# Evaluation of passenger riding comfort of a rail vehicle by means dynamic simulations

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**Abstract.** Dynamical analysis plays a key role in development and optimalization of rail vehicles. The article deals with simulation analysis of a rail vehicle with an active tilting system of the vehicle body, design of the rail vehicle in CAD program CATIA and dynamical analysis in program SIMPACK, with the RAIL expansion. Such body mounting on vehicle bogies is significantly more complicated than the design of conventional rail vehicles. The purpose of this type of body mounting is to increase the size of body tilt during ride in a curve and thus reduce the lateral unbalanced acceleration affecting the passengers, or allow higher driving speed in a curve with the same radius while keeping the lateral acceleration value respectively. Eight variants of different velocity, vehicle occupancy and setting of the tilting mechanism were analyzed. We determined the average value of passenger comfort from the simulation results. We have determined the value of passenger comfort during the ride in a curve from the simulation results.

**Keywords:** dynamical model, railway vehicle, dynamical analysis, mean comfort standard method, Comfort on Curve Transitions

## 1 Introduction

Dynamical analysis plays a key role in development and optimalization of railway rolling stock [1-6]. Simulation programs make it possible to perform analysis in different ways and thus help to optimize the financial and time requirements in comparison with testing of a rail vehicle using measuring device in real conditions [7, 8]. The computer analysis of rail vehicles will be widely used and continually developed in the future [9-14].

The dynamical behavior of a rail vehicle is evaluated by special qualitative indexes in relation to safety [15, 16]. The indexes include quantitative measurement of ride quality, vehicle stability and vehicle ability to ride in curve [17-20]. The tilting bogie mechanism provides good comfort for passengers also in case of high unbalanced lateral acceleration generated at higher speed in curve [21, 22].

In the paper we focused on the ride comfort of passengers in a rail vehicle with a tilting bogie riding along a defined track in relation to STN EN 12299:2009 standard. The standard

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defines five indexes of ride comfort and we have focused on Mean Comfort Standard Method $N_{MV}$ and Comfort on Curve Transitions $P_{CT}$ [11].

## 2 Comfort index

Mean comfort – perceived comfort level, continuously adjusted, as evaluated through measurement on a long - time basis (at least some minutes). The lateral acceleration measured on the floor of the vehicle body has to be known for Mean Comfort calculation. A scale for the comfort index $N_{MV}$ is given in Table 1. The $N_{MV}$ comfort index is calculated on the basis of the Equation (1):

$$N_{MV} = 6 \cdot \sqrt{\left(a_{XP95}^{W_d}\right)^2 + \left(a_{YP95}^{W_d}\right)^2 + \left(a_{ZP95}^{W_b}\right)^2}, \tag{1}$$

where:
- $a$ – acceleration values [m·s$^{-2}$],
- $W_d$, $W_d$, $W_b$ – superscript index relates to the weighted frequency values in accordance with the weighting curve (vertical, horizontal direction) [-],
- $X$, $Y$, $Z$ – subscript index relates to the measured direction of sensor (X – axis longitudinal, Y – axis: lateral , Z – axis: vertical) [-],
- *95* – subscript index indicating the percentile used (95 for the 95th percentile) [%],
- $P$ –subscript indices related to P: the floor interface [-],
- $MV$ – type of comfort index ($MV$ = mean comfort standard method) [-].

**Table 1.** Scale for the $N_{MV}$ comfort index [20]

| | |
|---|---|
| $N < 1.5$ | Very comfortable |
| $1.5 \le N < 2.5$ | Comfortable |
| $2.5 \le N < 3.5$ | Medium |
| $3.5 \le N < 4.5$ | Uncomfortable |
| $N \ge 4.5$ | Very uncomfortable |

Comfort on Curve Transitions is calculated on the basis of accelerometer and gyroscope measurements. These are carried out at different points on the floor. The assessment of passenger comfort according to $P_{CT}$ is useful in situations where curve transitions make a significant contribution to the passenger´s perception of comfort. It gives a measure of the passenger comfort for an individual transition curve without evaluation of cumulative effects. It is applicable to all vehicles and at any speed [3].

Wheel-rail contact geometry normally has little influence on Comfort on Curve Transitions evaluated as $P_{CT}$. No specific recommendations are needed.

The $P_{CT}$ comfort index is calculated on the basis of the Equation (2) with constants according to Table 2:

$$P_{CT} = (A\ddot{y} + B\dddot{y} - C) + D\dot{\vartheta}^E, \tag{2}$$

where:
- $\ddot{y}$ – the maximum absolute value of lateral acceleration in the vehicle body, in the time period between the beginning of transition curve and the end plus 1,6 s [m·s$^{-2}$],
- $\dddot{y}$ – the maximum absolute value of lateral jerk in the transition curve, in the time period between 1 s before the beginning of the transition curve, and the end of the transition, expressed in [m·s$^{-3}$],

- $\dot{\vartheta}$ – the maximum absolute value of roll velocity, in the time period between the beginning and the end of the transition curve [rad·s$^{-1}$],
- *A, B, C, D, E* – constants for $P_{CT}$ comfort index (Table 2).

**Table 2.** Constants for $P_{CT}$ comfort index [28]

| Condition | $A$ [s$^2$·m$^{-1}$] | $B$ [s$^3$·m$^{-1}$] | $C$ [-] | $D$ [s·rad$^{-1}$] | $E$ [-] |
|---|---|---|---|---|---|
| In rest - standing | 28.54 | 20.69 | 11.1 | 0.185 | 2.283 |
| In rest - seated | 8.97 | 9.68 | 5.9 | 0.120 | 1.626 |

As a result, the evaluation of Comfort on Curve Transitions is based on the relationship between the average percentage of dissatisfied passengers and the most relevant magnitudes of lateral acceleration, lateral jerk, and roll velocity of the vehicle body. The formula (2) has been validated for transitions with increasing magnitude of lateral acceleration, where curvature and can't change linearly with respect to distance along the track, having duration of at least 2 s. However, there are no alternative formulas for transition curves and cant transitions with other shapes of curvature and cant, and/or transition curves with a shorter duration than 2 s. [5]

## 3 Conditions of simulation

For the needs of the simulation, a model of a tilting bogie and car body of the rail vehicle were created in CATIA V5R20 program and imported into SIMPACK 9.10 program afterwards. It was necessary to define joints between individual parts using force elements in SIMPACK and set the characteristics of springs and dampers using input parameters. Important was also to define two hydraulic cylinders that cause the upper tilting bolster to tilt and therefore also the tilting of the car body in curve [2]. The model uses an active system of tilting. The created simulation model of the bogie can be seen in Fig. 1 and vehicle model in Fig. 2. The sensor elements used to read the needed signals are placed on the vehicle floor, see Fig. 3 [5].

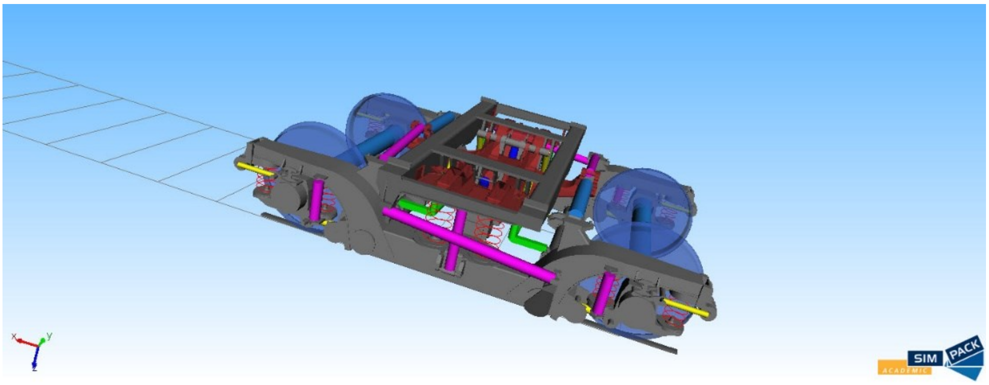



**Fig. 1.** Model of the bogie in program SIMPACK

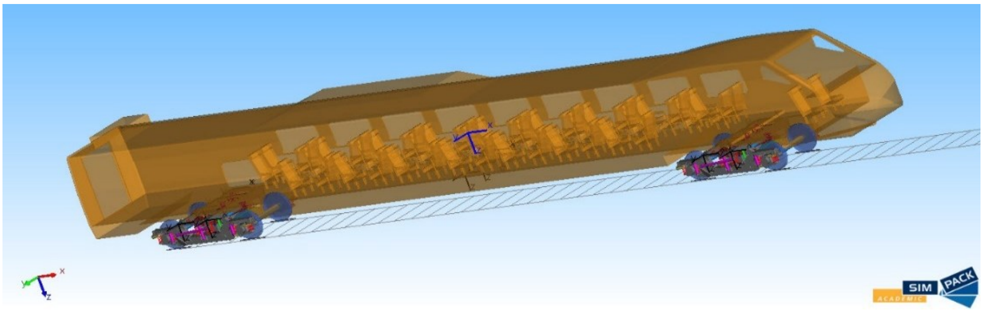


**Fig. 2.** Model of the bogie and car body vehicle in program SIMPACK

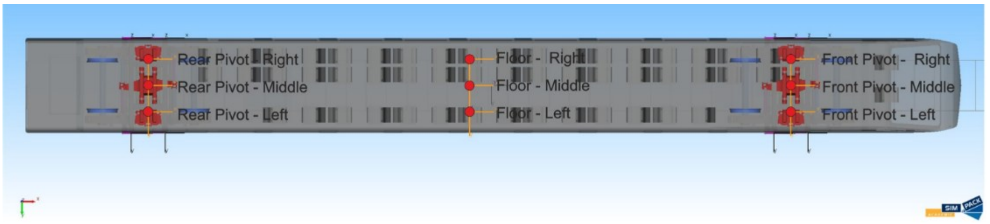



**Fig. 3** Sensor´s elements with descriptions placed at the floor

The vehicle ran along a track with the length of 5 km, composed of 4 curves with a radius of 600 m (Fig. 4). The superelevation of the track was set to 150 mm. Wheel profile S 1002 with a nominal radius of 445 mm and rail profile defined by the S91700_16 geometry were set for the track model.

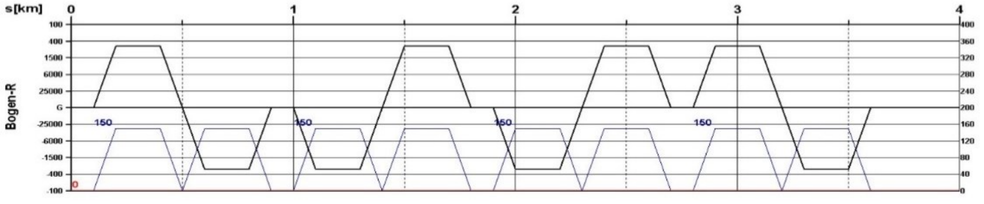



**Fig. 4.** Geometry of the track model

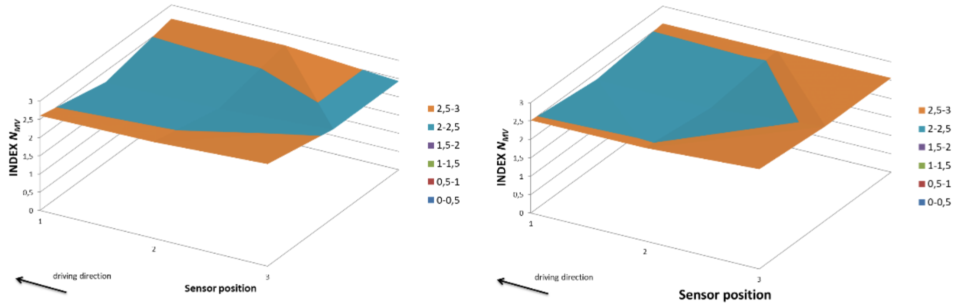
A series of simulations was performed for the 8 variants summarized in Tab. 3. The velocity of 87 km·h$^{-1}$ is for the lateral acceleration of 0.981 m·s$^{-2}$, velocity of 124 km·h$^{-1}$ is for the lateral acceleration of 1.987 m·s$^{-2}$ and the velocity of 152 km·h$^{-1}$ is for the lateral acceleration of 2.987 m·s$^{-2}$.

**Table 3.** Variants for a series of simulations

| Variant | Occupancy | Velocity | Tilting |
|---|---|---|---|
| 1 | unattended | 152 km·h$^{-1}$ | OFF |
| 2 | unattended | 124 km·h$^{-1}$ | OFF |
| 3 | unattended | 124 km·h$^{-1}$ | OFF |
| 4 | unattended | 87 km·h$^{-1}$ | OFF |
| 5 | attended | 152 km·h$^{-1}$ | ON |
| 6 | attended | 124 km·h$^{-1}$ | ON |
| 7 | attended | 124 km·h$^{-1}$ | ON |
| 8 | attended | 87 km·h$^{-1}$ | ON |

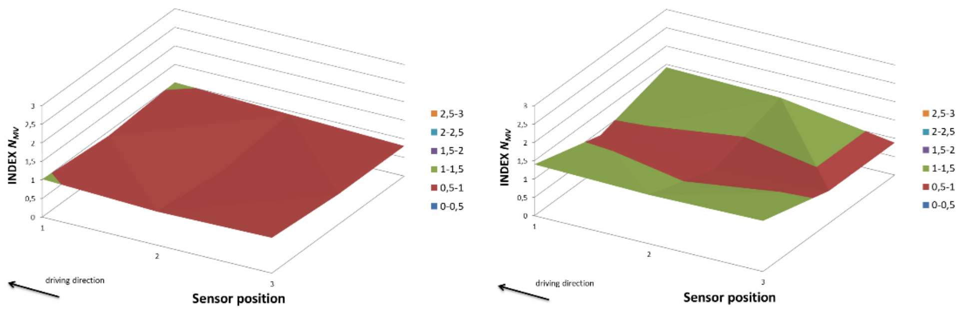
## 4 Mean Comfort Standard Method

When evaluating the ride comfort for passengers, we compared the calculated values of comfort index $N_{MV}$ with the values in Table 1. Distribution of the $N_{MV}$ index is shown on Fig. 5 to Fig. 8. The result comfort index values are given in Table 4.



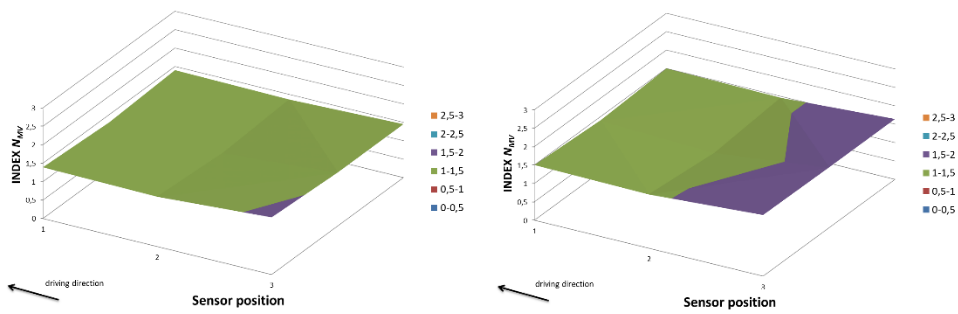

a) b)

**Fig. 5.** $N_{MV}$ index of Variant 1 (unattended occupancy, velocity 152 km·h$^{-1}$, tilting ON), b) $N_{MV}$ index of Variant 5 (attended occupancy, velocity 152 km·h$^{-1}$, tilting ON)



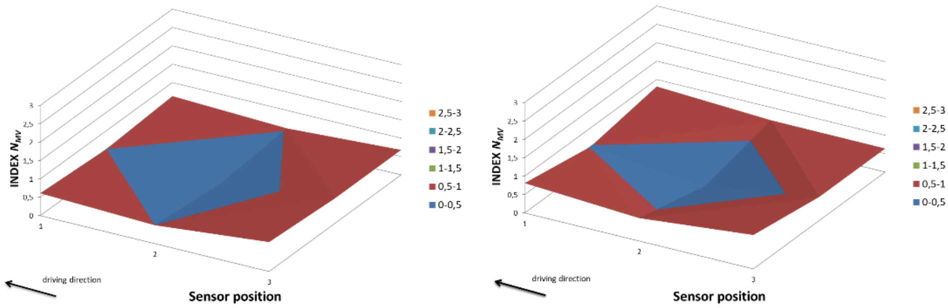

a) b)

**Fig. 6.** a) $N_{MV}$ index of Variant 2 (unattended occupancy, velocity 124 km·h$^{-1}$, tilting ON), b) $N_{MV}$ index of Variant 6 (attended occupancy, velocity 124 km·h$^{-1}$, tilting ON)




a) b)

**Fig. 7.** a) $N_{MV}$ index of Variant 3 (unattended occupancy, speed 124 km·h$^{-1}$, tilting OFF), b) $N_{MV}$ index of Variant 7 (attended occupancy, speed 124 km·h$^{-1}$, tilting OFF)




a) b)

**Fig. 8.** a) $N_{MV}$ index of Variant 4 (unattended occupancy, velocityť 87 km·h$^{-1}$, tilting OFF) b) $N_{MV}$ index of Variant 8 (attended occupancy, speed 87 km·h$^{-1}$, tilting OFF)

From the results of the analysis we can conclude, that the vehicle velocity has the biggest impact on the ride comfort of passengers. The impact of the occupancy becomes evident only at higher velocities. However, the occupancy has the biggest impact on passenger comfort index at a constant speed of 124 km·h$^{-1}$, where the difference between the comfort index with the tilting mechanism on and off was 35.97% for attended and 24% for unattended vehicle.

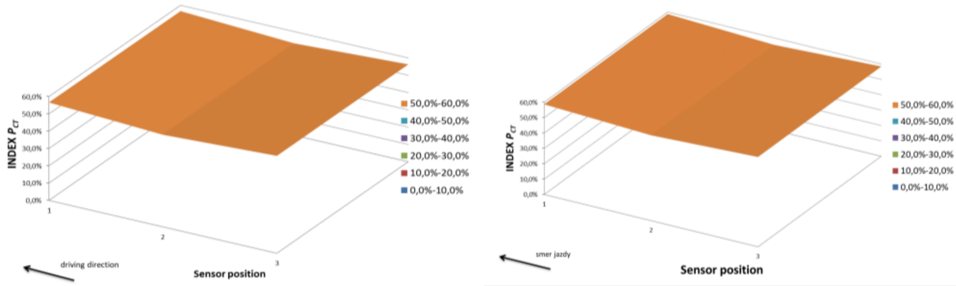
The passenger perceives the smallest impact of acceleration on his body in the area of the middle part (centre of gravity) of the vehicle. The highest values of comfort index affected by acceleration occur on the left and right side of the front and rear part of vehicle. It is notable, that none of the comfort index values has exceeded the 3.5 limit – the average comfort value.

**Table 4.** Comfort indexes for 8 variants

| Variant | $N_{MV}$ comfort index |
|---|---|
| 1 | 2.51 – Comfortable |
| 2 | 0.89 – Very comfortable |
| 3 | 1.39 Very comfortable |
| 4 | 0.58 – Very comfortable |
| 5 | 2.51 – Medium |
| 6 | 1.14 – Very comfortable |
| 7 | 1.50 – Comfortable |
| 8 | 0.64 – Very comfortable |

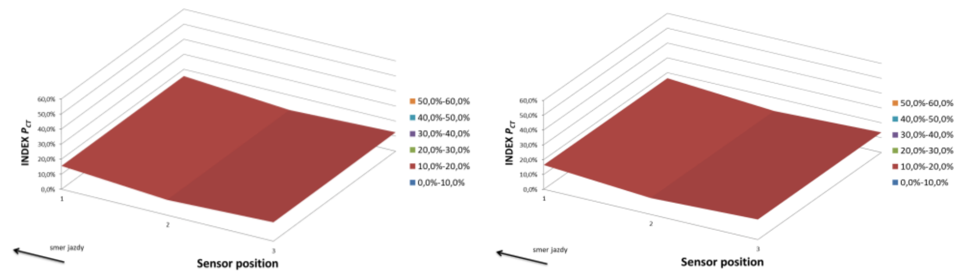
## 5 Comfort on Curve Transitions

Passenger comfort index values on the car floor $P_{CT}$ are calculated according to the valid standard STN EN 12299:2009. $P_{CT}$ index distribution is shown in Fig. 9 to Fig. 12. The result values of comfort index are given in Table 5.



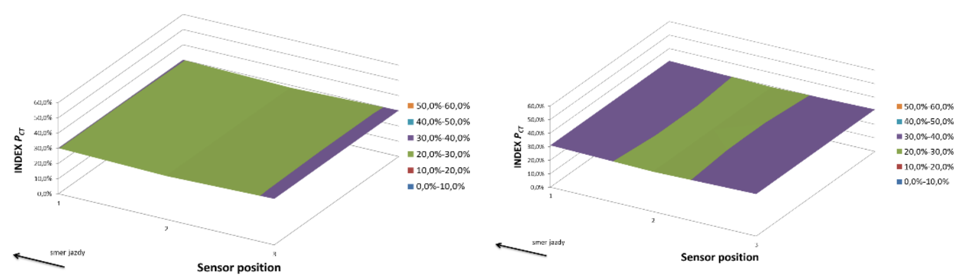

a) b)

**Fig. 9.** a) $P_{CT}$ index for Variant 1 (unattended occupancy, speed 152 km·h$^{-1}$, tilting ON) b) $P_{CT}$ index for Variant 5 (attended occupancy, speed 152 km·h$^{-1}$, tilting ON)



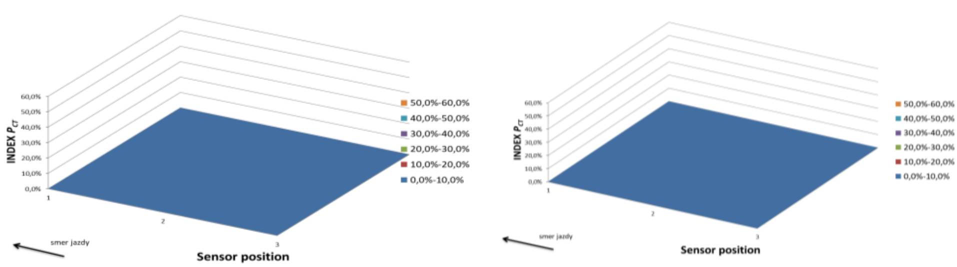

a) b)

**Fig. 10.** a) $P_{CT}$ index for Variant 2 (unattended occupancy, speed 124 km·h$^{-1}$, tilting ON) b) $P_{CT}$ index for Variant 6 (attended occupancy, speed 124 km·h$^{-1}$, tilting ON)




a) b)

**Fig. 11.** a) $P_{CT}$ index for Variant 3 (unattended occupancy, speed 124 km·h$^{-1}$, tilting OFF) b) $P_{CT}$ index for Variant 7 (attended occupancy, speed 124 km·h$^{-1}$, tilting OFF)




a) b)

**Fig. 12.** a) $P_{CT}$ index for Variant 4 (unattended occupancy, speed 87 km·h$^{-1}$, tilting OFF) b) $P_{CT}$ index for Variant 8 (attended occupancy, speed 87 km·h$^{-1}$, tilting OFF)

From the analysis results we can conclude that velocity of the vehicle has the biggest impact on passenger ride comfort. The impact of the vehicle occupancy becomes evident only at higher velocities. Again, the occupancy has the biggest impact on passenger comfort index at the constant speed of 124 km·h$^{-1}$, where the difference between the comfort index with the tilting mechanism on and off in this case was double the value (100%).

The passenger perceives the highest comfort in the proximity of the middle part of the vehicle (centre of gravity). The highest values of comfort index in the car appear on the left and right side of the front and rear part of the vehicle.

It is notable, that at the speed of 87 km·h$^{-1}$ there is almost no discomfort affecting the passengers. This can be caused by the track characteristics, which include rather big radius of 600 m and no irregularities defined, that would cause outer excitation of the vehicle and thus affect the passenger comfort in an undesirable way.

**Table 5.** Font styles for a reference

| Variant | $P_{CT}$ comfort index |
|---|---|
| 1 | 55.38% |
| 2 | 12.71% |
| 3 | 29.57% |
| 4 | 0% |
| 5 | 57.5% |
| 6 | 13.62% |
| 7 | 30.46% |
| 8 | 0.04% |

## 6 Conclusion

In this paper, we focused on simulation of a rail vehicle with a car body tilting mechanism. The vehicle model was created in program CATIA, the basic parameters were set and the model was then imported to SIMPACK. Sensor elements used to read the lateral acceleration during simulation of a vehicle ride on the track were placed on the vehicle model. The results of the simulation were used for evaluation of individual parameters affecting passenger ride comfort of the rail vehicle.

The vehicle showed excellent values of Mean Comfort index during the simulation. The best value of comfort was achieved at the lowest ride speed of 87 hm.h$^{-1}$, when the passengers were affected by a zero unbalanced lateral acceleration. An average value of comfort was achieved at the highest speed of 157 km·h$^{-1}$, the vehicle with an attended occupancy showed unbalanced lateral acceleration of 2 g.

From the analysis results we can conclude that tilting mechanism of the vehicle has the biggest impact on passenger ride comfort. The impact of the vehicle occupancy becomes evident only at higher velocities. The best passenger comfort is at the lowest speed of 87 km·h$^{-1}$. From comparison of the variants we can state, that the best passenger comfort is reached in the middle of the vehicle car.

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*Research-Educational Centre of Rail Vehicles (VVCKV)*

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