Estimation on the enhancement of permissible speeds around curves for the tilting train on the Gyeongbu line of the Korean Rail Network

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Abstract

The development of tilting trains in Korea started in 2001 as a research and development project. A 6-car prototype test tilting train, called the Tilting Train eXpress (TTX), was built in December 2006 and experimental trials began in 2007. TTX has distributed power, is designed to run at 200 km/h, and has a planned service speed of 180 km/h. In this paper, the running time and time saving of the tilting train was evaluated compared with today's conventional diesel multiple unit (DMU) trains and non-tilting electric multiple unit (EMU) trains, based on the Gyeongbu line, which was the candidate for the tilting train operation between Seoul and Busan (441.7km). We evaluated the potential of a speed-up of tilting trains on curves, on the basis of the trial run data of the tilting train on the Gyeongbu line and present the tilting train's competitiveness in terms of travel time and speed. We also analyzed dynamic running stability and riding comfort of tilting control through the trial run train. We found a significant reduction of the journey times compared with today's conventional trains. Approximately 11% reduction is expected on the Gyeongbu line.
Keywords: TTX (Tilting Train eXpress), riding comfort, dynamic running stability, conventional line, tilting control, diesel multiple unit (DMU), electric multiple unit (EMU).

1 Introduction

Tilting trains are kind of state-of-the-art vehicles applying active control technology in order to overcome a certain infrastructure limit of a conventional commercial line [1]. In Korea, the speed of trains could be enhanced on the

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existing railway network without a huge investment in infrastructure, by using tilting trains. An experimental test run was made in December 2006, to demonstrate the reliability and stability of a prototype train, and was conducted without critical failure on conventional lines. By the end of 2011, the experiment had resulted in a total of 153,000 km travelled.

The first TTX test run with the active tilting system was conducted on the Chungbuk line, which opened to the public on May 22, 2007. In February 2009, tests with increased speed, up to the planned service speed of 180 km/h, were made on the conventional line, with a maximum speed of 185 km/h. The test program of 100,000 km was completed on July 8, 2009, and was followed by high-speed testing on the Gyeongbu (Seoul–Busan) High Speed Railway (HSR) with 200 km/h achieved on November 19, 2009. In a further test in September 2010 on the second stage of the Gyeongbu HSR, the train achieved 222 km/h.

In addition, we conducted a trial run test to successfully speed-up 20%–30% on curves on a commercial service line in February, 2009. Normally conventional train has been operated 100km/h on the curve with 600m radius and 125km/h with 800m radius. But, the tilting train was tested 140km/h and 165km/h, respectively on the same curved section.

Figure 1: A trial run test photo of tilting EMU in Korea.

This paper describes firstly the development of the Korean tilting train. And then, we present a two step process mainly, which was used to determine the theoretic maximum acceptable speed on the curve sections. The first step is to define what maximum speed will maintain an acceptable maximum level of running stability and safety. The speed limit was applied to the TTX test run and we confirmed dynamic running stability was safety regarding wheel load, lateral force and bearing of track [2]. The second step is to identify the enhanced permissible speed for a tilting train that is adaptable to riding comfort on transition curves. We applied the new tilting control method based on GPS database and sensors. Finally, we present the estimated running times and time savings compared with today's conventional DMU trains and non-tilting EMU trains.

2 Main features of the Korean tilting train (TTX)

2.1 Performance factors of train

A prototype test tilting train is called the Tilting Train eXpress (TTX) with 6 coaches (distributed traction, 4 motor cars). TTX was manufactured in December 2006 and began an experimental trial run in 2007. TTX is designed to run at 200 km/h, and has a planned service speed of 180 km/h. Table 1 represents the key performance metrics list.

Table 1: Key performance factors, TTX.

Performance factor	Value
Train composition	6 cars tilting EMU (4 motor cars and 2 trailer cars)
Top speed in service	180 km/h
Length of train-set	143 m
Full weight with seated passengers	322 ton
Starting acceleration	0.50 m/s^2
Revenue braking rate	0.89 m/s^2
Emergency braking rate	1.00 m/s^2
Running resistance	$R=7{,}889+58.69v + 0.6507v^2$ (N) where v is speed (km/h)
Requested starting tractive effort	202 kN
Terminal speed of the constant torque area	85 km/h
Terminal speed of the constant power area	135 km/h

2.2 A lightweight composite vehicle

To minimize the impact of the increased forces that occur when running through curves at high speeds, the TTX should be as light as possible with a low center of gravity [3]. As shown by Figure 2, a hybrid body structure was developed to meet these requirements, with the upper part of the body shell made from a lightweight composite material, and the lower part fabricated from stainless and mild steel. The upper body of the TTX was fabricated using an aluminum honeycomb structure, sandwiched between carbon/epoxy skins. The use of this composite honeycomb plate reduced the overall weight of the body shell by around 20% compared with existing trains.

3 An evaluation on the speed up of the tilting train

3.1 Candidate Service Line

To improve the competitiveness of rail transport via increased speed passenger trains, the Gyeongbu line was considered a candidate for the tilting train service. As well, ensuring that the railway can offer the most attractive and reliable products and services, the upgrading of existing rail lines and the construction of new lines are in progress in Korea.

We reviewed the introduction of tilting train services into the Gyeongbu line (Seoul–Busan 441.7km) which is the first arterial rail corridor of the country. The existing Gyeongbu line links the first and second cities of the country along with the Seoul-Busan High-Speed Rail. It was upgraded from non-electrified double track to double electrified track with alignment upgrade as far as possible in 2004. Because the upgrade of the conventional Gyeongbu line was aiming at a double electrified track with the existing alignment utilized to the maximum, it has a lot of curves with small radii and a maximum track speed of only 140 km/h. As such, it is not expected to be further upgraded in terms of infrastructure and speed range (Figure 3).

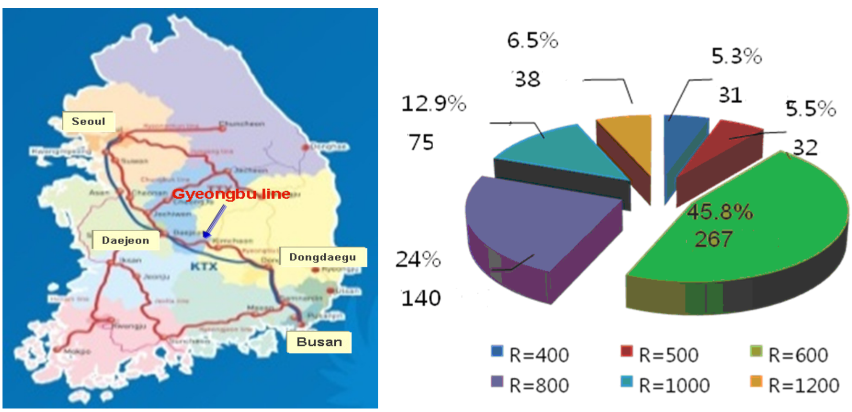

Figure 3: Distribution of the radius of curvature on the Gyeongbu line.

Nevertheless, customers demand a strengthened competitiveness through the introduction of new train services and the speed-up of the existing Gyeongbu line. Therefore, in order to achieve a speed-up without substantial investment on infrastructure improvement and meet the demands for enhanced train services, introducing tilting train services into the existing Gyeongbu line may be considered as an option.

The track may be characterized by the curve distribution which may be given as percentage of the total length of the track. Gyeongbu line (Seoul–Busan) has a variety of curves ranging from 400 m radius and up. The distribution of the radius of curvature is shown in Figure 4. The total length of this line is 441.7 km.

The length of the curves (circular curves and transition curves are included) constitutes in total 40.1% of the line.

3.2 Assumptions used in the running time calculation

The speed constraints for a tilting train around curves were calculated by section and curve radius, according to the two-step process shown in Figure 4 [4]. This process was used to determine the maximum acceptable speed, based on passenger comfort and safety evaluation by TTX test run. This speed limits are equal or 5~30 km/h higher than those of a non-tilting train following individual conditions of track alignment.

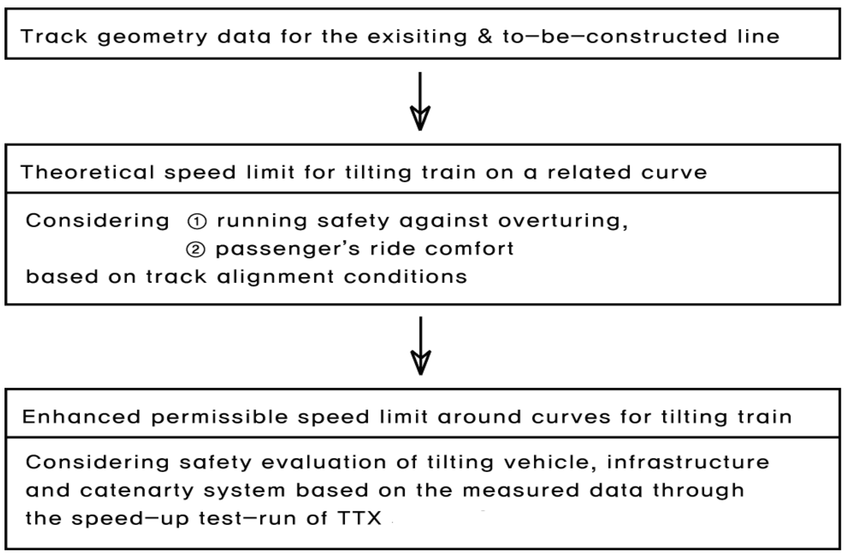

Figure 4: Process of setting the maximum speed for the tilting train in a given curved section of track.

The following Table 2 shows the travel times of Saemaul trains (existing train) under operation between Daejeon and East Daegu on the Gyeongbu line and those of TTX test-run. The comparison indicates about 11 minutes being saved by tilting trains when compared with the existing trains.

3.3 Running time results of tilting train on the Gyeongbu line

The Train-set Performance Simulation on Network Condition (TPS-ONC ver. 2.0) software was used to determine the running times. Route infrastructure and train performance characteristics were used to estimate the running times. A recovery margin of 11% of the simulated pure running time was added to the shortest run time between stops.

Table 2: Actual run test comparison between Saemaul and TTX train.

Station (From–To)	Distance (km)	Run-time for conventional train Saemaul from KORAIL timetable (A)	Run-time for TTX by actual test-run (B)	Reduced run-time (B-A)
Daejeon–Gimcheon	87.5	0:54	0:47	▽0:07
Gimcheon–Gumi	22.9	0:14	0:13	▽0:01
Gumi–Daegu	46.4	0:27	0:24	▽0:03
Daegu–East Daegu	3.2	0:03	0:03	▽0:00
Total	160.0	1:41[1]	1:30[1]	▽0:11

[1]3 minutes for 3 intermediate stops (1 minute for each stop) include in total.

In Table 3 different running times can be seen. First running time in third column from the timetable of KORAIL's web site was found. From this timetable, today's average running time (in 2011), included the stopping times at the intermediate stations, was calculated. Thereafter the simulated running times with today's speed limit for non-tilting train and the proposed speed limit for tilting train are shown in the fourth and fifth columns.

Table 3: Comparison between Saemaul and TTX train on Gyeongbu line.

Station	distance (Km)	2011 year Saemaul Time	Max. line speed 135~140km/h (10% spare time included)	
			EMU	Tilting-EMU
Seoul-Suwon	41	0:30	0:28 (△0:02)	0:27 (△0:03)
Seoul-Cheonan	97	1:05	1:00 (△0:05)	0:59 (△0:06)
Seoul-Deajeon	167	1:49	1:42 (△0:07)	1:37 (△0:12)
Seoul-Gimcheon	255	2:44	2:36 (△0:08)	2:27 (△0:17)
Seoul-Dongdaegu	327	3:31	3:23 (△0:08)	3:11 (△0:20)
Seoul-Milyang	383	4:12	4:00 (△0:12)	3:45 (△0:27)
Seoul-Busan	443	4:51	4:37 (△0:14)	4:20 (△0:31)
* ( ) reduction time compare to existing train(Saemaul)				

The running time for the tilting train in 2015 on the Gyeongbu line (Seoul–Busan) is 4 hours 20 minutes, which is 31 minutes shorter than that of conventional train journey in 2011, which took 4 hours 51 minutes. We showed 11 percentage of travel reduction time compared to the existing train (Saemaeul).

3.4 Test results of dynamic running stability and ride comfort

We tested dynamic running stability of tilting train on Gyeongbu line regarding wheel load and lateral force [5]. Figure 5 represents wheel load, lateral force and derailment coefficient values when tilting train has run at 165km/h on the curved section with R=800m. Figure 6 showed also a lateral acceleration running stability data of Gyeongbu line. According to these data, we confirmed running stability was safety regarding derailment coefficient and vehicle dynamic behaviors.

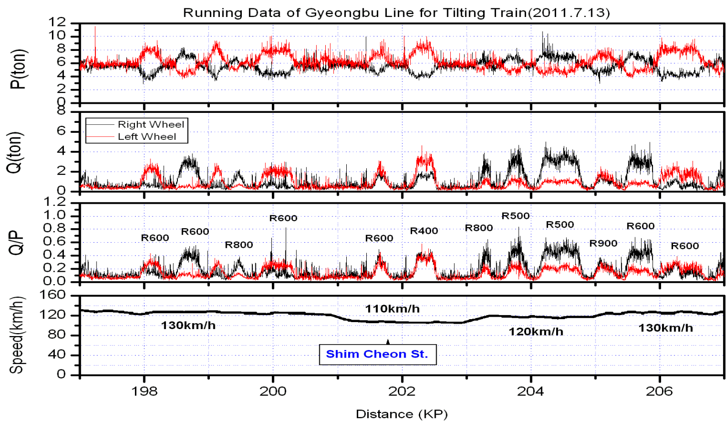

Figure 5: Wheel load, lateral force and derailment coefficient values when tilting train has run at 165km/h on the curved section with R=800m.

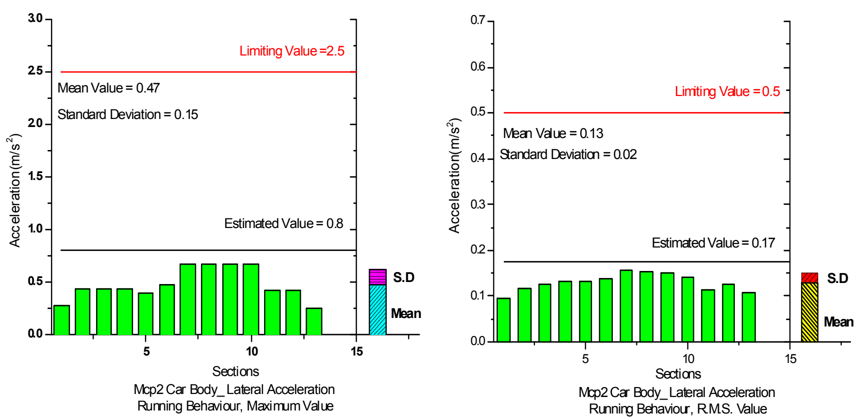

Figure 6: A lateral acceleration running stability data of Gyeongbu line.

Determining the start point of the tilting and tilting speed in the tilting control system play an important role to maintain the riding comfort. Generally the decreased train speed at curves is to prevent the decreased riding comfort rather than to adapt to the track conditions or train performance. That is, the speed limit is set for the lateral acceleration felt by passenger not to exceed a set value (0.08g for KORAIL) when the train negotiates a curve.

Tilting control using the satellite navigation devices was carried out for precision control of the electric tilting system. As shown by Figure 3, the front car, recognizing the curve in front of the train, sends the curve information to rear cars. The disadvantage of this method is that the riding comfort may be sacrificed due to the delayed tilting of the front car. In the case of pre-control method using satellite navigation system, however, the tilting operation can be carried out before the train enters the curve and the desired tilting commands can be executed to overcome the problems resulted from the delayed tilting time. With the improved control applied to the train to apply the tilting train in reality and improve the riding comfort, safer and more accurate control will be carried out. Train position was detected on curves from GPS database. Accelerate meter and Gyroscopic sensors detect the magnitude of the centrifugal acceleration, and each carriage is independently tilted by up to 8° as the train moves through a curved section of track.

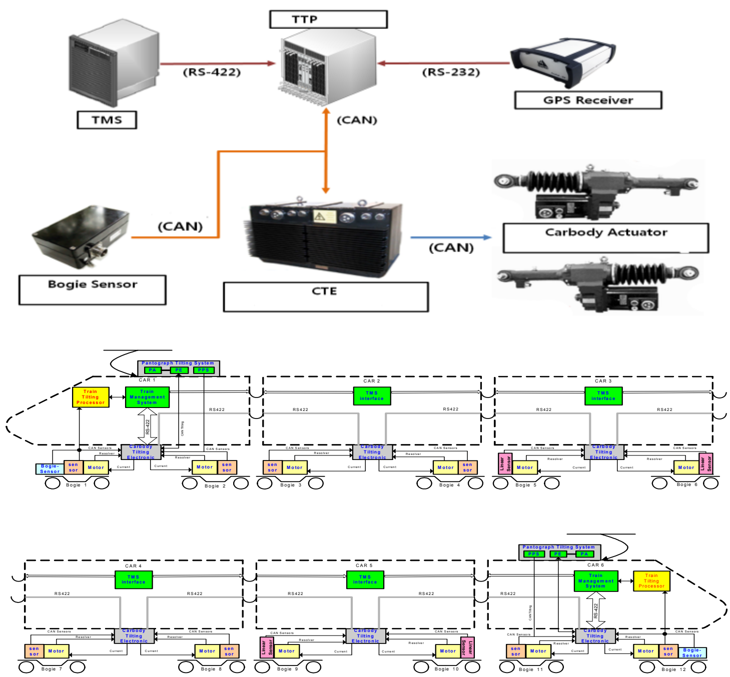

Figure 7: Configuration of the tilting control devices and network.

Figure 8 represents the position on curve with radius 800 m to get track condition and information using GPS data base. Figure 9 showed a ride comfort running data of Gyeongbu line (0.4-10Hz Bandpass filter) measured from the front coach. We confirmed ride comfort was satisfied in 0.8 m/s2 set values for KORAIL when the train go through a curve.

Figure 8: The position of rail condition measurement with GPS data base.

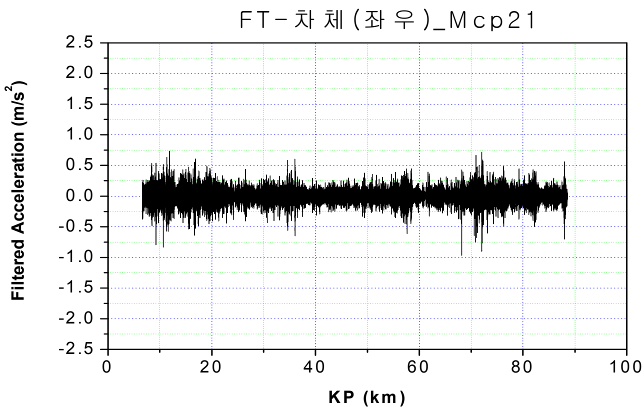

Figure 9: A ride comfort running data of Gyeongbu line (0.4–10Hz Bandpass filter).

4 Conclusions

Tilting train technology can be used to increase the speed on conventional tracks, where the cant would otherwise be insufficient to counteract the later acceleration [5]. As such, tilting trains consider as a solution to decrease travel times that is cost-effective because it does not require new track to be laid.

In this research, we evaluated the potential of a speed-up of tilting trains on curves, on the basis of tilting train trial run data on the Gyeongbu line and present tilting trains' competitiveness in terms of travel time and speed. We hope this will lead to introduce tilting train service on the existing Gyeongbu line in Koran rail network. Thus we anticipate tilting trains make rail travel more competitive with (a) a reduction in running time, (b) more frequent train departures, due to the reduced running time, (c) higher service quality, and (d) an improved image of the rail network from the point of view of the customer.

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