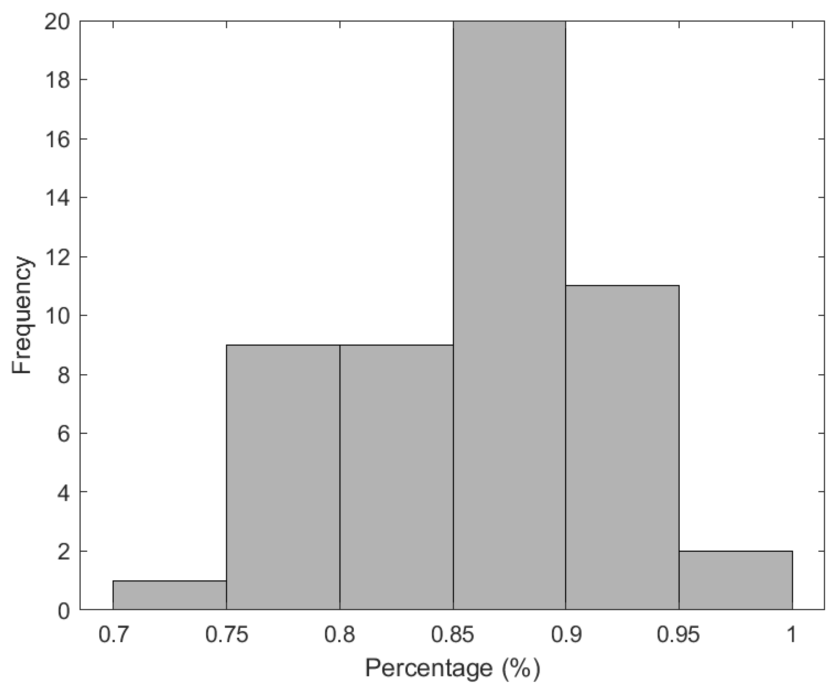

Figure 4.6. Changes of max. deformation values compared with FWRB frontal crash test data – Car 52 – Stiffness reduced by 0.7/0.4.

4.1.3. Summary of Results for Different Stiffness Reduction and Different Closing Speed

Table 4.7. Mean acceleration values that occur when each vehicle collides with other vehicles – 85 km/h closing speed

Vehicle	Maximum (g)	Minimum (g)	Average (g)
Car 1	21.81	14.68	18.17
Car 2	20.19	14.18	17.18
Car 3	20.71	14.99	17.88
Car 4	24.05	17.04	20.54
Car 5	20.27	14.43	17.36
Car 6	19.98	14.36	17.20
Car 7	24.86	17.97	21.44
Car 8	24.48	17.14	20.79
Car 9	19.85	13.79	16.81
Car 10	25.74	18.20	21.96
Car 11	22.44	16.52	19.54
Car 12	19.85	14.00	16.93
Car 13	21.34	15.24	18.31
Car 14	24.78	17.77	21.29
Car 15	31.75	22.47	27.07
Car 16	24.34	17.38	20.87
Car 17	19.71	13.74	16.72
Car 18	19.40	13.48	16.43
Car 19	28.88	20.91	24.92
Car 20	21.36	15.37	18.39
Car 21	22.55	16.68	19.67
Car 22	21.29	14.94	18.11
Car 23	28.04	19.43	23.67
Car 24	19.57	13.29	16.38
Car 25	21.84	15.49	18.67
Car 26	20.75	14.99	17.90
Car 27	22.43	16.80	19.69
Car 28	21.85	14.99	18.38
Car 29	21.75	16.31	19.10
Car 30	29.19	21.52	25.41
Car 31	24.83	17.48	21.14
Car 32	23.72	16.74	20.23
Car 33	20.58	14.67	17.64
Car 34	18.87	13.35	16.12
Car 35	23.81	17.84	20.90
Car 36	23.31	17.28	20.36
Car 37	21.13	14.99	18.07

Car 38	21.65	15.74	18.74
Car 39	23.69	17.97	20.91
Car 40	23.84	17.51	20.73
Car 41	21.19	14.97	18.08
Car 42	25.70	17.72	21.65
Car 43	26.12	19.30	22.76
Car 44	25.00	17.59	21.28
Car 45	20.63	14.64	17.65
Car 46	20.65	14.56	17.61
Car 47	23.73	17.27	20.54
Car 48	22.39	16.02	19.22
Car 49	22.73	16.30	19.53
Car 50	23.01	16.33	19.68
Car 51	21.20	14.92	18.06
Car 52	22.06	16.27	19.22
Maximum	31.75	22.47	27.07
Minimum	18.87	13.29	16.12
Average	22.79	16.30	19.56

Table 4.8. Change of mean acceleration compared to the FWRB test data – 85 km/h closing speed

Vehicle	Average (g)	Maximum (g)	Minimum (g)
Car 1	-37%	-24%	-49%
Car 2	-29%	-17%	-42%
Car 3	-23%	-11%	-36%
Car 4	-26%	-13%	-39%
Car 5	-27%	-14%	-39%
Car 6	-25%	-13%	-37%
Car 7	-21%	-9%	-34%
Car 8	-28%	-15%	-40%
Car 9	-32%	-20%	-44%
Car 10	-26%	-13%	-38%
Car 11	-18%	-5%	-30%
Car 12	-31%	-19%	-43%
Car 13	-34%	-23%	-45%
Car 14	-41%	-31%	-50%
Car 15	-1%	17%	-18%
Car 16	-14%	1%	-28%
Car 17	-30%	-18%	-43%
Car 18	-48%	-38%	-57%
Car 19	3%	19%	-14%
Car 20	-23%	-11%	-36%
Car 21	-41%	-32%	-50%
Car 22	-29%	-17%	-42%

Car 23	-7%	11%	-23%
Car 24	-30%	-16%	-43%
Car 25	-20%	-6%	-33%
Car 26	-35%	-24%	-45%
Car 27	-13%	-1%	-26%
Car 28	-37%	-25%	-48%
Car 29	-31%	-21%	-41%
Car 30	6%	22%	-10%
Car 31	-6%	10%	-23%
Car 32	-18%	-4%	-32%
Car 33	-28%	-16%	-40%
Car 34	-35%	-24%	-46%
Car 35	-13%	-1%	-26%
Car 36	-15%	-3%	-28%
Car 37	-29%	-17%	-41%
Car 38	-25%	-13%	-37%
Car 39	-23%	-13%	-34%
Car 40	-29%	-18%	-40%
Car 41	-25%	-12%	-38%
Car 42	-12%	4%	-28%
Car 43	-12%	1%	-25%
Car 44	-17%	-2%	-31%
Car 45	-32%	-20%	-43%
Car 46	-34%	-23%	-46%
Car 47	-15%	-2%	-28%
Car 48	-25%	-12%	-37%
Car 49	-23%	-10%	-36%
Car 50	-37%	-27%	-48%
Car 51	-32%	-20%	-44%
Car 52	-11%	2%	-25%
Maximum	6%	22%	-10%
Minimum	-48%	-38%	-57%
Average	-24%	-11%	-37%

There is an average of 24% decrease in mean acceleration and maximum of 22% increase compared to FWRB data.

Table 4.9. The vehicles that are more unsafe than the FWRB frontal crash test result and number of vehicles they are more unsafe when they collide – based on acceleration – 85 km/h closing speed

Vehicle	Number of Vehicles
Car 7	1
Car 11	3
Car 15	44
Car 16	13
Car 19	48
Car 23	36
Car 25	2
Car 27	13
Car 30	51
Car 31	37
Car 32	3
Car 35	13
Car 36	7
Car 42	19
Car 43	21
Car 44	5
Car 47	7
Car 52	25

Table 4.10. Max. deformation values that occur when each vehicle collides with other vehicles – 85 km/h closing speed

Vehicle	Maximum (m)	Minimum (m)	Average (m)
Car 1	0.415	0.279	0.345
Car 2	0.543	0.382	0.462
Car 3	0.608	0.440	0.525
Car 4	0.497	0.352	0.424
Car 5	0.575	0.410	0.493
Car 6	0.606	0.436	0.522
Car 7	0.530	0.383	0.457
Car 8	0.464	0.325	0.394
Car 9	0.523	0.363	0.443
Car 10	0.467	0.330	0.398
Car 11	0.617	0.454	0.537
Car 12	0.561	0.396	0.479
Car 13	0.563	0.402	0.483
Car 14	0.512	0.367	0.440
Car 15	0.393	0.278	0.335

Car 16	0.511	0.365	0.438
Car 17	0.534	0.372	0.453
Car 18	0.531	0.369	0.450
Car 19	0.473	0.343	0.408
Car 20	0.581	0.418	0.500
Car 21	0.626	0.463	0.546
Car 22	0.520	0.365	0.442
Car 23	0.395	0.274	0.334
Car 24	0.471	0.320	0.395
Car 25	0.537	0.381	0.459
Car 26	0.603	0.436	0.520
Car 27	0.660	0.495	0.580
Car 28	0.458	0.314	0.385
Car 29	0.678	0.508	0.595
Car 30	0.505	0.372	0.439
Car 31	0.470	0.331	0.400
Car 32	0.494	0.349	0.421
Car 33	0.573	0.408	0.491
Car 34	0.589	0.417	0.503
Car 35	0.632	0.473	0.554
Car 36	0.616	0.456	0.538
Car 37	0.551	0.391	0.471
Car 38	0.602	0.438	0.521
Car 39	0.664	0.503	0.586
Car 40	0.584	0.429	0.508
Car 41	0.540	0.381	0.461
Car 42	0.414	0.286	0.349
Car 43	0.557	0.412	0.486
Car 44	0.466	0.328	0.397
Car 45	0.560	0.397	0.479
Car 46	0.543	0.383	0.463
Car 47	0.565	0.411	0.489
Car 48	0.547	0.391	0.469
Car 49	0.547	0.392	0.470
Car 50	0.518	0.368	0.443
Car 51	0.530	0.373	0.451
Car 52	0.628	0.463	0.547
Maximum	0.678	0.508	0.595
Minimum	0.393	0.274	0.334
Average	0.541	0.388	0.465

Table 4.11. Change of max. deformation compared to the FWRB test data – 85 km/h closing speed

Vehicle	Maximum (g)	Minimum (g)	Average (g)
Car 1	-24%	-49%	-37%
Car 2	-17%	-42%	-29%
Car 3	-11%	-36%	-23%
Car 4	-13%	-39%	-26%
Car 5	-14%	-39%	-27%
Car 6	-13%	-37%	-25%
Car 7	-9%	-34%	-21%
Car 8	-15%	-40%	-28%
Car 9	-19%	-44%	-32%
Car 10	-13%	-38%	-26%
Car 11	-7%	-31%	-19%
Car 12	-16%	-41%	-29%
Car 13	-13%	-38%	-25%
Car 14	-11%	-36%	-23%
Car 15	-11%	-37%	-24%
Car 16	-11%	-37%	-24%
Car 17	-18%	-43%	-31%
Car 18	-19%	-44%	-32%
Car 19	-8%	-34%	-21%
Car 20	-12%	-37%	-24%
Car 21	-6%	-30%	-18%
Car 22	-17%	-41%	-29%
Car 23	-16%	-41%	-29%
Car 24	-24%	-48%	-36%
Car 25	-14%	-39%	-26%
Car 26	-11%	-36%	-23%
Car 27	-3%	-28%	-15%
Car 28	-20%	-45%	-33%
Car 29	-4%	-28%	-15%
Car 30	-16%	-38%	-27%
Car 31	-14%	-40%	-27%
Car 32	-14%	-39%	-27%
Car 33	-14%	-39%	-27%
Car 34	-16%	-41%	-29%
Car 35	-3%	-27%	-15%
Car 36	-5%	-30%	-17%
Car 37	-14%	-39%	-27%
Car 38	-10%	-34%	-22%
Car 39	-1%	-25%	-13%
Car 40	-6%	-31%	-19%
Car 41	-15%	-40%	-28%
Car 42	-18%	-44%	-31%
Car 43	-4%	-29%	-16%

Car 44	-14%	-39%	-27%
Car 45	-15%	-39%	-27%
Car 46	-16%	-41%	-29%
Car 47	-8%	-33%	-20%
Car 48	-13%	-38%	-25%
Car 49	-12%	-37%	-24%
Car 50	-14%	-39%	-26%
Car 51	-16%	-41%	-29%
Car 52	-16%	-38%	-27%
Maximum	-1%	-25%	-13%
Minimum	-24%	-49%	-37%
Average	-13%	-38%	-25%

There is an average of 25% decrease in max. deformation and minimum of 1% decrease compared to FWRB data.

It can be seen in Table 4.11; with calculated maximum safe closing speed (85 km/h) it can be said all vehicles are safer based on deformation values.

The simulations were repeated with stiffness reduction ratio 0.85/0.7.

Table 4.12. Mean acceleration values that occur when each vehicle collides with other vehicles – Stiffness reduced by 0.85/0.7

Vehicle	Maximum (m)	Minimum (m)	Average (m)
Car 1	26.50	17.83	22.07
Car 2	24.53	17.23	20.88
Car 3	25.16	18.20	21.72
Car 4	29.22	20.70	24.96
Car 5	24.62	17.52	21.09
Car 6	24.28	17.45	20.90
Car 7	30.19	21.83	26.05
Car 8	29.74	20.82	25.25
Car 9	24.11	16.75	20.42
Car 10	31.26	22.10	26.67
Car 11	27.27	20.07	23.74
Car 12	24.11	17.01	20.57
Car 13	25.92	18.51	22.24
Car 14	30.11	21.59	25.87
Car 15	38.58	27.29	32.89
Car 16	29.57	21.12	25.36
Car 17	23.94	16.69	20.31
Car 18	23.57	16.38	19.96
Car 19	35.08	25.41	30.27

Car 20	25.95	18.67	22.34
Car 21	27.39	20.26	23.90
Car 22	25.87	18.15	22.00
Car 23	34.06	23.61	28.76
Car 24	23.77	16.15	19.90
Car 25	26.53	18.82	22.68
Car 26	25.21	18.21	21.75
Car 27	27.24	20.41	23.91
Car 28	26.55	18.21	22.33
Car 29	26.42	19.81	23.20
Car 30	35.46	26.14	30.86
Car 31	30.16	21.23	25.68
Car 32	28.82	20.34	24.57
Car 33	25.01	17.82	21.44
Car 34	22.92	16.22	19.58
Car 35	28.93	21.67	25.39
Car 36	28.32	21.00	24.74
Car 37	25.66	18.21	21.95
Car 38	26.30	19.13	22.76
Car 39	28.78	21.82	25.41
Car 40	28.96	21.28	25.18
Car 41	25.74	18.19	21.97
Car 42	31.22	21.52	26.30
Car 43	31.73	23.44	27.65
Car 44	30.37	21.37	25.85
Car 45	25.06	17.78	21.44
Car 46	25.09	17.69	21.39
Car 47	28.82	20.99	24.95
Car 48	27.21	19.46	23.35
Car 49	27.61	19.80	23.73
Car 50	27.96	19.84	23.91
Car 51	25.76	18.13	21.94
Car 52	26.80	19.76	23.35
Maximum	38.58	27.29	32.89
Minimum	22.92	16.15	19.58
Average	27.68	19.80	23.76

Table 4.13. Change of mean acceleration compared to the FWRB test data – Stiffness reduced by 0.85/0.7

Vehicle	Maximum (g)	Minimum (g)	Average (g)
Car 1	-23%	-8%	-38%
Car 2	-14%	1%	-29%
Car 3	-7%	8%	-22%
Car 4	-10%	5%	-25%
Car 5	-11%	4%	-26%
Car 6	-9%	6%	-24%

Car 7	-4%	11%	-20%
Car 8	-12%	3%	-28%
Car 9	-17%	-2%	-32%
Car 10	-10%	6%	-25%
Car 11	0%	15%	-15%
Car 12	-16%	-2%	-31%
Car 13	-20%	-6%	-33%
Car 14	-28%	-16%	-40%
Car 15	21%	42%	0%
Car 16	5%	23%	-12%
Car 17	-15%	0%	-30%
Car 18	-37%	-25%	-48%
Car 19	25%	44%	5%
Car 20	-6%	9%	-22%
Car 21	-28%	-18%	-39%
Car 22	-14%	1%	-29%
Car 23	13%	34%	-7%
Car 24	-14%	2%	-31%
Car 25	-2%	14%	-19%
Car 26	-21%	-8%	-34%
Car 27	6%	20%	-10%
Car 28	-23%	-8%	-37%
Car 29	-16%	-4%	-28%
Car 30	29%	48%	9%
Car 31	14%	34%	-6%
Car 32	0%	17%	-17%
Car 33	-13%	2%	-27%
Car 34	-21%	-7%	-34%
Car 35	6%	21%	-9%
Car 36	3%	18%	-12%
Car 37	-14%	1%	-28%
Car 38	-9%	5%	-23%
Car 39	-7%	6%	-20%
Car 40	-13%	0%	-27%
Car 41	-9%	6%	-25%
Car 42	7%	27%	-13%
Car 43	7%	23%	-9%
Car 44	1%	19%	-17%
Car 45	-17%	-3%	-31%
Car 46	-20%	-6%	-34%
Car 47	3%	19%	-13%
Car 48	-8%	7%	-24%
Car 49	-6%	9%	-22%
Car 50	-24%	-11%	-37%
Car 51	-17%	-3%	-31%
Car 52	8%	24%	-8%
Maximum	29%	48%	9%

Minimum	-37%	-25%	-48%
Average	-7%	8%	-23%

There is an average of 23% decrease in mean acceleration and maximum of 48% increase compared to FWRB data.

Table 4.14. The vehicles that are more unsafe than the FWRB frontal crash test result and number of vehicles they are more unsafe when they collide – based on acceleration, Stiffness reduced by 0.85/0.7

Vehicle	Number of Vehicles	Percentage
Car 7	1	2%
Car 11	3	6%
Car 15	44	85%
Car 16	13	25%
Car 19	48	92%
Car 23	36	69%
Car 25	2	4%
Car 27	13	25%
Car 30	51	98%
Car 31	37	71%
Car 32	3	6%
Car 35	13	25%
Car 36	7	13%
Car 42	19	37%
Car 43	21	40%
Car 44	5	10%
Car 47	7	13%
Car 52	25	48%

Table 4.15. Max. deformation values that occur when each vehicle collides with other vehicles – Stiffness reduced by 0.85/0.7

Vehicle	Maximum	Minimum	Average
Car 1	0.593	0.399	0.494
Car 2	0.776	0.545	0.661
Car 3	0.870	0.629	0.751
Car 4	0.710	0.503	0.606
Car 5	0.822	0.585	0.704
Car 6	0.867	0.623	0.746
Car 7	0.757	0.547	0.653
Car 8	0.663	0.464	0.563
Car 9	0.747	0.519	0.632
Car 10	0.667	0.472	0.569
Car 11	0.881	0.649	0.767

Car 12	0.802	0.566	0.684
Car 13	0.805	0.575	0.691
Car 14	0.732	0.525	0.629
Car 15	0.561	0.397	0.479
Car 16	0.730	0.521	0.626
Car 17	0.763	0.532	0.647
Car 18	0.759	0.527	0.643
Car 19	0.676	0.490	0.583
Car 20	0.830	0.597	0.715
Car 21	0.895	0.662	0.781
Car 22	0.743	0.521	0.632
Car 23	0.565	0.392	0.477
Car 24	0.674	0.458	0.564
Car 25	0.767	0.544	0.656
Car 26	0.862	0.623	0.744
Car 27	0.944	0.707	0.829
Car 28	0.655	0.449	0.551
Car 29	0.968	0.726	0.851
Car 30	0.721	0.532	0.628
Car 31	0.672	0.473	0.572
Car 32	0.706	0.498	0.602
Car 33	0.818	0.583	0.701
Car 34	0.841	0.595	0.719
Car 35	0.903	0.676	0.792
Car 36	0.880	0.652	0.769
Car 37	0.787	0.558	0.673
Car 38	0.861	0.626	0.745
Car 39	0.949	0.720	0.838
Car 40	0.835	0.614	0.726
Car 41	0.771	0.545	0.658
Car 42	0.592	0.408	0.499
Car 43	0.796	0.588	0.694
Car 44	0.667	0.469	0.567
Car 45	0.800	0.568	0.684
Car 46	0.777	0.547	0.662
Car 47	0.808	0.588	0.699
Car 48	0.782	0.559	0.671
Car 49	0.781	0.560	0.671
Car 50	0.740	0.526	0.633
Car 51	0.757	0.533	0.645
Car 52	0.897	0.661	0.781
Maximum	0.968	0.726	0.851
Minimum	0.561	0.392	0.477
Average	0.774	0.554	0.665

Table 4.16. Change of max. deformation compared to the FWRB test data – Stiffness reduced by 0.85/0.7

Vehicle	Maximum	Minimum	Average
Car 1	9%	-27%	-10%
Car 2	19%	-17%	1%
Car 3	27%	-8%	10%
Car 4	24%	-12%	6%
Car 5	22%	-13%	5%
Car 6	24%	-11%	7%
Car 7	30%	-6%	12%
Car 8	21%	-15%	3%
Car 9	15%	-20%	-3%
Car 10	24%	-12%	6%
Car 11	34%	-2%	16%
Car 12	20%	-16%	2%
Car 13	24%	-11%	7%
Car 14	28%	-8%	10%
Car 15	27%	-10%	8%
Car 16	27%	-9%	9%
Car 17	17%	-19%	-1%
Car 18	16%	-20%	-2%
Car 19	31%	-5%	13%
Car 20	26%	-10%	8%
Car 21	35%	0%	18%
Car 22	19%	-16%	1%
Car 23	21%	-16%	2%
Car 24	9%	-26%	-9%
Car 25	23%	-13%	5%
Car 26	28%	-8%	10%
Car 27	38%	3%	21%
Car 28	14%	-22%	-4%
Car 29	38%	3%	21%
Car 30	20%	-12%	4%
Car 31	23%	-14%	4%
Car 32	23%	-13%	5%
Car 33	23%	-13%	5%
Car 34	20%	-15%	2%
Car 35	38%	4%	22%
Car 36	36%	1%	18%
Car 37	22%	-13%	5%
Car 38	29%	-6%	12%
Car 39	42%	7%	25%
Car 40	34%	-2%	16%
Car 41	21%	-14%	3%
Car 42	17%	-20%	-2%
Car 43	37%	1%	20%

Car 44	23%	-13%	5%
Car 45	22%	-13%	4%
Car 46	20%	-16%	2%
Car 47	32%	-4%	14%
Car 48	25%	-11%	7%
Car 49	26%	-10%	8%
Car 50	23%	-13%	5%
Car 51	20%	-16%	2%
Car 52	20%	-11%	5%
Maximum	42%	7%	25%
Minimum	9%	-27%	-10%
Average	25%	-11%	7%

There is an average of 7% increase in max. deformation and maximum of 42% increase compared to FWRB data.

The simulations made with 2 different stiffness reduction values were examined together and the acceleration and deformation changes interval in the vehicle fleet were created in Table 4.17.

Table 4.17. Interval of mean acceleration and max. deformation values according to simulations of different stiffness values

Vehicle	Max. Deformation	Mean Acceleration
Car 1	-%10 and %0	-%38 and -%44
Car 2	%1 and %11	-%29 and -%36
Car 3	%10 and %21	-%22 and -%29
Car 4	%6 and %17	-%25 and -%32
Car 5	%5 and %16	-%26 and -%33
Car 6	%7 and %18	-%24 and -%31
Car 7	%12 and %24	-%20 and -%27
Car 8	%3 and %14	-%28 and -%34
Car 9	-%3 and %7	-%32 and -%38
Car 10	%6 and %17	-%25 and -%32
Car 11	%16 and %28	-%15 and -%23
Car 12	%2 and %12	-%31 and -%37
Car 13	%7 and %17	-%33 and -%39
Car 14	%10 and %21	-%40 and -%45
Car 15	%8 and %19	%0 and -%9
Car 16	%9 and %20	-%12 and -%21
Car 17	-%1 and %9	-%30 and -%37
Car 18	-%2 and %8	-%48 and -%53

Car 19	%13 and %25	%5 and -%5
Car 20	%8 and %19	-%22 and -%29
Car 21	%18 and %30	-%39 and -%45
Car 22	%1 and %12	-%29 and -%36
Car 23	%2 and %12	-%7 and -%16
Car 24	-%9 and %1	-%31 and -%37
Car 25	%5 and %16	-%19 and -%26
Car 26	%10 and %21	-%34 and -%40
Car 27	%21 and %34	-%10 and -%18
Car 28	-%4 and %5	-%37 and -%43
Car 29	%21 and %33	-%28 and -%35
Car 30	%4 and %15	%9 and -%1
Car 31	%4 and %15	-%6 and -%15
Car 32	%5 and %15	-%17 and -%25
Car 33	%5 and %16	-%27 and -%34
Car 34	%2 and %13	-%34 and -%40
Car 35	%22 and %34	-%9 and -%18
Car 36	%18 and %31	-%12 and -%20
Car 37	%5 and %15	-%28 and -%35
Car 38	%12 and %23	-%23 and -%31
Car 39	%25 and %38	-%20 and -%27
Car 40	%16 and %28	-%27 and -%34
Car 41	%3 and %14	-%25 and -%32
Car 42	-%2 and %8	-%13 and -%21
Car 43	%20 and %32	-%9 and -%17
Car 44	%5 and %15	-%17 and -%24
Car 45	%4 and %15	-%31 and -%37
Car 46	%2 and %12	-%34 and -%40
Car 47	%14 and %26	-%13 and -%21
Car 48	%7 and %18	-%24 and -%31
Car 49	%8 and %19	-%22 and -%29
Car 50	%5 and %16	-%37 and -%43
Car 51	%2 and %13	-%31 and -%38
Car 52	%5 and %15	-%8 and -%17
Maximum	%25 and %38	%9 and -%1
Minimum	-%10 and %0	-%48 and -%53
Average	%7 and %18	-%23 and -%30

When the average values are considered, it can be said that the change of values related to FWRB test data may be in the following ranges:

- Mean acceleration: Decrease between %23 and %30
- Maximum deformation: Increase between %7 and %18

The 5 vehicles with the best results and the 5 vehicles with the worst results are shown in Tables 4.18 and 4.19 respectively with their specifications and overall front star ratings.

Table 4.18. The 5 worst-performing vehicles and their features.

Vehicle Number	Mass (kg)	Loading Stiffness (N/m)	Unloading Stiffness (N/m)	Segment	Overall Front Star Rating	Model Year
Car 39	1284.8	706520.23	429060.56	B	4	2016
Car 35	1337.4	776858.19	712922.01	B	5	2016
Car 27	1430.5	748433.2	86527.78	B	4	2015
Car 29	1475.5	729731.8	395859.82	C	5	2015
Car 43	1265.8	914491.22	508722.37	B	4	2016

Table 4.19. The 5 best-performing vehicles and their features.

Vehicle Number	Mass (kg)	Loading Stiffness (N/m)	Unloading Stiffness (N/m)	Segment	Overall Front Star Rating	Model Year
Car 1	2073.3	1680657.7	2049281.84	E	4	2011
Car 24	2279.8	1458635.9	2655119.81	S	5	2014
Car 28	1960.3	1440745.07	564729.59	D	4	2015
Car 9	2101.3	1229628.25	997258.86	D	5	2012
Car 18	2154.7	1212736.81	1548558.5	D	5	2014

Best and worst performed vehicles are determined based on maximum deformation value as there is no significant mean acceleration increase due to stiffness reductions. These results show that vehicles that receive 4 or 5 stars in the FWRB frontal crash test are not as safe in head-on collisions. It is seen that the worst-performing vehicles have low stiffness and mass.

For example, Car 39 is 24% lighter than the average mass of the selected 52 vehicles and 77% lighter than the heaviest vehicle. It also has the least stiffness and 35% less stiffness than the average stiffness. All worst-performed vehicles have more maximum deformation of all collisions than FWRB frontal crash test results.

Finally, loading stiffness vs average change of maximum deformation and mass vs average change of maximum deformation compared with FWRB frontal crash test results plotted in Figure 4.7 and Figure 4.8.

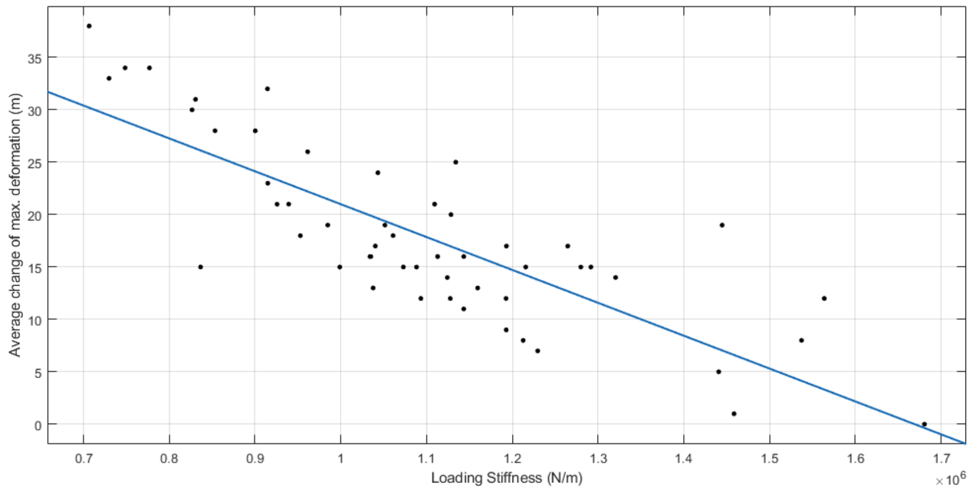

Figure 4.7. Loading stiffness vs average change of max. deformation

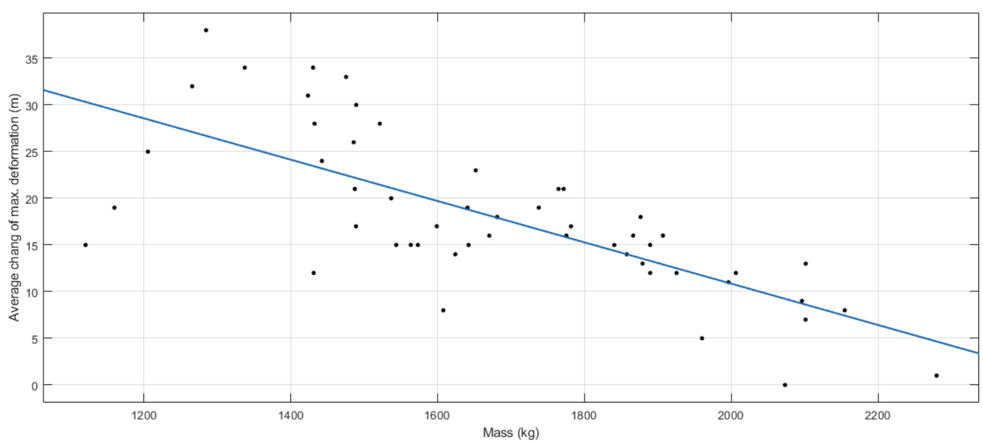

Figure 4.8. Mass vs average change of max. deformation

5. CONCLUSION AND RECOMMENDATION

It can be seen from the test results, as expected, when the vehicles collide with each other in real world, they do not show the success they showed in the NHTSA FWRB tests. This is a result of the vehicle compatibility issue. In addition, in this study, the structural performances of the vehicles are evaluated only, but the performances of safety systems such as airbags and seatbelts also affect the star ratings of crash tests results.

Also, less stiff vehicles and lighter vehicles are also seen to be more unsafe when colliding with stiffer or heavier vehicles.

In collision simulations with maximum safe closing speed, it has been observed that all vehicles are safer as both vehicles absorb less energy than FWRB frontal crash tests.

The results show that FWRB crash tests do not reflect real world results. In addition, these crash tests encourage the vehicles to be stiffer as it is seen that stiffer vehicles are more successful in the tests. Although it is safe to increase the stiffness for the safety of the vehicle itself, it is not meaningful to solve crash safety problems in real life, as it reduces the safety of the less stiff crash partner vehicle. Therefore, it can be suggested to reduce stiffness of vehicles with high stiffness.

In this thesis, compatibility of the vehicles was investigated in terms of stiffnesses and masses with a stiffness reduction assumption to represent geometric incompatibilities. Regardless of the effect of mass and stiffness, geometric incompatibility should also need to be investigated separately.

Since the proposed model is only valid for 100% overlap impacts, more complex models can be constructed to estimate offset crashes. Also, models can be used with finite element methods to obtain more accurate results.

Testing organizations should implement test procedures that represent head-on collisions. Certain geometric regulations may be introduced for vehicles, or it may be recommended to design by targeting a lower stiffness value for vehicles that are over safe in FWRB tests.

In addition, recommending the maximum safe closing speed as the legal speed limit for most roads seems unrealistic in today's conditions, but it can be considered for roads with possibility of head-on frontal impact. Based on the maximum safe closing speed found in this study (85 km/h), approximately 45 km/h speed limit can be applied on these types of roads. But to find a more appropriate speed limit, the maximum closing speed calculations should be repeated with more vehicles.

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