

DEDICATED TO CRR/MINISTRY OF RAILWAYS/INDIAN RAILWAYS/IIT KHARAGPUR/RDSO

## HIGH SPEED TILTING TRAIN TECHNOLOGY

Shripad Shashikant Chopade

*M Tech (Machine Design & Robotics), UPSC (IES) IRSME (R&D), Government of India, Ph.D Research Scholar, India*

\*\*\*

**Abstract:** Tilting Train consists of tilting mechanism that enables to increase the speed on regular tracks. In the upper part of tilting trains that is in which the passengers are seated can be tilted sideways. During the motion of the train if the train has to steer to left in a left turning the coaches of the train will be tilted to the left in order to compensate the centrifugal push to the right and conversely during the right turn. Tilting trains can be classified into different categories according to the features of their tilting system. On every types of tilting trains the tilting systems shall perform three main functions: first, they have to identify accurately and without delay the initial position of curve transitions, then second they have to tilt the car body according to the tilting algorithm provided for the system and finally they have to verify that the provided amount of tilt corresponds to the tilt demand.

**Keywords:** Accelerometer, Adaptive Control, Bogie, Cant, Cant Deficiency, Centrifugal Force, Creep, Cross Wind Stability, Curvature, Gauge, Locomotive, Higher Speed, Hydraulic Systems, Motion Sickness, Passenger Discomfort, Running Time, Tilting, Railway, Track, Tractive Power, Stone Lift, Warping.

### I. INTRODUCTION

Tilting trains show increased levels of vertical and roll motions at frequencies below 1 Hz compared with non-tilting. Train with capability to tilt the car body inward in track curves, thus reducing the lateral acceleration perceived by the passengers. The amount one running rail is raised above the other running rail in a curve. Track cant is positive when the outer rail is raised above the inner rail. Cant deficiency is the difference between applied cant and a higher equilibrium cant. Travel time is the most obvious performance indicator that may be improved by introducing high-speed trains. Trains with capability to tilt the car bodies inwards in track curves constitute a less costly alternative than building new tracks with large curve radii. The tilt inwards reduces the centrifugal force felt by the passengers, allowing the train to pass curves at enhanced speed with maintained ride comfort. Trains capable to tilt the bodies inwards are often called tilting trains. Car body tilting is today a mature and relatively inexpensive technology. International Union of Railways (UIC) [1998, 2005] has reported on tilting train technology where tilting trains and known tilting technology are described briefly. The present report covers tilting trains and known tilting technology as well as an analysis of the present situation. Motion sickness is also experienced in other modes of transportation. Motion sickness at sea is the most known, but the knowledge derived at sea cannot be applied on trains as the motions differ. The levels of vertical acceleration at sea are proven to cause motion sickness during laboratory tests, but no single motion can explain the onset of motion sickness in tilting trains.

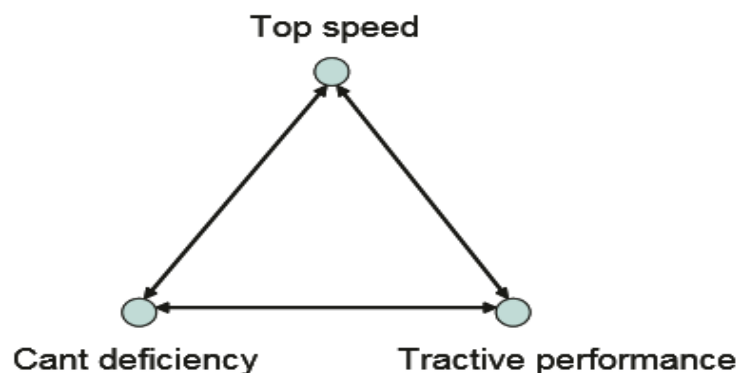


Fig1. Cant Deficiency, Top Speed and Tractive Performance.

Running time simulation performed on representative tracks. Running times are dependent on many factors. Cant deficiency, top speed and tractive performance are key factors which are like a chair with their legs, where a change on one leg must go together with changes on the other legs to make a good chair in Fig 1.

Simulations of running times are performed at 3% lower speeds than allowed from the equilibrium cant and maximum speed points of view. This is made in order to achieve a running time margin due to non- optimum performance of the train driver. Further running time margins and dwelling times must be added to receive running times suitable for time tables.

Assumptions for the calculations are:

- ✓ The maximum speed is set depending on the equilibrium cant, i.e. the track cant and length of transitions of today may be changed where needed.
- ✓ Maximum permissible cant deficiency is 300 mm up to 225 km/h and above that reduced with 1 mm per 1 km/h due to cross-wind effects.
- ✓ Enhanced speed is allowed at the same track sections as today.
- ✓ Maximum permissible cant excess for freight trains is 110 mm at 90 km/h.

In Pendulum System, curving velocity can be increase 20-30 km/h over the basic curving velocity restriction. Greater the pendulum of tilting angle, the more the car body gravity centre geometrically shifts to the outside of the curve as shown in Fig.2 and Table 1.

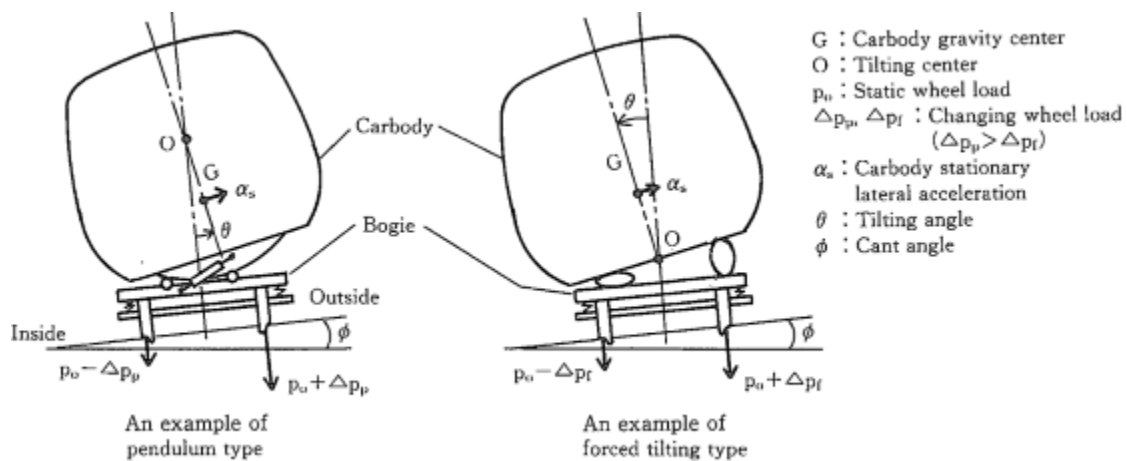


Fig 2. Example of Pendulum Type and Forced Tilting System

	Forced Tilting System	Pendulum System
Tilting Centre Height	Under Car body Gravity Centre which is Allowable	Over Car body Gravity Centre which is necessary
Tilting Force	Pneumatic power or Hydraulic Power	Auxiliary Pneumatic Power & Centrifugal Force

Table1. Comparison between Forced Tilting System and Pendulum System.

It means that running safety margin on curves tends to be reduced. Therefore the increase in curving speed using pendulum systems will soon reach its limitation. For the purpose of solving the above problem, a forced tilting control system is required. This system enables the car body gravity centre to shift toward the inside of a curve.

## II. PRINCIPAL/ CONCEPT/CAR BODY OF TILTING TRAINS

Two Types of Tilting. Active Tilt and Passive Tilt.

- The active tilt relies on active technology, controlled by sensors and electronics and executed by an actuator, usually hydraulic or electric. Tilt as such has normally not an impact on safety of actively tilted train, as the centre of gravity does not essentially change its lateral position.
- The passive tilt relies on physical laws with a tilt centre located well above the centre of gravity of the car body. In a curve, under the influence of centrifugal force, the lower part of the car body then swings outwards. It should be noted that passive tilt has a negative impact on safety due to the lateral shift of the centre of gravity of the car body.

The basic concept of tilting trains is the roll of the car bodies inwards the curve in order to reduce the lateral force perceived by the passenger shown in Fig 3.

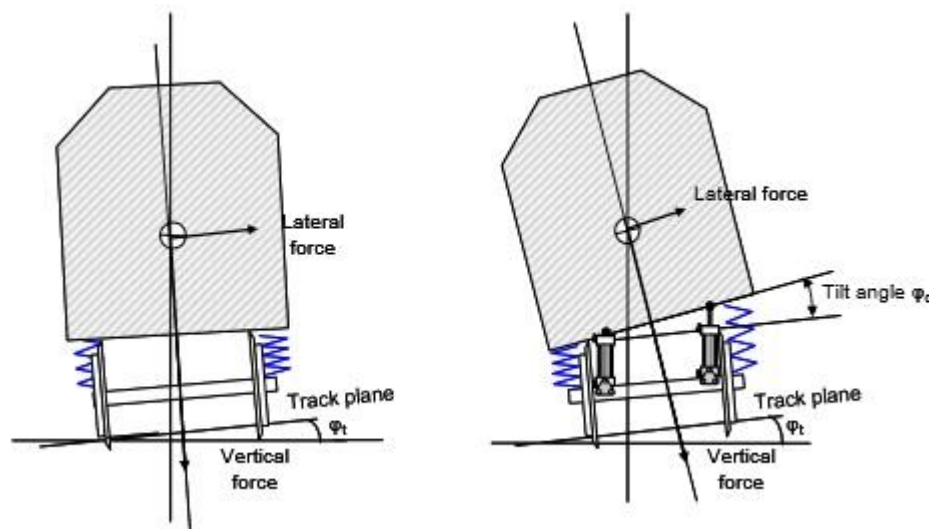


Fig 3 The basic principle/concept of tilting trains. Despite the higher track plane acceleration for the tilting train (right), the lateral force in the car body is lower than for the non-tilting train (left).

When a train is running on a horizontal curve, there will be a horizontal acceleration that is a function of speed  $v$  (m/s) and curve radius  $R$  shown in equation 1 given below,

Horizontal Acceleration = (Function of Speed)<sup>2</sup> / Horizontal Curve Radius.

$$(a_h) = v^2/R \tag{1}$$

The lateral acceleration in the track plane can be reduced compared with the horizontal acceleration by arranging a track cant  $D$ . The angle between the horizontal plane and the track plane  $\varphi_t$  is a function of the track cant and the distance between the two contact points of a wheel set  $2b_0$ .

$$\varphi_t = \arcsin(D/2b_0) \tag{2}$$

The lateral acceleration, as perceived by the passenger, it can be further reduced by arranging a car body tilt angle  $\varphi_c$  in relation to the track. The lateral acceleration in the car body is normally denoted  $\ddot{y}$  shown in equation (3). The vertical acceleration, perpendicular to the vehicle floor, is normally denoted as  $\ddot{z}$  shown in equation (4), given below,

$$\ddot{y} = v^2/R \times \cos(\varphi_t + \varphi_c) - g \times \sin(\varphi_t + \varphi_c) \tag{3}$$

$$\ddot{z} = \frac{v^2}{R} \times \sin(\varphi t + \varphi c) + g \times \cos(\varphi t + \varphi c) \quad (4)$$

A reduction of lateral acceleration by increased track cant or car body tilt is correlated with a slightly increased vertical acceleration. Some points are noted for research work.

- The real value is 15 to 30 % higher due an outward sway of the car body due to flexibility in primary and secondary suspensions.
- The vertical acceleration is here given as offset from g.
- Tilt angle corresponds to an actively tilted train.

### III. WORKING/ MECHANISM OF TILTING TRAINS

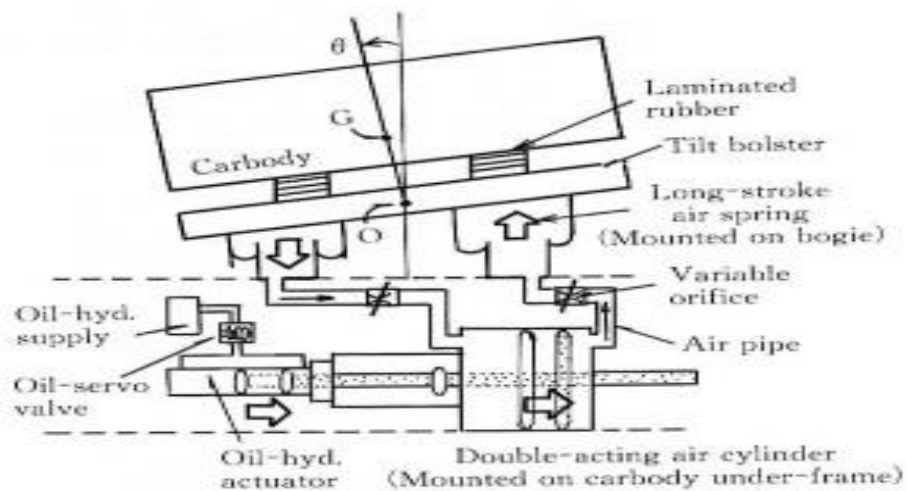


Fig 4 Mechanism of Tilting Trains

Fig 4 Shows Working of Tilting Train Mechanism. This Mechanism consists of two long stroke air springs mounted on bogie and a double acting air cylinder driven by an oil hydraulic actuator.



Fig 4 (a) Long-Stoke Air Spring Mounted on Bogie

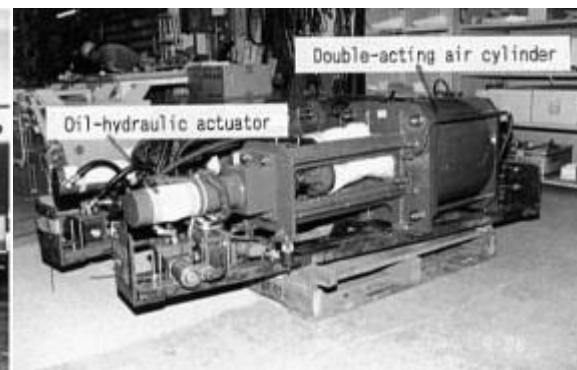


Fig 4 (b) Tilting Drive Unit

Fig 4 (a) Shows a Long-Stoke Air Spring. This air spring can vertically expand or compress up to  $\pm 140$  mm for a 7 degree tilting angle. Fig 4 (b) Shows Tilting Drive Unit consisting of a double acting air cylinder and an oil hydraulic actuator. The unit is mounted on a car body under frame. The double-acting air cylinder enables a car body to tilt without air consumption. Fig 4 (a) Shows a bogie equipped with the tilting device. This bogies performance provides high ride quality, light weight, excellent

running stability. A Tilting system using air springs was selected as the forced tilting system on account of the following advantages.

- ✓ Bogies can be relatively simple and light.
- ✓ Tilting centre height can be low. i.e. less than (0.8 m to 0.9 m) above the rail.

A Tilting control system using air springs, with tilting angle limited to about 2 degrees. This system consumes compressed air whenever the car body tilts. Considering consecutive curve negotiation with a 7 degree tilting angle instead of 2 degrees, large air consumption causes a supply shortage of compressed air for the air springs. Consequently a non-air consuming tilting mechanism has been developed.

### ❖ Amendment of the Conventional Railway Operational System

In adopting this technology the stumbling block existing in the operation of high speed are removed to the extent possible. These stumbling blocks are in the form shown in given below,

- **Barrier/Fencing** In high speed lines encroach on tracks cannot be permitted. Thus the entire high speed line has to be fenced.
- **Vertical Curves** The desirable values of radii of vertical curves for high speed operation are much higher.
- **Grade Separations/Level Crossing** For high speed operation, all level crossings are required to be replaced by suitable grade separation works.
- **Track Geometry** Very close tolerances in track geometry are required to be maintained requiring study track layouts and sophisticated track maintenance and monitoring system.
- **Horizontal Curves** Centrifugal force generated on the curves vary with the square of the speed. Therefore the curves are required to be eased out to keep the centrifugal forces within a manageable limit.

### ❖ Achievement of Tilting

Tilting trains exploit the fact that speed through curves is principally limited by passenger comfort not by either lateral forces on the track or the risk of overturning. The principles and basic equations related to tilting are well known. Two things are formed. The first is maximum tilt angle to be provided ( $\dot{E}_{\text{tilt}}$ ); this is based upon the mechanical design of the vehicle. Second thing is what cant deficiency the passengers should experience on a constant radius curve ( $\dot{E}_{\text{CDtilt}}$ ), which is of primary importance to comfort.

Given these two things, the value cant deficiency that applies for the increase in curving speed up offered by tilt, the equation given below,

$$\frac{V_{\text{tilt}}}{V_{\text{non-tilt}}} = \frac{\sin(\dot{E}_{\text{tilt}} + \dot{E}_{\text{CDtilt}} + \dot{E}_{\text{cant}})}{\sin(\dot{E}_{\text{CD non-tilt}} + \dot{E}_{\text{cant}})} \quad (5)$$

Maximum track cant is usually 6° and typically 6° of cant deficiency is specified for a non-tilting train. Applying 9° of tilt and with a cant deficiency of 6° for the tilting train, the calculations indicates a speed up of 32%. In light of the above facts tilting trains speed up the trains by about 30%. It is however important to design the transition curves properly, so as to ensure the comfort level to be within the acceptable limits.

### ❖ Dedicated High Speed Tilting Corridors and Construction Parameters

For High Speed Tilting operation exclusive corridors have been designed and constructed. In this corridors construction parameters have been appropriately selected for smooth, safe operation and efficient at the designated speed. The construction parameters which need special attention on these corridors are,

- **Track Structure** Both ballasted and ballast less track structures have been adopted on high speed tilting lines.
- **Vertical Curves** For better passenger comfort, gentler vertical curves are provided on high speed tilting lines as compared to that adopted on conventional lines.

- **Horizontal Curves** These curves have their radius, cant, cant-deficiency etc. easiest possible curves are provided on high speed tilting corridors.
- **Ruling Gradient** As the high speed tilting trains are lighter in load and are provided with high tractive power, steeper gradients can be allowed on high speed tilting lines.
- **Spacing Tracks** In high speed tilting tracks, provision on wider centre to centre spacing for double lines is important in view of the higher air pressure generated during the crossing of their trains.

❖ **Tilting Control Method**

Fig 5 Shows Tilting Control Method. The tilting control adopts a program control method in order to compensate for tilting or restoring response lag at the beginning or end of the curves. The control cycle starts with measuring running velocity using a Tacho-generator. Integrating the running velocity then obtains the calculated running position. The calculated running position is occasionally corrected at correcting points. Using corrected running position and previously memorized curve data, a target tilting pattern for the next curve can be estimated in advanced. This pattern is generated earlier than the curve entry point for response lag compensation. Finally a control signal is output to the servo valve by a control adopting the deviation between the target tilting angle of the pattern and the measured tilting angle.

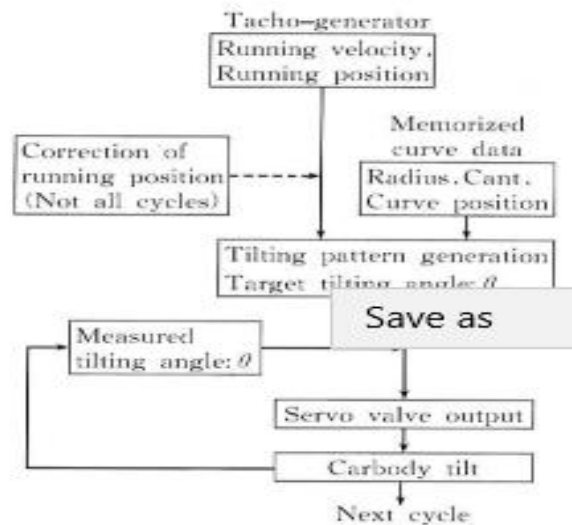


Fig 5 Tilting Control Flow Chart

❖ **Correcting Method of Running Position of Tilting**

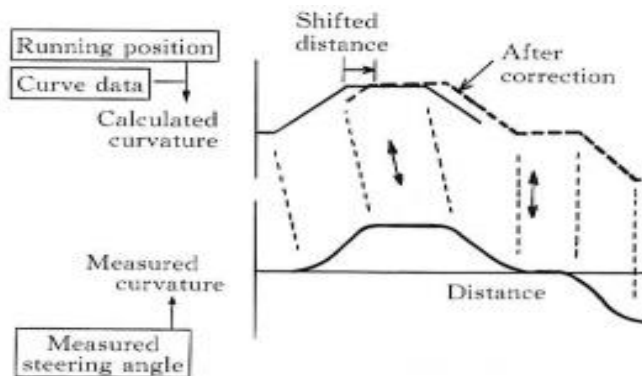


Fig 6 Idea of Correcting Method

Fig 6 Shows an Idea of Correcting Method. The calculated running position must be corrected because errors are gradually accumulated. A calculated curvature is caused by the calculated running position and by the curves data. When the calculated curvature is locationally shifted toward measured curvature, it is locationally shifted toward the measured curvature. Therefore calculated running position is corrected in terms of the distance shifted. Since this method does not require wayside devices such as ground coils, it can apply to all railway systems.

### ❖ Why Tilting Trains Necessary

- Often train operating companies face a decision for building a high speed railway transport system.
- In order to eliminate the problem with corners we have to either build high speed railway tracks or by introducing tilting mechanisms.
- When we are choosing the 1<sup>st</sup> option we have to construct tracks on the corners with higher radius of curvature.
- In passive tilting on a curve, under the influence of centrifugal force, the lower part of the car body swings outwards.
- It should be noted that passive tilt has a negative impact on safety due to the lateral shift of centre of gravity of the car body.
- The active tilt relies on active technology controlled by a controller and executed by an actuator.
- Tilt as such has normally not an impact on safety on actively tilted train.

### ❖ Admonishment of Further Research

Further research should be carried out on areas where research can improve the competitiveness of tilting trains. The admonishment made here is based on the knowledge won in the present study.

- **The Choice of Tilting as Function of Track Cant and Cant Deficiency** Developing a guideline devoted to train operators and manufactures as the best compromise between low risk for motion sickness and comfort.
- **Guidelines Track Geometry** Guidelines on track geometry consider safety and comfort, but it would also be possible to consider motion sickness.
- **Benefits of Running Time** The running times with non-tilting trains have been improved by increased applied track cant and increased cant deficiency. Tilting trains take advantage of the increased track cant, but the running time benefit in percent compared with non-tilting trains decays. Could the limitation on cant deficiency for tilting trains be updated? Would a limitation as function of speed be feasible? The present study has identified the existing types of limits; but at what levels should the limits be set? Particularly the limitation due to cross-wind is interesting to study.
- **Speed Setting for Low Risk of Motion Sickness and Good Comfort** Developing a guideline devoted to train operators and infrastructure owners as a best compromise between low risk for motion sickness and comfort. The guideline shall consider the influence of track cant and length of transition curves and the influence of perceived dose of motion sickness relevant motion.
- **Control of Car Body Roll Motions** Tilt systems control the roll angle between the tilting bolster and the bogie frame. Modern control theory and practice would make control of the car body roll possible. Control of car body roll motions opens up for the possibility to minimize the dynamic contribution to car body roll motions, which is believed beneficial for minimizing the risk of motion sickness.

### • Advantages of Tilting Train

- ✓ The control system is very simple if needed at all.
- ✓ Inverse tilting cannot occur.
- ✓ The system is simple and reliable.
- ✓ The system has low initial and maintenance costs.
- ✓ Running time benefits.
- ✓ Speed setting for good comfort and low risk of motion sickness.
- ✓ The choice of tilting as function of track cant and cant deficiency.
- ✓ Control of car body rolls motions.
- ✓ Track geometry guidelines.

- **Disadvantages of Tilting Train**

- ✓ Tilting train technology has more expensive in the absence of other technologies.
- ✓ The lateral movement of car body lower section reduces the possible car body width where it is most needed.
- ✓ The high position of the rotation centre gives a lateral movement of the car body mass centre, which increases the risk of overturning.
- ✓ The car body's moment of inertia will delay the tilt motion. A low-frequency lateral acceleration, caused by imbalance between track plane acceleration and the compensation by tilting will thus appear in transition curves. This low-frequency lateral acceleration may be both uncomfortable and motion sickness inducing.

#### IV. CONCLUSION

- In case of tilting train technology mechanism, these are expensive in the absence of other technologies. Tilting Train Technology has an important role in high speed and safe railway transport system. In future Tilting Train Technology mechanism will be the part of Indian Railways.
- In India, with its continental dimensions, provides a good scope for a adoption of High-Speed Tilting Train Technology, to meet the transport needs of its fast growing economy.
- High-Speed Tilting Train lines new technologies in the form of floating slabs, noise barriers, rubber bearing etc. are being adopted for certain noise and vibration levels within the acceptable limits.
- High speeds can be achieved by tilting mechanism to reduce journey time with excellent comfort, safety and satisfaction by innovative technological aspect of Tilting Trains. It is possible to give some conclusions on how the risk of motion sickness shall be limited in tilting trains. These conclusions can be given despite lacking knowledge of the main cause to motion sickness.
- Tilting Trains cause more motion sickness than non-tilting ones. The largest differences are vertical acceleration and roll velocity. Minimizing the roll angle will not only limit roll velocity, but also vertical acceleration. However, reduced roll angle may be in conflict with requirements on comfort (increased quasi-static lateral acceleration).
- Car body tilting has today become a mature technology accepted by most operators, but not favored by many. There are different reasons behind this fact that non-tilting trains have increased their speed in curves, reducing the potential for travel time reduction by tilting trains to approximately 10 - 15 %. The attractiveness is also impacted by low reliability and motion sickness on certain services. The risk of motion sickness and the running time benefit compared with non-tilting trains are addressed in the present study.
- In tilting case system, in order to raise the speeds to 120 km/h curving velocity on 400 m radius curves. In case of successful tilting control, adequate running safety and good riding performance also verify with the target curving velocity being achieved. We are confident that this tilting control system is very appropriate for achieving higher speeds on sections with many consecutive curves.
- Improvement of conventional railway system by the adoption of tilting train technology offers very limited advantage in the increase of speed only up to a maximum of 30 percent.
- On Dedicated High-Speed Tilting Train corridors, construction, parameters particularly the curves and the grades are appropriately selected for smooth, efficient and safe operation at designated speed.
- High-Speed Tilting Trains are being increasingly adopted on world railways.
- Both ballasted and ballast less track structures have been adopted on world railways on their High-Speed Tilting Trains lines. Ballast-less track structure with many of its plus points, particularly its long service life, safety of operation and lower life cycle cost, is gaining favors.
- In High-Speed Tilting Trains of ballast less tracks, where adopted on earth formations, the sub grade structure is required to be properly designed to ensure minimal settlement of track during service.

#### V. ACKNOWLEDGMENT

I Deeply Express My Hearty Gratitude and Thanks to International Research Journal of Engineering and Technology.



**REFERENCES**

- [1] Switzerland Technical Research Institute- Switzerland Projects
- [2] www.chron.com
- [3] en.wikipedia.org
- [4] www.dbamanufacturing.com
- [5] www.ieee.com
- [6] www.singnet.com.sg
- [7] news.bbc.co.uk
- [8] The Official Transrapid Site- lots of information about Tilting.
- [9] "New study shows how to eliminate motion sickness on tilting trains", Icahn School of Medicine at Mount Sinai, 4 August 2011
- [10] Rickard Persson, "Tilting trains Enhanced benefits and strategies for less motion sickness"
- [11] K. Sasaki, "Position Detection System Using GPS for Carbody Tilt Control" , Quarterly Report of RTRI. Volume 46, No 2, pp 73-77, Japan, 2005
- [12] International Railway Journal
- [13] UIC – High Speed Division - First Report on Tilting Train Technology – The state of Art – Paris, June 1998.
- [14] M. Testa – R. Roberti – Requirements on Infrastructure Maintenance and Track Geometry By Higher Curving Speed – UIC-UNIFE-ERRI Interactive Seminar, Paris May 1999.
- [15] F. Cheli – G. Diana – F. Resta – Numerical model of a Tilting Body Railway Vehicle Compared with Rig and on Track Tests – appearing on Vehicle System Dynamics 2001

**BIOGRAPHIES**

My Name is Shripad Shashikant Chopade, Working in Indian Railways, Researcher on High Speed Tilting Train Technology (R&D), Government of India, Ministry of Railways. Dedicated to Ministry of Railways / Indian Railways / CRR / IIT Kharagpur / RDSO.