ISSN 1648-4142 TRANSPORT
http:/www.vtu.lt/english/editions

TRANSPORT – 2004, Vol XIX, No 4, 184–190

RESEARCH INTO OCCUPANT'S MOTION IN VEHICLES DURING CRASHES

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Received 2004-01-07; accepted 2004-04-01

Abstract. Traffic accidents depend on many factors and circumstances. Important data are registered by taking photos of the accident place, measuring the deformations of vehicles and skidding and sliding traces. Weather conditions, drivers' and pedestrian's actions are also taken into account. However the existing data are far from sufficient to conduct a research into traffic accidents. In such cases mathematical modelling and the application of computer programs are very helpful.
This article deals with the processes during the collision of vehicles as well as the occupant's dynamics inside the vehicle. The research studies on what the occupant motion depends and what is the power balance between the occupant and safety means. The article offers a way of evaluating injuries, measuring the occupants' acceleration and velocity, taking into account different distances inside the vehicle during an accident.

Keywords: accident, occupant, injuries, speed, acceleration.

1. Introduction

Approximately 500 000 people are killed and 20 million injured in vehicle crashes in the world every year. Fast growing car numbers cause more and more problems in traffic safety. In western countries its growth is 1,5 times larger than in Lithuania, but the number of accidents is much lower. Due to long and persistent work which is being actively continued nowadays according to crash statistics analysis, crash causes and the comparison with the situation in other countries, a number of people killed in traffic accidents has decreased from 80 to 50,000. However the number of cars during this period has doubled.

Lithuania over the last 20 years annually loses about 850 persons,.5500 persons suffer from complicated traumas, often causing disability. Over the last 20 years every 36th person has been injured in traffic accidents. The recent 10-year accident rate analysis shows that since 1992 till 1998 the number of injured as well as killed rose sharply. In 1998 the number of traffic casualties was: 6445 injured and 829 dead. Since 1999 till 2001 both numbers slightly dropped, but till 2002 they increased and now there are 6090 injured and 700 dead [1].

Analysing the world's and Lithuania's traffic accident data it has become obvious that over a half of all casualties are due to drivers (26,44 %); to passengers (34,28 %); to pedestrians (40 %).

According to the age the injured adults make 78 % and dead 85 %. The rest are children.

Most passengers and drivers suffer during vehicle collisions, overturns or meeting obstacles.

In order to produce a safe car and to avoid the most dangerous injures it is important to know how an occupant moves in a car during an accident, on what parameters occupant dynamics depends, what surfaces inside the car an occupant smashes and which body parts are the most vulnerable.

Generalizing the conducted researches it is possible to affirm that an occupant motion depends on the following aspects:

In car collision cases:
- Front crash;
- Side crash;
- Overturn;
- Rear crash.

Person's places in a car during accidents:
- Driver;
- Passenger on the front seat;
- Passenger on the back seat.

Support systems:
- Safety belts;
- Air bags;
- Child's chair.

Variety of colliding vehicles:
- Their type, height, weight;
- Running mode before the collision (braked, unbraked, accelerating, moving angulary, skidding sideways, falling, etc);

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– Total colliding velocities;

– How vehicles move after collision: spin round the centre of gravity, skid – slip until final stop or overturn, or run from the road, etc.

Appealing to traffic statistics both in the world and in Lithuania we can confirm that 60 % of collisions is frontal, i.e. vehicle front part collides with moving or stationary objects.

2. Processes in cars during their collisions

Analysing any car collision at a time interval it is possible to differentiate two phases since the beginning of a collision till its complete stop [2].

The first collision phase is when cars crash into each other or into an immovable object and get deformed.

A car crashes with certain acceleration. It sharply decreases and its direction changes. Meanwhile a human body by inertia moves in the moving direction of the car (Fig 1). During the collision a man is affected by the impact power, which is directly proportionate to crash acceleration. The crash impact is transferred through bordering systems: safety belt, air bag, seat, etc. So while calculating it is important to evaluate their indirect action characteristics. They appear because of ineffective safety belt deformation, inadequate tension, sometimes because of clothes. While using an air bag ineffective deformation occurs because of the distance between an air bag and a person.

The second colliding phase is when cars or a car and an obstacle start pushing each other and separate. A car gets deformed till a certain limit and under the influence of elasticity and centrifugal force bounces back from the object. At this moment an air bag becomes flat and belt tension decreases. The passenger's acceleration direction coincides with car acceleration, i.e. operator strikes against the seatback (Fig 2).

If the collision force is eccentric, i. e. angular acceleration and tangential force appear, then vehicles change their moving direction or spin. As the contact is extremely brief it is considered that the position

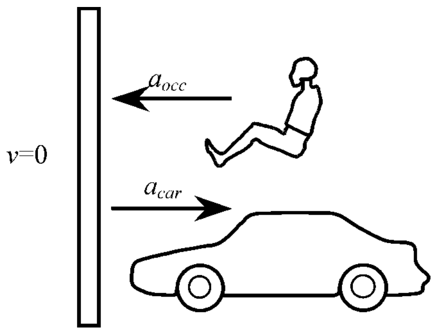


Fig 1. First car crash phase

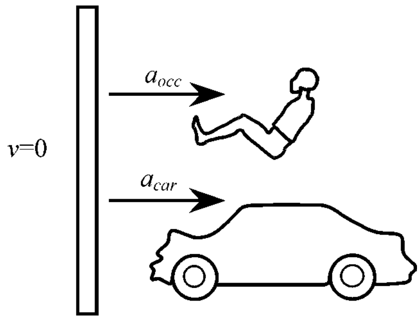


Fig 2. Second colliding phase

hardly changes, consequently a general direction of deformations as a rule coincides with adequate relative speed direction or slightly deviate. If the direction of deforming forces is precisely determined, it is possible to set the collision (attack) angle. This fact is of high importance in a technical expertise.

At the collision moment kinetic energy is absorbed by the car contacted part. In case the collision is very strong, a part of energy is transmitted to interior. The larger deformation area, the smaller probability to get injuries.

3. Methodology of research of occupant's dynamism in collisions

On purpose to find out more about occupant's dynamism and its affecting forces, a simplified model of three occupant mass centres is used in Fig 3.

While applying this model or a system: obstacle-car-occupant it is possible to describe it as a system of a few occupants. Then it is acceptable that classical mechanical laws can be applied to each mass separately [3].

A human body is being treated as a set chain composed of three main parts: head, thorax and pelvis. The forces affecting a human body could be described according to the second Nuton law:

$$m_{head} \times a_{head} = F_{head};$$
$$m_{thorax} \times a_{thorax} = F_{thorax};$$
$$m_{pelvis} \times a_{pelvis} = F_{pelvis}.$$

While analysing an occupant motion in a car dur-

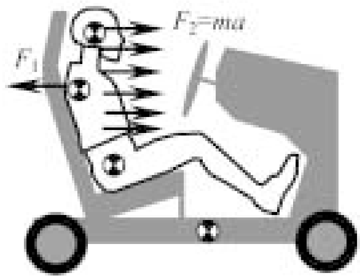


Fig 3. Simplified model of three occupant mass centres

ing the crash we accept the facts that:

1. Car acceleration deceleration does not depend on occupant acceleration deceleration

$a_{car} >> a_{occupant.}$

2. Car deformation does not depend on occupant and safety systems.

Let us analyse an uncomplicated frontal collision when car interior stays non-deformed and the decrease of general occupant energy is an invariable measure and equals to kinetic energy existing at the beginning of the collision.

Such simplifications allow us to analytically analyse the characteristics of car deformations and the lowest possible occupant's head, thorax and pelvis acceleration deceleration during collisions. The essence of the analyses is setting of constants of the smallest possible occupant's acceleration and deceleration using the total occupant's forward displacement.

It is acceptable that car and occupant velocities, accelerations and shift distance are time functions:
car acceleration $a_{Fzx}(t)$;
car velocity $v_{Fzx}(t)$;
car travel $s_{Fzx}(t)$;
occupant acceleration $a_{Occx}(t)$
(head, thorax and pelvis baseline points);
occupant velocity $v_{Occx}(t)$
(head, thorax and pelvis baseline points);
occupant travel $s_{Occx}(t)$
(head, thorax and pelvis baseline points);
the largest body displacement $s_{Occx}(t)$
(head, thorax and pelvis baseline points).

At the initial phase of collision the occupant moves forward out of inertia [3, 4]. As the car after the collision moves back so the occupant's travel forward decreases. You can see the displacement and time in the following picture (Fig 4):

It is possible to present a mathematical model for motion analyses.

Acceleration is accepted as a fixed measure. a = const. Occupant (head, thorax and pelvis) having a certain mass is displaced (covers a certain distance):

$$s = s_{interior\,total} + s_{Fz}\left(t_{thorax\,rebound}\right) - s_{thorax}\left(t_{start}\right), \qquad (1)$$

where $s_{int\,erior\,total}$ – obstacle, distance in a car from thorax (body) till the closest obstacle, that occupant can be displaced; $s_{Fz}\left(t_{thorax\,rebound}\right)$ – distance, that the car covers, until the collision moment when thorax hits an obstacle; $s_{thorax}\left(t_{start}\right)$ – distance that thorax (body) covers at the initial moment of collision.

Time required to reach the final point and kinetic energy disappearance is equal to:

$$t_{end} = t_{start} + \left(\frac{2 \cdot s_{req}}{a_{const}}\right)^{0,5}, \qquad (2)$$

s_{req} – distance, required for the body not to be injured during the accident. It is calculated from the following formula:

$$s_{req} = \frac{1}{2} v \cdot t = \frac{1}{2} a \cdot t^2 = \frac{E_{kin}}{m \cdot a_{const}}. \qquad (3)$$

The time at the beginning of the collision t_{start}, during which thorax (occupant) is displaced by the distance $s_{thorax}\left(t_{start}\right)$, acceleration function:

$$t_{start} = f\left(a_{thorax} = a_{const}\right).$$

After calculating s and s_{req}, the following variants are possible:

$s > s_{req}$ – occupant gets injured, safety decreases while s increases; $s < s_{req}$ – occupant does not suffer, safety increases; $s \approx s_{req}$ – occupant does not suffer.

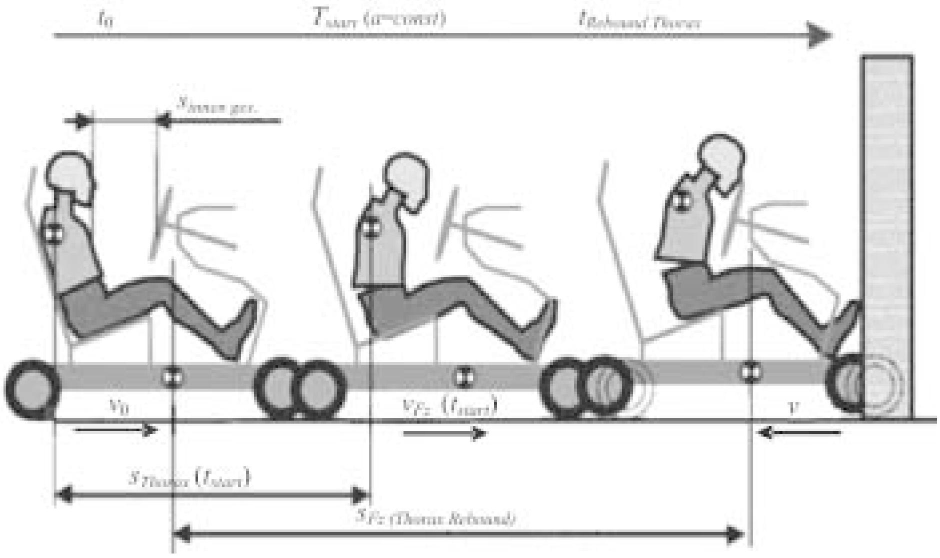


Fig 4. Occupant motion until repercussion

If variants two or three are received, modelling is finished. If variant one is received, then calculations are to be continued.

The energy E is set at the beginning of the collision, when t_{start}. This energy depends on the occupant velocity at the collision moment:

$$E(t_{start}) = E_{kin} = \frac{1}{2} m_{thorax} \cdot v_{thorax}^2 (t_{start}), \qquad (4)$$

where: m_{thorax} – thorax weight; v_{thorax} – thorax velocity at the collision moment.

Using the received data it is possible to calculate a coefficient of injuries.

4. Injury Assessment

Euro NCAP (European New Car Assessment Programme) has the highest reputation in analysing collisions. Through different tests it has set head, thorax and legs injuries, probability and extent in cases of frontal collisions [5].

Head injuries are assessed by HIC (Head Injury Criterion) coefficient Table 1.

Table 1. Head injury coefficient meanings

HIC factor	
Meaning	Injury size
750	Low probability that brains will be injured
750–1250	Probable brains injury
1250	Brains injury

According to HIC scale, when meanings are below 500, probability to get injured is very low. At 1000 approximately one out of six passengers might be in danger after skull fraction or brain damage. When HIC is above 2000 almost all the passengers get their heads injured. In such cases either death follows or long hospitalisation.

HIC test is conducted using a 5 kg head model which is connected with a dummy. Impact speed meter is constructed into the 'head' and used to measure the impact velocity [6].

Leg injuries are assessed by force (kN) affecting the upper part of the leg (Table 2).

Thorax injuries and probability are assessed by deformation deapth of chest (ribs) Table 3.

Head injury coefficient can be calculated using formula [6]:

Table 2. Legs injury meanings

Legs injury	
Force, kN	Injury size
< 5	Low probability to get legs injured
5–10	Probable legs traumas
> 10	High probability to get injured

Table 3. Chest injury meanings

Chest injury	
Deformation mm	Injury size
50	Low probability to injured chest
50–75	Probable serious traumas
>75	High probability to get injured

$$HIC = \left[\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a dt \right]^{2.5} \cdot (t_2 - t_1), \qquad (5)$$

where: t_1 and t_2 – any time moments during the impact between the earlier mentioned t_{start} and end t_{end} time; a– acceleration in time interval $t_1 - t_2$.

Calculations are done under the asumption that a frontal impact is ideal, occupant body is one-piece and in accidents it moves rectillineally. It is also assumed that occupant acceleration is invariable (a=*const*). For calculations formulas (1)–(4) are used. Motion acceleration can be expressed by ratio $a = \frac{a_t}{g}$, then in a general case the occupant motion during the accident $s = s_0 + v_0 \cdot t + \frac{1}{2} a \cdot t^2$, but as analysis is simplified (a = *const*), so $s = \frac{1}{2} a \cdot t^2$. Since an occupant motion $v = v_0 + a \cdot t$. Having in mind a=const, so $v = a \cdot t$. Occupant motion travel during accident $s = \frac{v^2}{2a}$. However an occupant during the accident moves in the car interior, so his maximum travel is as long as up to the closest obstacle (windshield, panel, etc.). Time required to gain the initial acceleration equals to the ratio of velocity and acceleration $t = \frac{v}{a}$. Since an occupant is likely to move up to an obstacle, opposition system will start functioning when an occupant moves distance s until the obstacle. According to formula (3) $t_2 = t_1 + \sqrt[2]{\frac{2s}{a}}$, as t_1=0 so $t_2 = \sqrt[2]{\frac{2s}{a}}$. Occupant's velocity during his impact is $v = a \cdot t_2$.

Using the formulas it is possible to calculate the occupant motion accelerations, their duration, occupant motion during an impact against opposing system and *HIC*. Since the acceleration is invariable so its volumes are selected.

Calculation in a few cases:

- when the distance from occupant till opposing system is s= occupant acceleration a_1=10 g, 20 g, 30 g, 40 g, 50 g, 60 g.
- when s_2 = 0,4 m, occupant acceleration a_1= 1 g, 10 g, 20 g, 30 g, 40 g, 50 g.
- when s_3 = 0,6 m, occupant acceleration a_1= 1 g, 10 g, 20 g, 30 g, 40 g, 50 g.

Received results are included into Table 4 and presented in Figs 5–7.

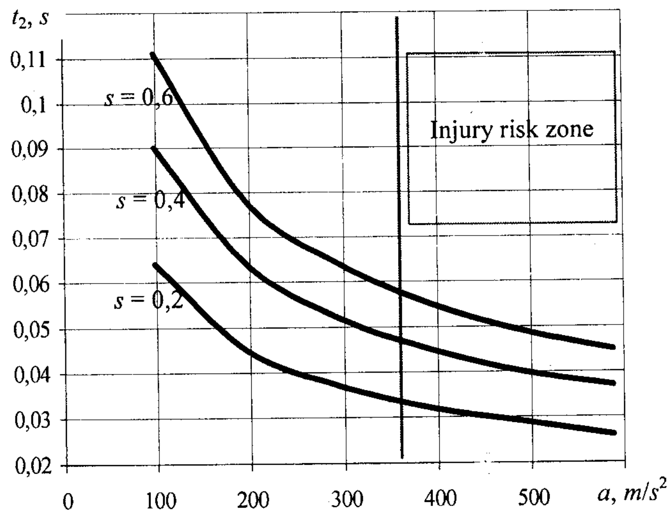


Fig 5. Occupant acceleration dependability on time

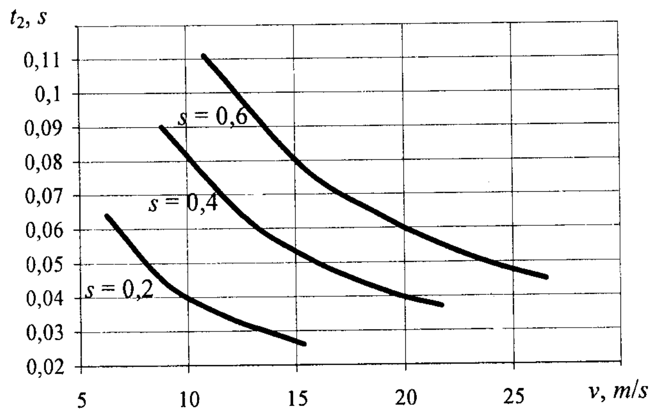


Fig 6. Occupant velocity dependability on time

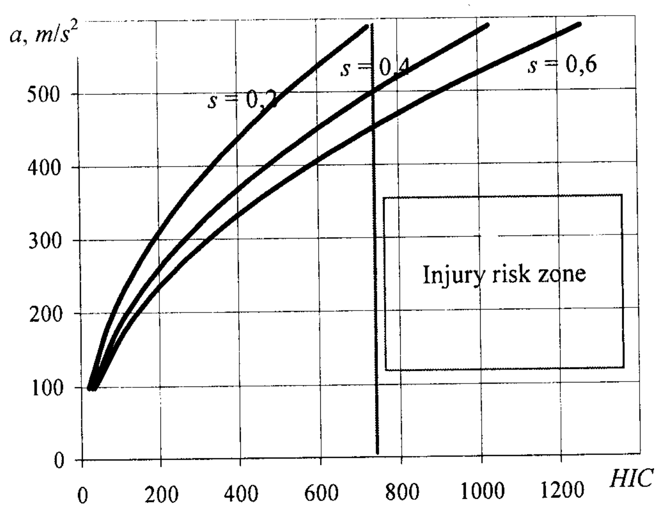


Fig 7. *HIC* dependability on acceleration

Table 4. The count results

s, m	*a, m/s²*	t_2*, s*	*v, m/s*	*HIC*
0,2	98,1	0,064	6,264	20,19
	196,2	0,045	8,859	80,77
	294,3	0,037	10,85	181,73
	392,4	0,032	12,58	323,08
	490,5	0,029	14,007	504,81
	588,6	0,026	15,344	726,93
0,4	98,1	0,09	8,859	28,55
	196,2	0,064	12,528	114,22
	294,3	0,052	15,344	257,01
	392,4	0,045	17,718	456,91
	490,5	0,04	19,809	713,92
	588,6	0,037	21,7	1028
0,6	98,1	0,111	10,85	34,97
	196,2	0,078	15,344	139,89
	294,3	0,064	18,793	314,77
	392,4	0,055	21,7	559,59
	490,5	0,049	24,261	874,37
	588,6	0,045	26,557	1259

5. Force balance between an occupant and safety means

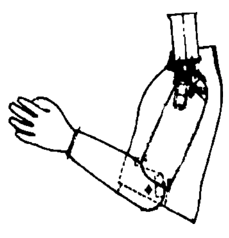
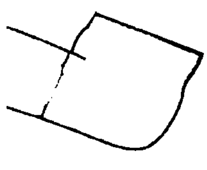
The basic means insuring safety are airbags and safetybelts. In order to better understand the processes occuring during accidents it is important to know occupant and safety means interaction and occupant's internal reactions. We need:

- to determine occupant affecting forces arising from his contact with safety means;
- to assess the volumes of all forces, accelerations and their direction in local and absolute systems of axes;
- to make complete forces balance for head, thorax and pelvis including the forces operating in an occupant body.

In order to better understand what safety means forces affect an occupant in accidents, he is split into 3 main parts (head, thorax and pelvis) and it is assumed that each part moves rectilineally. The forces occuring because of a contact with car parts are in Table 5 [3].

The work of safety means is possible to asses the slowing down of affecting forces and separate body parts centres of gravity. Safety systems work is described using the following formula:

Table 5. The forces occuring because of a contact with car parts

Affecting forces	Body part
Force from contact with airbag. Force from contact with steering wheel and interior. Force from head interaction with neck.	Head 
Force from contact with safety belt. Force from contact with airbag. Force from contact with steering weel and interior. Force from chest position change among neck, vertebra and chest spondils. Contact force between chest and abdomen.	Chest 
Force from contact with safety belt. Force from contact with airbag. Contact force between chest and abdomen. Force from contact with seat and its back. Force from pelvis position change with legs.	Pelvis 

$$W = \int F \cdot ds_{s.c} = \int F \cdot \frac{ds_{s.c}}{dt} \cdot dt = \int F \cdot v_{s.c} \cdot dt, \quad (6)$$

where: $s_{s.c}$ – absolute any centre of gravity travel; $v_{s.c}$ – any centre of gravity velocity; F – forces of safety systems.

This safety system work has a direct connection with separate body parts centres of gravity displacement. It is determined by car travel and relative occupants push forward in respect to the car. Adequately safety systems work can be analysed as the sum of separate movements performed by a moving car and an occupant moving forward in respect to the car [3]:

$$W_{general} = W_{deceleration} + W_{deformation}, \quad (7)$$

$$W_{deceleration} = \int F_{safe} \cdot ds_{car}, \quad (8)$$

$$W_{deformation} = \int F_{safe} \cdot ds_{occ}. \quad (9)$$

Assessing that any force $\vec{F} = m \cdot \vec{a}_{c.g.}$, we receive:

$$W_{c.g.\ general} = \int F_{c.g.\ general} \cdot ds_{c.g.} = m \cdot \int a_{c.g.} \cdot v_{c.g.} \cdot dt, \quad (10)$$

where: $a_{c.g.}$ – any centre of gravity acceleration, m – body (thorax, head, pelvis) mass.

6. Conclusions

Received data allow to set what distance in the car to the obstacle is the safest.

1. After research it is possible to say that cases of an occupant motion in a car depend on collision case, sitting place and safety systems.

2. According to traffic statistics in the world and in Lithuania it is obvious that 60 % of accidents is frontal collisions.

3. While applying a mathematical motion model it has become clear that after calculating occupant travel s and necessary body travel s_{reik}, the following versions are possible:

$s > s_{req}$ – passenger suffers, safety increases, if s decreases;

$s < s_{req}$ – passenger does not suffer, safety increases;

$s \approx s_{req}$ – passenger does not suffer.

4. Making further analyses when a passenger suffers and gets injured, velocity and acceleration dependability on time has been surveyed, taking into account different distance to the obstacle in the car. It has been set that the larger $s_{obstacle}$ the higher velocity the body reaches. Risk zone is reached when velocity during 0,02 s reaches 20 m/s limit, distance $s_{obstacle}$ – 0,4 m.

5. Having analysed *HIC* injuries it was concluded that the longer the distance to the obstacle and the greater velocity, the larger possibility to be deadly in-

jured. Risk zone starts when sobst = 0,4 m, acceleration reaches 500 m/s.

6. The performance of human safety ensuring systems could be determined by slowing down the affecting forces and separate body parts centers of gravity Adequately, the performance of safety systems could be analysed as a sum of different kinds of movements which are completed by a running car and a human being provisory moving forward in respect to the car.

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