Running-time comparison of Tilting EMUs with Non-tilting trains on the Korean conventional railway, Jungang line

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ABSTRACT: Korea is a mountainous country, with as much as 70% of the area is covered by hills and mountains. This geography places constraints on the minimum radius of curvature for the rail network. It was expected that the speed of trains could be enhanced on the existing railway network without a huge investment in infrastructure by using tilting trains. The development of tilting trains in Korea started in 2001 as research & 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, we first describe the development of the Korean tilting train, and then present the estimated running times, and the time saving compared with today's conventional trains and non-tilting trains, based on the Jungang line. So the time saving could be separated into two effects by higher track top-speed and tilting devices.

1 GENERAL INTRODUCTION

Rail networks are attracting renewed attention in many countries, and in Korea railways are expected to play an increasingly important role in future transport infrastructure. To attract more traffic to the railways, it is important for railways to have competitive travel times. Growing competition from other modes of transport has necessitated a move towards in-creased performance. The running time of trains is the most obvious performance index, and this can be improved by introducing high-speed trains and upgrading the rail infrastructure, by constructing new high-speed tracks and improving existing tracks. High-speed trains require straighter tracks, and building a new high-speed track with a large radius of curvature is costly, and could only be justified where the passenger base is large, meaning that social and economic benefits are likely to be gained. There is also a need to shorten travelling times on existing lines where demand is too low to make it economically viable to construct new lines. Tilting trains, where it is possible to tilt the carriages towards the center of the curve, are a less expensive alternative to building new tracks with a larger radius of curvature. Tilting trains, such as the Italian Pendolino and Swedish X-2000, can reach speeds in excess of 200 km/h, and have seen considerable commercial success.

In Korea, the speed of trains could be enhanced on the 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 2010, the experiment had resulted in a total of 139,000 km travelled. We first describe the development of the Korean tilting train, and then present the estimated running times and the time saving compared with today's conventional trains, based on the Jungang line.

2 DEVELOPMENT OF THE TILTING-TRAIN IN KOREA

Korea is a mountainous country, with as much as 70% of the area is covered by hills and mountains. This geography places constraints on the minimum radius of curvature for the rail network, and as such favors the introduction of tilting trains. The benefits of using tilting trains in the Korean rail network are high-speed operation on new lines, replacement for diesel locomotives on conventional lines, and increased speed on conventional lines.

Since November 1985, the fastest trains on the conventional network were the Saemaul diesel unit, which has a maximum service speed of 140 km/h, and has now been running for over 20 years. On June

1, 2009, the new eight 4-car EMUs (electric multiple unit), branded Nooriro, but made by Japan Technology, were put into service on trunk lines, with a maximum service speed of 150 km/h. The tilting train would close the speed gap between the Saemaul (or Nooriro) and the KTX series, and is designed to operate at speeds up to 200 km/h. Furthermore, the growing concern over air pollution and noise emission has provided motivation for the move from the diesel-powered Saemaul trains to electric trains.

Figure 1 Photographs of the TTX tilting-train

The development of tilting trains in Korea started in 2001. 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.

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. 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 30% compared with existing trains.

Conventional trains must slow down considerably on curved sections of track to reduce the effects of centripetal acceleration on passenger comfort. On tilting trains, a set of computer-controlled actuators alter the angle of the carriage with respect to the track to compensate for the centripetal acceleration so that the resulting acceleration experienced by the passengers remains perpendicular to the floor of the carriage. Gyroscopic sensors detect the magnitude of the centripetal acceleration, and each carriage is independently tilted by up to 8° as the train moves through a curved section of track. Figure 2 illustrates the concept of the tilting train; the effect is analogous to that achieved by the ice skaters shown in the top right of the figure.

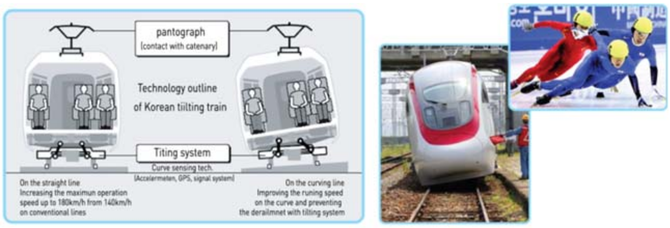

Figure 2 The concept of the tilting-train

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 High Speed Railway (HSR) with 200 km/h achieved on November 19, 2009. In a further test in September 2010 on the (not yet opened) second stage of the Gyeongbu HSR, the train achieved 222 km/h.

3 PERFORMANCE OF A TILTING-TRAIN

The running times depend strongly upon the dynamic (acceleration/deceleration) capabilities of the trains. So, to get more reliable running time through simulation, the simulated dynamic performance of TTX needs to be evaluated in comparison with its actual result of test-run.

The comparison is made by acceleration profile for a TTX, of which key performance factors are shown in Table 1, on the 2.9km straight track around Noan station in Honam line (Figure 3).

Table 1 Key performance factors, TTX

Performance factor	Value
Train composition	6 cars tilting EMU (4 motor cars & 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	$R=7{,}889 + 58.69\ v + 0.6507\ v^2$ (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

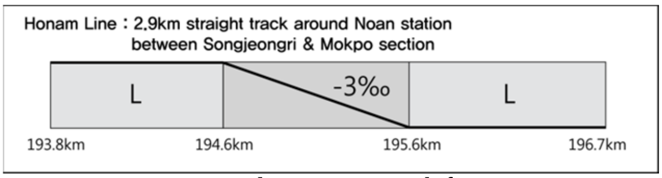

Figure 3 Acceleration test track for a TTX

Figure 4 shows the acceleration simulation curve (bottom, green line) of the TTX as compared to its actual test-run result (middle, red line). It can be seen that there is hardly any difference in acceleration between simulation and real full-scale test. Therefore, the running times can be simulated with advanced computer package for train performance and track geometry data.

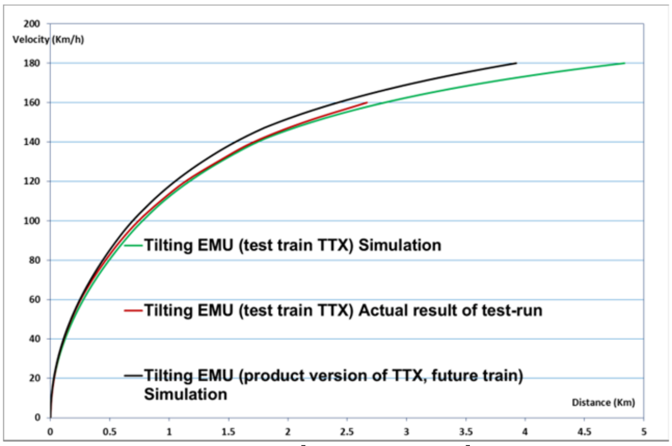

Figure 4 Comparative tilting EMU acceleration curves

Meanwhile, the base running times is for the future train with key performance metrics listed in Table 2. Future train assumed a typical tilting EMU, which will be a production version of TTX, and the performance was in accordance with KORAIL specification for a 180 km/h non-tilting EMU.

Table 2 Key performance metrics, future train version of TTX

Performance factor	Value
Train composition	6 cars tilting EMU (4 motor cars & 2 trailer cars)
Top speed in service	180 km/h
Length of train-set	141 m
Full weight with seated passengers	330 ton
Starting acceleration	0.56 m/s^2
Revenue braking rate	0.83 m/s^2
Emergency braking rate	1.11 m/s^2
Running resistance	R=4,401 +56.30v + 0.5040 v^2 (N), where v is speed (km/h)
Requested starting tractive effort	212 kN
Terminal speed of the constant torque area	90 km/h
Terminal speed of the constant power area	135 km/h

As shown above Figure 4, the production version of TTX (top, black line) is able to accelerate much faster than TTX. This difference in acceleration can result in a substantial improvement in starting acceleration rate and starting tractive effort. Particularly, the terminal speed of the constant torque area, up to which starting tractive effort continues long, is 5 km/h higher than test train.

4 RUNNING-TIME COMPARISON OF TILING EMUS WITH NON-TILGING TRAINS

4.1 *Candidate service line*

To improve the competitiveness of rail transport via increased speed trains, Jungang line was considered for the new passenger train service.

As well, to ensure 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. The modernization of the railway infrastructure is being undertaken on the above Jungang line, and an improved situation, which is expected to come into service in 2013, is taken into account in the running time calculation.

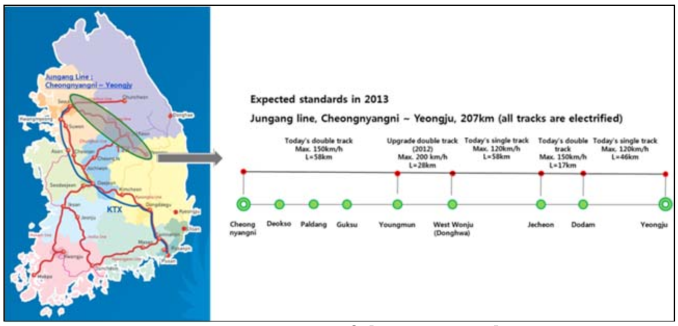

Figure 5 Location of the Jungang line

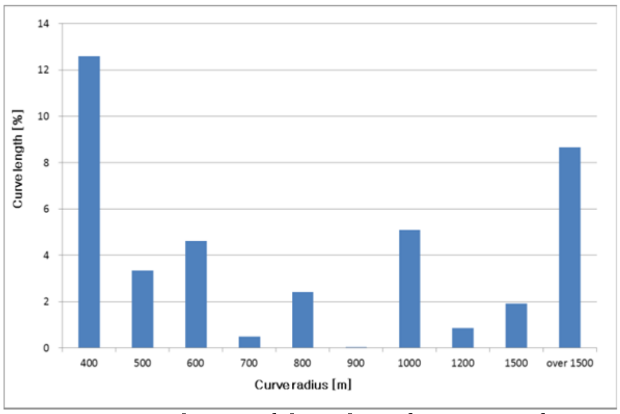

Figure 6 Distribution of the radius of curvature of the bend on the Jungang line

The track maybe characterized by the curve distribution which may be given as percentage of the total length of the track. Jungang line (Cheongnyangni ~ Yeongju) has a variety of curves ranging from 400 m radius and up. The distribution of the radius of curvature is shown in Figure 6. The total length of this line is 207 km as of 2013. The length of the curves (circular curves and transition curves are included) constitutes in total 40.1% of the line. 31.4% of the length of the track consists of curves with a radius of curvature of less than 1,500 m.

4.2 Assumption used in the running time calculation

It is assumed that new passenger train will be operated as an express service between hub stations. The stopping pattern includes five intermediate stops (excluding the start and end stops) for the Jungang line. The dwell time at each stop is 1 minutes.

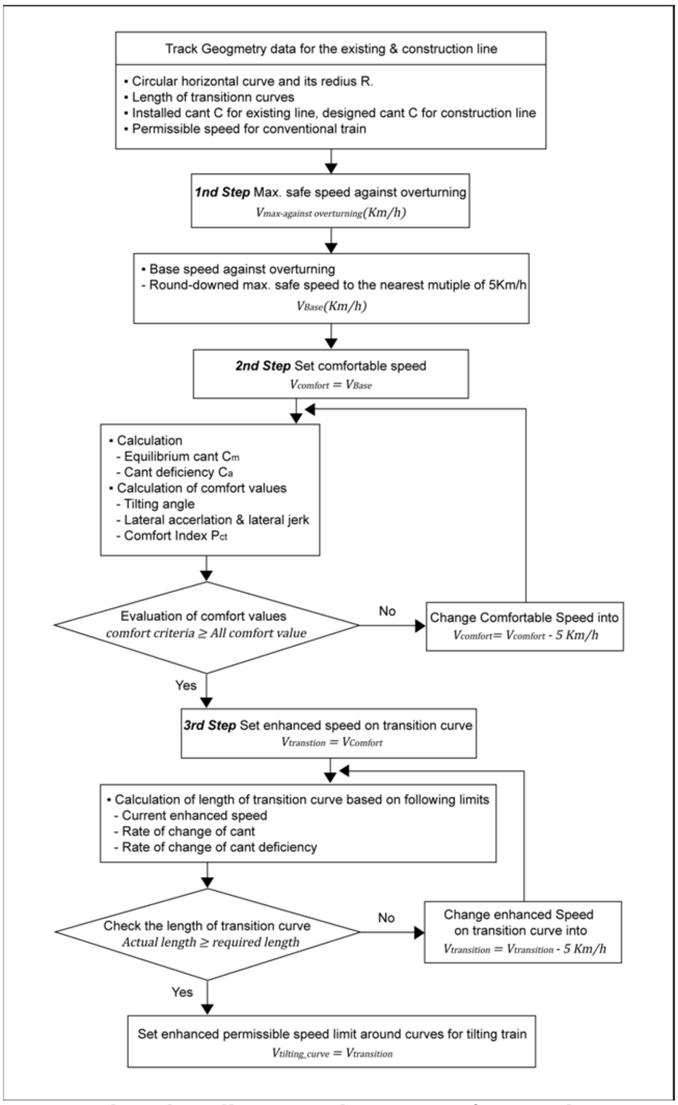

Figure 7 Flow chart illustrating the process of setting the maximum speed for the tilting train in a given curved section of track

According to the *Detailed rules for the driving of train (train operation rule)*, there are three different speed restrictions in a given section of track: down-grade sections, station boundaries, and curve sections. The down-grade speed limits are applied both the existing line and the to-be-constructed line. The speed level at the station boundaries are prescribed by this rule only for the existing railway. With the help of consultation with KORAIL experts, these speed limits for the to-be-constructed line will be reduced to 20 km/h below the maximum track design speed.

The speed constraints for a tilting train around curves were calculated by section, and curve radius, according to the three-step process, summarized in the flow chart shown in Figure 7. This process was used to determine the maximum acceptable speed, based on passenger comfort. This speed limits are 20~30 km/h higher than those of a non-tilting train.

4.3 Running time saving of tilting-train compared to non-tilting train around curve

With tilting-trains the maximum speed in curves can be heighten. Trains with tilting technique switched on use a separate speed profile like shown Figure 8.

This figure shows speed limits around an example curve section on the Jungang line. It contains straight sections and a curved section with radius R=600 m.

The yellow line represents the speed progress of the active train for the selected line section. The red and green lines show the difference of speed band between a non-tilting and a tilting train. Especially in the curved section the tilting train can reach higher speed (+30 km/h in this example Figure 8) and due to this, shorter running times.

So the running time can be shortened depending on the line equipment and status. The example tilting train in Figure 8 can be driving 6.1 sec faster than non-tilting train, which is an almost 14% reduction in running time from 42.8 sec. for non-tilting train to 36.7 sec.

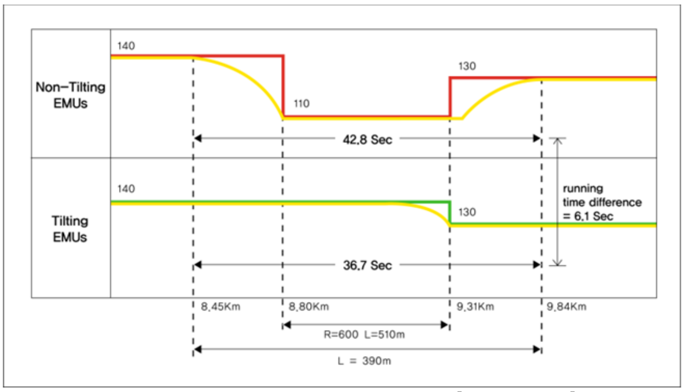

Figure 8 Running time comparison around an example curve on the Jungang line

4.4 Possible running-time comparison between non-tilting and tilting train on the Jungang 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 3 Possible running time comparison

Relations	Distance in 2013 (km)	Avg. running time for **conventional train** in 2009 (min.) (A)	Simulated 11% margin (in 2013)			
			Exp. Running time for **non-tilting train** (min.) (B)	Exp. Running time for **tilting train** (min.) (C)	Reduces Rate (%)	
					$\frac{A-B}{A}$	$\frac{B-C}{B}$
Cheongnyangni~ Wonju	97.9	1:48	0:55 (▽0:53)[1]	0:53 (▽0:02)[2]	49	4
Cheongnyangni~ Jechon	144.5	2:31	1:33 (▽0:58)[1]	1:30 (▽0:03)[2]	38	3
Cheongnyangni~ Yeongju	207.2	3:33	2:23 (▽1:10)[1]	2:16 (▽0:07)[2]	33	5

1) Reduced run-time for non-tilting compared with today's conventional train is written in parenthesis.
2) Reduced run-time for tilting compared with non-tilting train is written in parenthesis.

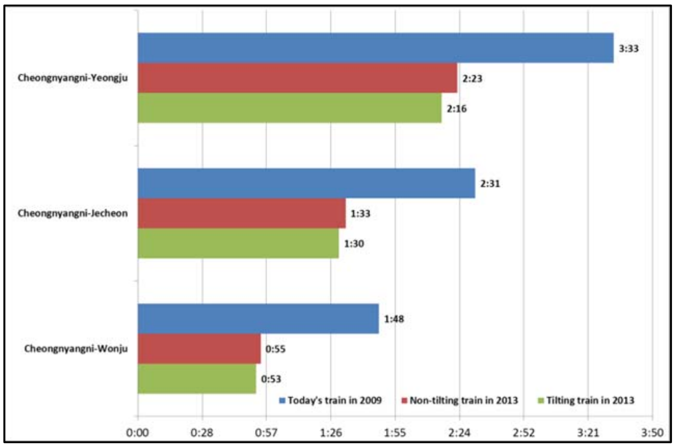

Figure 9 Possible running time comparison between current conventional train, non-tilting and tilting train

In Table **3** different running times can be seen. First running time in second column from the timetable of KORIL's web site was found. From this time table, today's average running time (in 2009), included the stopping times at the 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 third & fourth columns. Note that today there are eight or more stops, but in the simulations there are only five intermediate stops.

There is a large discrepancy between run-time for today's conventional train and the simulated run-time for non-tilting train with today's speed limits, especially between Cheongnyangni and Wonju. In 2013, the running time for non-tilting train on this section will be 55 minutes, which is 53 minutes shorter than today's journey, a 49% time saving. Because most parts of this section were rebuilt or will be rebuilt to larger curve radii, and maximum track speed is to be higher.

By introducing a tilting train, a time reduction of more 4% is achieved on the same section. The simulation for tilting train shows that the running time will be further decreased with 2 minutes.

The running time for the tilting train in 2013 on the Jungang line (Cheongnyangni~Yeongju) is 2 hours 16 minutes, which is 1 hour 17 minutes shorter than that of conventional train journey in 2009, which took 3 hours 33minutes. This decrease is separated into two effects.

The first effect is due to the increased top-speed of track, which results from upgrading the line to larger curve radii. 1 hour 10 minutes, 90%, of the total time saving is explained by this effect. But on the other hand, the time saving benefit with tilting device is only 10% - 7 minutes - from reduced total running time.

5 CONCLUSION

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. 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 paper, the running time of tilting train on the Jungang line was evaluated and we found a significant reduction of the journey times as of 2013 compared with today's conventional trains. Approximately a 36% reduction is expected on the Jungang line, from Cheongnyangni (east Seoul) to Youngju. But the 90% of this reduction is due to the increased track speed through upgrading the line and the rest 10% by tilting technology. This large difference is explained by the fact that most sections of the line were rebuilt or will be rebuilt to larger curve radii, thus this leads not to fully use the speed benefits through tilting.

Therefore further research should be made where research can improve the competitiveness of tilting train. We need to find the best railway lines, where tilting trains reduce the running times more than the infrastructure upgrade does, which have speed restrictions in some curves to avoid large costs for changes in the infrastructure.

This will be expected to make rail travel more competitive for the following reasons: (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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