An important role of the railways at the moment is to increase the speed of passenger traffic. This task is because of international agreements as well as the need to keep the competitiveness of railways in the transport market. The paper presents the opportunity to increase travel speed of passenger transport with using tilting body vehicles. For the selected section of the ZSR lines travel times for vehicles with classic designs and tilting body vehicles were calculated. From their comparison a remarkable reduction of driving times showed up. Energy consumption of classical design vehicles and Pendolino type trains on the existing section of Slovak railway, considering the current speed limits and the theoretical speed limits for trains with tilting technology was assessed.

INTRODUCTION

To stay competitive in the transport market, rail operators have to look for new solutions. One of the advantages of rail transport is its speed, but this is not true in the case of obsolete personal railcars and locomotives, especially when new highways are built parallel with railway lines. This means that the increasing speed on railway is a major problem that the majority of European and world railways have to cope with at the moment. On the top are the systems of high speed trains where maximum speed is over 250 km/h. Basically, there are two ways how to increase running speed.

One way is construction of special high speed tracks with curves with large radii corresponding to high speed of railway vehicles.

The second way is utilization the existing tracks, certainly with enhancement of their technical conditions, and use of railway vehicles with tilting bodies which allow faster run in curves by tilting body inward the curve and thus reducing effects of centrifugal forces on passengers. These vehicles, according to the experience of several European countries, are able, also on existing lines intended for passenger and freight transport, to achieve high speeds and thus significantly reduce travel times.

Tilting body vehicles have much better aerodynamics which results in lower energy consumption when used in comparable speeds as classical trains used in Slovakia. Energy consumption can be also used as an initial indicator (diagnostic signal) of a potential failure. [6] [7]

1. RAIL VEHICLES WITH BODY TILTING

There are two basic principles of body tilting:

- passive tilting (Fig. 1),
- active tilting (Fig. 2).

Passive tilting is based on the chassis air springs located above the centre of gravity. This support allows tilting of a vehicle body inside the curve as effect of centrifugal force, and thus partially offset the effects of centrifugal force on passengers. The best known representative of trains with natural body tilting is Spanish RENFE train-set called Talgo.

Forced body tilting of railway vehicle is based on principle of tilting vehicle body by action of hydraulic, pneumatic or electrical actuators.

Into the group of vehicles with forced body tilting belong e.g. Italian train units FS Pendolino, its derivate German DB – ICE T, or on partly different principle designed Swedish train SJ - X2 [1]. Many other systems exist in the world (Japanese, using body supported on
rollers and electric actuators; active secondary air suspension raising outer and lowering inner side of body during curve run, etc.)

2. THE FORCES ACTING ON THE RAILWAY VEHICLE WHILE DRIVING IN A CURVE

When driving in a curve, the centrifugal force is applied to the vehicle.

The corresponding transverse (centrifugal) acceleration presents several side effects:
- discomfort for passengers,
- the possibility of derailment of the vehicle,
- transversal forces on the track.

To minimize the above mentioned side-effects can be done by:
- use the maximum possible curve radius,
- reduce speed on a curve
- create railway superelevation to compensate centrifugal force.

Forces applied to the vehicle when driving in a curve are shown in figure 3, where [1]:

\[ a_c = \text{balanced transversal acceleration (m.s}^{-2}\text{)} \]
\[ a_n = \text{unbalanced transversal acceleration (m.s}^{-2}\text{)} \]
\[ g = \text{gravitation acceleration (m.s}^{-2}\text{)} \]
\[ e = \text{distance of rail head centres (1500 m)} \]
\[ R_1 = \text{vector sum of accelerations (m.s}^{-2}\text{)} \]
\[ I, I' = \text{balanced acceleration (m.s}^{-2}\text{)} \]
\[ \Delta = \text{- unbalanced acceleration (m.s}^{-2}\text{)} \]

![Diagram](image)

**Fig. 3 Effects acting on railway vehicle during running in curve [8]**

In conventional vehicles without body tilting, superelevation of outer rail to the inside the arc is used to compensate the centrifugal force acting on the vehicle when negotiating the curve.

This elevation with the fully compensated centrifugal force is called theoretical elevation \( p_t \).

For standard track gauge 1435 mm, it is possible to calculate the theoretical elevation as follows:

\[ p_t = 11.8 \cdot \frac{V^2}{R} \text{ (mm; km.h}^{-1}\text{, m)} \]  \( \text{(1)} \)

Where:
\( V \) - train speed (km.h\(^{-1}\)),
\( R \) - curve radius (m).

The overall tilt of the body of the vehicle when driving in a curve is the sum of elevations (railway elevation) of the outside rail and fictive superelevation resulting from the body tilt. [2]

On the railways fully compensated theoretical elevation is not used but allows a certain size of unbalanced centrifugal acceleration, which is represented by the so-called elevation deficiency \( p_{np} \).

The basic type of elevation on 2SR is “lower elevation” – \( p_n \) reduced by 70 mm from the theoretical. Other types of elevation is “lowered elevation” (reduced by 85 mm) and the smallest, reduced by 100 mm of the theoretical. To calculate the passage of a tilting body vehicle in a curve the maximum permissible speed \( V_{dm} \) has to be determined.

The formula for its calculation can be derived as follows:

1. The formula to calculate the maximum permitted speed when driving through curves with radius \( R \), with a maximum elevation \( p_m \) and elevation deficiency \( p_{np} \) is:

\[ V = \sqrt[3]{\frac{R}{11.8} \cdot (p_m + p_{np})} \text{ (km.h}^{-1}\text{; m, mm)} \]  \( \text{(2)} \)

2. A further increase in speed without degradation of passenger comfort \((a_v=0.457\text{m.s}^{-2})\) brings the vehicle body inclination to arc by a certain angle \( \beta \), which represents an additional elevation \( p_b \).

We get the speed limit of the vehicle with body tilting:

\[ V = \sqrt[3]{\frac{R}{11.8} \cdot (p_m + p_{np} + p_b)} \text{ (km.h}^{-1}\text{; m, mm)} \]  \( \text{(3)} \)

This is not a complete solution because the increased speed in addition to compensation of the transverse force applied to the passenger also brings increased effects of the vehicle on track.

Increased transversal forces from higher speed acting on track are becoming limiting criterion (risk of derailment, track stability, etc.) which is given by Proudhom’s formulae. It shows the maximum radial force limit of the wheelset on the track, which can be made at erratic vehicle acceleration \( a_m = 1.65 \div 1.8 \text{ m.s}^{-2} \) and rarely \( a_m = 2.0 \text{ m.s}^{-2} \).

Maximum permissible speed in the overall lateral acceleration \( a_c \) is:

\[ V_{dm} = 3.6 \cdot \sqrt[3]{a_c \cdot R} \text{ (km.h}^{-1}\text{; m.s}^{-2}\text{, m)} \]  \( \text{(4)} \)

The effects acting on the vehicle with a tilting body when driving in a curve are presented in figure 4, where [1]:

\( a \) – Total transversal acceleration (m.s\(^{-2}\)),
\( g \) – gravitation acceleration (m.s\(^{-2}\)),
\( \alpha \) – railway superelevation (˚),
\( \beta \) – angle of body tilt relative to bogie frame (˚),
\( \gamma \) – anlge of body tilt (˚).
The most important advantage of body tilting vehicle compared with conventional vehicles is that they can pass the curve with significantly higher speed and thus significantly shorten the travel time. Considering the curves of the same elevation (railway super-elevation) $p = 150$ mm and a reduced elevation of $70$ mm, respectively $100$ mm, we can draw a diagram showing a relation between the maximum speed in the curves for the conventional vehicles and a body tilting vehicles (Fig. 5).

It can be seen that the tilting body vehicles can achieve remarkably higher speed in the small-diameter curve over conventional vehicles. But the increased lateral force from the higher operating speeds on the track becomes a limiting criterion (risk of derailment, stability tracks, etc.)

3. ATTAINABLE TRAVEL TIMES ON SELECTED ŽSR RAILWAY LINE

Run of express trains on ŽSR (Slovak railways) infrastructure is limited by maximum track speed, which is rather low comparing to western countries. For domestic traffic, one of the principle lines of ŽSR is the line Košice - Žilina - Bratislava.

We performed simulations in the program "Dynamics" (Fig. 6) for the route Žilina – Košice with stops in Ružomberok, Liptovský Mikuláš, Štrba, Poprad-Tatry and Kysak in both directions which are regular stops for Pendolino type train.

In the analysis we used the electrical multiple unit CDT 680 (Fig. 7) with additional weight of 30 tons for passengers, which is a representative of vehicles with tilting body and classical designed train with electric locomotive class 362 (Fig. 8) and 7 passenger coaches;
weight of 350 tons and length of 185 meters. These vehicles are actually used on this line.

We compared their travel times and energy consumption.

Fig. 7 Electrical multiple unit CDT 680 (Czech Pendolino) [4]

Fig. 8 Electrical locomotive class 362

In simulation we used three different modes with settings as follows (Tab. 1) where:

- normal - the current driving speed limits on the track,
- effective - effective rate of speed and consumption,
- max. speed - theoretical maximum possible driving speed limits on the track.

On the route from Žilina to Košice (Fig. 8) with using normal mode CDT 680 reaches about 27% (661 kWh) less energy consumption than train with electrical locomotive class 362, but travel time is approximately the same. In max. speed mode CDT 680 reaches about 28% (47 min) less travel time, but with high energy consumption. In effective mode the electrical multiple unit CDT 680 reaches 6% (157 kWh) less energy consumption and 26% (43 min) less running time.

Fig. 9 Evaluation of the energy consumption and travel time on the line from Žilina to Košice

On the route from Žilina to Košice (Fig. 10) with using normal mode CDT 680 reaches about 37% (1143 kWh) less energy consumption than train with electrical locomotive class 362, but travel time is approximately the same. In max. speed mode CDT 680 reaches about 31% (52 min) less travel time, but with high energy consumption. In effective mode the electrical multiple unit CDT 680 reaches 21% (657 kWh) less energy consumption and 27% (45 min) less running time.

Fig. 10 Evaluation of the energy consumption and travel time on the line from Košice to Žilina

<table>
<thead>
<tr>
<th>Train set</th>
<th>Setting limits</th>
<th>From Žilina to Košice</th>
<th>From Košice to Žilina</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>362+350t</td>
<td>normal 167,76</td>
<td>2453,70</td>
<td>169,31</td>
<td>3117,60</td>
</tr>
<tr>
<td></td>
<td>normal 167,82</td>
<td>1792,60</td>
<td>168,02</td>
<td>1974,40</td>
</tr>
<tr>
<td></td>
<td>effective 124,83</td>
<td>2296,10</td>
<td>124,18</td>
<td>2459,80</td>
</tr>
<tr>
<td></td>
<td>max. speed 121,11</td>
<td>2917,40</td>
<td>117,03</td>
<td>3125,00</td>
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</table>
The aim of the study was to show the possibility of increasing the speed on the existing railway line without track rebuilding by using tilting body vehicles. It has been also pointed at the energy performance of tilting body vehicles at higher speeds, which constitutes a significant item of operating costs. Utilization of tilting body railway vehicles is suitable especially when there is need to increase passenger transport speed and there are not sufficient investments for construction of new high speed lines. Tilting body vehicles gain travel time savings especially by higher speed when running in curves in comparison with conventional vehicles. So the highest travel time reduction is achieved on lines with high number of curves with small curve radii. The results confirm the possibility of significant shortening of travel times, while pointing out the need to pay attention to choosing the speed limits in terms of energy versus travel time.

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