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Prediction of speed limit on the railway track using track quality index and multibody dynamics simulation

Hera Widyastuti[1,a] *, Amisani Fatah Sedayu[2,b], Wahyu Satyaning Budhi[3,c], Wing Kong Chiu[4,d], Istiar[1,e]

[1]Department of Civil Engineering-ITS, Jl. Arief Rahman Hakim, Surabaya, Indonesia

[2]Under-Graduate of Civil Engineering Department-ITS, Jl. Arief Rahman Hakim, Surabaya, Indonesia

[3]Civil Engineering, Politeknik Negeri Banyuwangi, Jalan Raya Jember KM 13, Banyuwangi, Indonesia

[4]Mechanical and Aerospace Department, Monash University, Melbourne 3800, Australia

[a]*hera.widyastuti@yahoo.co.uk, [b]amisani2249@gmail.com, [c]wahyu.satyaningbudhi@poliwangi.ac.id, [d]wing.kong.chiu@monash.edu, [e]istiar@yahoo.com

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Abstract. The performance of track conditions must be thoroughly assessed to ensure the safe operation of the train that travels through the track. The Track Quality Index (TQI) is used to determine the condition of the railway track. The TQI value is a statistical summary of track geometry parameters measured over a specified track length. There are several methods used to analyze TQI including the Indonesian Railway standard (PT. KAI). The KAI's analysis method of the TQI is a sum up of four parameters which are alignment, longitudinal level, cross-level, and track gauge. Moreover, TQI is used to determine the speed limit allowed for the train to pass through the track. A multibody dynamic system simulation was recently performed as a reference to compare track quality assessments based on driving safety and vertical loads on rails, in which one of the outputs is the speed limit. This result shows that the speed limit based on the multibody system is slightly lower at certain segments compared to the TQI.

Introduction

In the last two decades, the train has become one of the most popular modes of land transportation in Indonesia, appealing to people of all socioeconomic backgrounds. As a mode of transportation, trains are quite efficient as they have used less land per passenger as well as environmental impact compared with other modes of land transport [1]. Therefore, improving the service quality should be considered to maintain passenger satisfaction. This is closely related to the importance of monitoring the railway track and rolling stock condition [2]. One of the parameters of user satisfaction is the absence of delays and travel time that can compete with private transportation. Where the delay will have an impact on the quality of its railway capacity [3]. The travel time will be related to the running speed of the train. The higher the speed needed, the better railway track condition needed.

Track Quality Index (TQI) is one of the methods that provides the possibility to assess the performance indicators of a railway line. In addition, TQI can also summarize and display the condition of most train tracks which can be used to monitor track quality degradation [4]. Meanwhile, technological innovations significantly impact developments in transportation maintenance, especially railway maintenance. The Multibody System (MBS) is one of the software that is used to represent the railway condition such as critical speed, passenger comfort, derailment, wear, and fatigue. It has been widely utilized to analyze the dynamic behavior of rolling stock running on arbitrary tracks while arbitrary maneuvers [5].

Further research is needed on the application of TQI in Indonesia. In this study, analysis was carried out in a comparative way using quantitative and descriptive methods. The results of speed recommendations based on TQI analysis are compared with vehicle responses from multibody dynamics simulation. It is essential to comprehend the value of railway quality in each approach as well as the factors that could affect it.

Experimental Objective

The Operational Areas or Daerah Operasional (DAOP) of the railway in Java are divided into nine operational areas. This study is conducted on Java at several points of train track locations in Operational Area Seven (Daerah Operasional (DAOP) VII). The trajectory point under review starts from Kertosono - Mojokerto at KM 82 - KM 86. In addition, this location was chosen because this segment has expanded to being a double track [3], [6]. The detailed location of this case study is shown in Fig. 1.

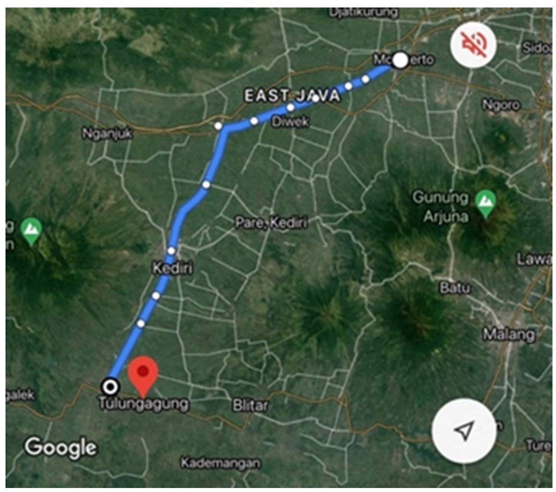

Fig. 1 Operational Area Seven Location (Kertosono – Mojokerto)

Source: Google Maps

Literature Review

Track Quality Index (TQI) Method

The railway track's quality and evaluation of its condition will relate to its maintenance. As a basis for determining the quality of railways and evaluating their condition, a standard value is needed to evaluate the quality of railways called the Track Quality Index (TQI) [4], [7]. The safety risks from the trackside and the rail maintenance method on the train depending on the track's maintenance and the speed limits of the trains operating on the track [8]. In measuring the track quality index, several parameters of the geometry of the railway are needed that affect the measurement of the quality of the rail, including the lift, the alignment, the height, the width of the track, twist, curvature, and warp [7], [9]–[11].

In Indonesia, the quality index is obtained by adding up 4 (four) measurement parameters, namely crosslevel, alignment, profile, and track gauge. To get the data of these geometric parameters, measurements are needed by the train. The measuring train used by PT. Kereta Api Indonesia is the EM-120 type [12]. The calculation segmentation depends on the method used, including 25-40 meters at every 200 meters [8], [13]. In addition, the quality index can also be used to monitor track degradation and summarize most railway track conditions. The rail quality index is calculated by taking the standard deviation of the parameters in each segment that has been determined.

The track quality index is calculated using the standard deviation of each parameter in this approach. Eq. 1**.** is used to calculate its value.

$$SD = \sqrt{\frac{\sum Xi^2 - \frac{Xi^2}{n}}{n-1}} \quad (1)$$

Where SD represents Standard Deviation, Xi represents the current value of the data, while n represents the number of values in the data.

The track quality index value is calculated by adding the standard deviation values of each track geometry parameter, as shown in Eq. 2**.**

$$TQI = SD1 + SD2 + SD3 + SD4 \quad (2)$$

The standard deviation values of the four geometric parameters, namely cross-level, alignment, profile, and track gauge, are represented by the values SD1, SD2, SD3, and SD4.

In calculating the quality of railway, the necessity for a limit is employed to derive the quality index. Table 1 shown the speed limit standard implemented by PT. Kereta Api Indonesia based on the TQI value calculated using KAI's method.

Table 1 The standard Track Quality Index assessment [14]

Number	TQI Total	Speed (km/hour)	Category
1	<20	100-120	Very Good
2	20-35	80-100	Good
3	35-50	60-80	Moderate
4	>50	<60	Poor

Multibody Dynamic Testing Method

Technological advances have greatly influenced developments in the field of transportation. Assistive applications are being developed to maximize productivity. Especially in the multibody dynamics simulation which uses Universal Mechanism (UM). The Universal Mechanism (UM) is a software system in the form of modeling the dynamics of railway vehicles by representing vehicles with a system of rigid and/or elastic bodies (Multibody System, MBS). This software has been made to simulate trains to the computer from the kinematic and dynamic processes of different mechanical systems [15]. Examples of bogies of a locomotive model can be seen in Fig. 2.

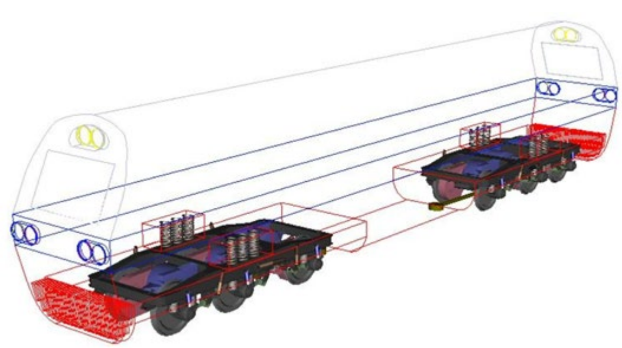

Fig. 2 Model of Bogie and Locomotive [16]

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Universal Mechanism Simulation

Throughout this simulation stage, dynamic testing is performed to analyze 2 (two) aspects: driving safety and railway load. Dynamic testing is carried out at various speeds in accordance with the universal mechanism standard. Dynamic test simulations were also conducted on 15 straight railway segments with a track length of 1 km per segment. In addition, each railway segment will have a different KAI standard TQI value.

Driving safety is obtained from the large value of the lateral force on the railway wheel device. The simulation variable used is the combination of the right wheels' lateral forces, which are added to the left wheels' lateral force to obtain the lateral force of each wheel. All simulation results analyzed are the lateral forces of the wheels on each bogie. The simulation results are compared to the limit of driving safety. The driving safety limit is determined by estimating the lateral load weight exerted by the railway wheels on the rails, which can be accomplished using Eq.3 [17].

$$Drivingsafetylimit = \alpha\left(10 + \frac{P_0}{3}\right) \tag{3}$$

Where α is a traction unit, and P_0 is the axle load. In addition, the driving safety limit and P_0 are stated in kN.

The load assessment on the railway can be done by using the maximum vertical force that occurs on the wheels. The simulation variable is the vertical force on each wheel. The vertical style of the trained model has 8 wheels on each set. The results of the simulation of the vertical forces obtained are compared with the maximum and minimum limits of the vertical forces. The track loading limit is determined by calculating the weight of the vertical forces applied by train wheels to the rail. This can be achieved by using Eq.4 [17]**.**

$$Trackloadinglimit = 90 + Q_0 \tag{4}$$

Where Q_0 is a static load on each wheel of the train. Furthermore, the track loading limit and static load are expressed in kN.

Result and Analysis Discussion

TQI Analysis

The data used was obtained from the measuring train. The measuring train is computed in segments, which are 200 m long and have 800 data in every segment. The track quality index is calculated by adding the standard deviation values of each track geometry parameter using Eq. 1 and 2 above. After obtaining the standard deviation calculation results, the track quality index value can be calculated using the existing method. The TQI value is shown in Table 2.

As seen in Table 2 above, the TQI value for all segments is below 20, which means that the train is allowed to pass at speeds between 100-120 km/hour at that segment.

Table 2 TQI values of Kertosono-Mojokerto

INDONESIAN STANDART					
Trip	**Segment**	**KM**	**TQI**	**Category**	**Speed Limit**
Ktsn-Mjkt	I	82+000 - 82+200	16,1146425	< 20	100-120 km/h
Ktsn-Mjkt	II	82+200 - 82+400	15,8793248	< 20	100-120 km/h
Ktsn-Mjkt	III	82+400 - 82+600	11,2537936	< 20	100-120 km/h
Ktsn-Mjkt	IV	82+600 - 82+800	14,9633809	< 20	100-120 km/h
Ktsn-Mjkt	V	82+800 - 83+000	19,4361028	< 20	100-120 km/h
Ktsn-Mjkt	I	84+000 - 84+200	9,96042939	< 20	100-120 km/h
Ktsn-Mjkt	II	84+200 - 84+400	10,5794153	< 20	100-120 km/h
Ktsn-Mjkt	III	84+400 - 84+600	7,97946557	< 20	100-120 km/h
Ktsn-Mjkt	IV	84+600 - 84+800	18,9112343	< 20	100-120 km/h
Ktsn-Mjkt	V	84+800 - 85+000	16,8108981	< 20	100-120 km/h
Ktsn-Mjkt	I	85+000 - 85+200	10,0887644	< 20	100-120 km/h
Ktsn-Mjkt	II	85+200 - 85+400	6,84086827	< 20	100-120 km/h
Ktsn-Mjkt	III	85+400 - 85+600	10,2196279	< 20	100-120 km/h
Ktsn-Mjkt	IV	85+600 - 85+800	12,835213	< 20	100-120 km/h
Ktsn-Mjkt	V	85+800 - 86+000	9,07318428	< 20	100-120 km/h

The Driving Safety Limit and the Load on Track Result

Dynamic testing is carried out to analyze two aspects, which are driving safety and the load on the railway. Dynamic testing was carried out at several different speeds, 60 km/hour; 80km/hour; 100 km/hour, and 120 km/hour. In addition, the lateral and vertical loads that occur on the wheels were also tested. The maximum lateral load limit deemed to be safe at a certain speed is 25.671kN. Meanwhile, the maximum vertical load allowed is 94.273 kN.

Table 3 Lateral and Vertical Load Simulation Results of DAOP VII (Kertosono - Mojokerto)

Trip	Segment	KM	Lateral Load (kN)	Speed Limit	Vertical load Testing (kN)	Speed Limit
Ktsn-Mjkt	I	82+000 - 82+200	26,80520898	80 km/h	119,3827656	100 km/hour
Ktsn-Mjkt	II	82+200 - 82+400				
Ktsn-Mjkt	III	82+400 - 82+600				
Ktsn-Mjkt	IV	82+600 - 82+800				
Ktsn-Mjkt	V	82+800 - 83+000				
Ktsn-Mjkt	I	83+000 - 82+200	15,75104199	100 km/h	106,2932344	80 km/hour
Ktsn-Mjkt	II	83+200 - 83+400				
Ktsn-Mjkt	III	83+400 - 83+600				
Ktsn-Mjkt	IV	83+600 - 83+800				
Ktsn-Mjkt	V	83+800 - 84+000				
Ktsn-Mjkt	I	84+000 - 84+200	16,31691406	100 km/h	115,829125	100 km/hour
Ktsn-Mjkt	II	84+200 - 84+400				
Ktsn-Mjkt	III	84+400 - 84+600				
Ktsn-Mjkt	IV	84+600 - 84+800				
Ktsn-Mjkt	V	84+800 - 85+000				
Ktsn-Mjkt	I	85+000 - 85+200	27,56689844	80 km/h	99,75774219	80 km/hour
Ktsn-Mjkt	II	85+200 - 85+400				
Ktsn-Mjkt	III	85+400 - 85+600				
Ktsn-Mjkt	IV	85+600 - 85+800				
Ktsn-Mjkt	V	85+800 - 86+000				

Based on the 100km/hour simulation, there were several segments that went over the vertical and/or lateral load limit. For that reason, it is recommended to reduce the speed limit to below 100km/hour in those segments.

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The results of lateral and vertical load testing as load limits on the rails and speed limits on each track tested can be seen in Table 3.

Table 4 Final Speed Limit Results by DAOP VII Simulation DAOP VII (Kertosono - Mojokerto)

Trip	Segment	KM	Parameters	Speed Limt
Ktsn-Mjkt	I	82+000 - 82+200	**Load on rail**	100 km/hour
Ktsn-Mjkt	II	82+200 - 82+400		
Ktsn-Mjkt	III	82+400 - 82+600		
Ktsn-Mjkt	IV	82+600 - 82+800		
Ktsn-Mjkt	V	82+800 - 83+000		
Ktsn-Mjkt	I	83+000 - 82+200	**Load on rail**	80 km/hour
Ktsn-Mjkt	II	83+200 - 83+400		
Ktsn-Mjkt	III	83+400 - 83+600		
Ktsn-Mjkt	IV	83+600 - 83+800		
Ktsn-Mjkt	V	83+800 - 84+000		
Ktsn-Mjkt	I	84+000 - 84+200	**Load on rail**	100 km/hour
Ktsn-Mjkt	II	84+200 - 84+400		
Ktsn-Mjkt	III	84+400 - 84+600		
Ktsn-Mjkt	IV	84+600 - 84+800		
Ktsn-Mjkt	V	84+800 - 85+000		
Ktsn-Mjkt	I	85+000 - 85+200	**Driving safety, Load on rail**	80 km/hour
Ktsn-Mjkt	II	85+200 - 85+400		
Ktsn-Mjkt	III	85+400 - 85+600		
Ktsn-Mjkt	IV	85+600 - 85+800		
Ktsn-Mjkt	V	85+800 - 86+000		

Meanwhile, the results of driving safety limits and railway loads on the DAOP VII (Kertosono - Mojokerto) are shown in Table 4.

Comparison of Speed Limit Calculation Results for Each Method

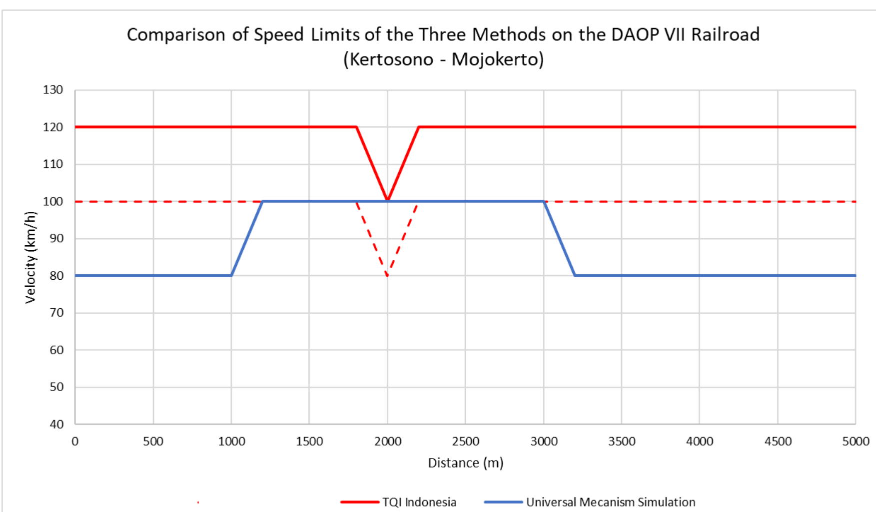

Fig. 3 Comparison of Speed Limits of the Three Methods on the DAOP VII Railway (Kertosono - Mojokerto)

At this stage, the comparison is carried out as a whole and at several points. As illustrated in Fig. 3, the TQI value shows the calculation of the TQI for railways using the KAI's method and UM train simulation. The result using the KAI's method dominated by the "Very Good" category for the railway span with a speed limit of 100 km/hour - 120 km /hour and followed by the "Good" category with a speed limit of 80 km/hour - 100 km/hour in one segment. Furthermore, in the calculations using the Universal Mechanism (UM) train simulation, the speed is dominated by 80 km/hour and followed by 100 km/hour in several segments. With this comparison, it is found that the suitability of the average speed limit approach with TQI the KAI's of the UM simulation is around 80.58%. Therefore, considering safety, it has been recommended that operating speed at Kertosono - Mojokerto in the range of 80 km/hour - 100 km/hour.

Conclusion

From the analysis above, it can be seen that the travel speed limit using the simulation is lower in some segments compared to when using the TQI analysis. This might happen because the TQI speed analysis is based on the standard deviation, meanwhile, the UM analysis method is based on a combination of track condition values, which are influenced by lateral and vertical forces that occurs on the wheels. Therefore, in determining the speed limit on the Indonesian Railway, it is necessary to consider the influence of lateral and vertical loads.

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