

Original Paper

Estimating the Reliability of Travel Time on Railway Networks for Freight Transportation

Safoura Salehi¹ & Abbas Mahmoudabadi^{2*}

¹ Faculty of Civil Engineering, Islamic Azad University, South Tehran Branch, Tehran, Iran

² Department of Industrial Engineering, MehrAstan University, Guilan, Iran

* Abbas Mahmoudabadi, Department of Industrial Engineering, MehrAstan University, Guilan, Iran

Received: April 27, 2018

Accepted: May 10, 2018

Online Published: May 17, 2018

doi:10.22158/uspa.v1n1p75

URL: <http://dx.doi.org/10.22158/uspa.v1n1p75>

Abstract

Railway freight transportation is an important transport system that its reliability causes economic issues. Freight carriers require predictable travel times to schedule their programs in competitive environment, so the estimation of reliability of travel time is very important. The present study proposes a travel time index that estimates the reliability of railway freight transportation and evaluates performance as well. Travel time reliability is estimated based on the shortest path between O-D pairs. Statistical measures of travel time, defining as the ratio of the 95th percentile travel time and the shortest path mean travel time as an ideal travel time, for each obtained route are calculated according to their selected links. Experimental data on Iranian rail network has been used as case study and results revealed that the routes less than 400 kilometers should be improved in terms of their reliabilities, because they are less reliable than long distance routes.

Keywords

reliability, travel time reliability, railway network, railway freight transportation

1. Introduction

1.1 Background

In the 20th century, transportation programs were focused on developing transportation network infrastructures while in the 21st century the focus has shifted to network management and operations (Shawn, 2003). Transportation agencies are now dealing with improving the reliability of the transportation system to reduce the growth of congestion and provide mobility operations. Thus, there should be measures of both average conditions and indications of how often and/or how much the performance varies from the average (Lomax et al., 2003).

The theory of reliability has been associated with the design and management of communication and performance of mechanical equipment. It is defined as “the probability that an entity will perform its intended function(s) satisfactory or without failure for a specified length of time under the stated operation conditions at a given level of confidence” (Kececioglu, 1991).

Travel time reliability is one of the important system performance measures for transport operations. It is an indicator for facility operational consistency over an extended period (Emam et al., 2006). Travel time reliability is defined as the probability that a trip between a given origin-destination pairs can be successfully made within a specific period of time (Recker et al., 2005). There are many different definitions for travel time reliability and subsequently different measures for estimating that in transportation networks. All these measures relate to properties of the (day-to-day) travel time distribution and the distribution curve shape (Van Lint et al., 2008). In fact, the reliability of travel time may be more important than the travel time itself for travelers, shippers, and transport managers for planning and programming (Lyman et al., 2008). A reliable travel time is more important than a delay-free travel time for some segments of nations’ economy. It is also important because urban residents react to unexpected travel time rather than mean/average travel time. Any interruptions can significantly decrease shippers and traveler satisfaction and increase frustration (Lomax et al., 2003).

Today, railway freight transportation is one of the most important transport systems that its disruption may cause remarkable economic issues including delayed delivery penalties and customer losses. Shippers and freight carriers require predictable travel times to schedule their transport programs in the competitive environment, so, they seek the systems which can deliver the raw materials with the minimum or at least predictable delays. The estimation of the reliability of travel time is an effective method to find such systems which improve regional transportation planning systems and their operations.

The aim of the present research work is to estimate the reliability of railway network based on the reliability of routes’ links. This article is organized as follows. The following section briefly recalls a number of common used travel time reliability measures. In the next section, another measure of travel time (un)reliability is derived. Then, the travel time reliability of a selected railway network is estimated using empirical data set followed by comparing the new and old measures based on experimental data. Discussion on obtained results at the final section offers some conclusions and recommendations for researchers and practitioners.

1.2 Common Used Travel Time Reliability Measures

The travel time reliability measures are more generally defined and directly applied to the data and derived from continuous probability distributions. There are two categories of travel time reliability measures. The first category is including measures based on the moment (e.g., mean, standard deviation, Skewness, Kurtosis, and coefficient of variance) and measures based on percentile are the second category, e.g., the 90th or 95th percentile, buffer index, planning time index (Yang et al., 2016). The following provides a subset of travel time reliability measures that are used by different sources

over time and collected in periodic special studies, estimates from continuous point-based detector data, or estimation created through simulation (FHWA, 2007).

1.2.1 Standard Deviation

Standard deviation is a classic stat which is suitable for travel time reliability in studies with classic mathematical or statistical models (Dong et al., 2009). In standard deviation, all late and early arrivals have equal weights; thus, U.S. DOT guide (Texas Transportation Institute and Cambridge Systems, 2009) and NCHRP Report (Cambridge Systematic, 2008) discouraged its use as a reliability performance measure. Segments with narrow curves of average travel time have insignificant travel time variation from day to day; hence, they are more reliable than others. This measure is incomplete because it shows travelers' acceptability of travel time less than variation in travel time (Emam et al., 2006).

1.2.2 95th Percentile Travel Time

The 90th or 95th percentile travel time is the "simplest method to measure travel time reliability". It estimates the amount of delay that will be on the heaviest travel days (FHWA, 2007).

1.2.3 Planning Time Index

The total travel time including buffer time is the planning time that is calculated as the 90th or 95th percentile travel time (Texas Transportation Institute and Cambridge Systems, 2009). Planning time index is defined as equation (1) and shows that the extra travel time that should be specified in addition to free-flow travel time to arrive on time 95% of the time (FHWA, 2010).

$$\text{Planning Time Index} = \frac{95 \text{ percentile travel time}}{\text{free-flow travel time}} \quad (1)$$

1.2.4 Buffer Index

Passengers usually add some buffer time and departure earlier to avoid travel delay and deal with travel time variability (Li et al., 2013). Buffer index is an extra time that travelers require to add to their average travel time to arrive on time. Buffer index, obtained by equation (2), is defined as the ratio of the difference of the 95th percentile travel time and average travel time over the average travel time (Van Lint et al., 2008).

$$\text{Buffer Index} = \frac{(95 \text{ percentile travel time} - \text{average travel time})}{\text{average travel time}} \quad (2)$$

Since, buffer index is defined based on the average travel time, it is preferred for commuters that are familiar with everyday congestion and the planning time index that is based on free-flow travel time may be preferred for those who aren't familiar with that (Pu, 2011). In comparison the differences among different paths, the path with bigger buffer index is less reliable than others (Li et al., 2013).

1.2.5 Travel Time Index

The ratio of actual average travel time over free-flow travel time is defined as travel time index which is shown in equation (3). "Strictly speaking, the travel time index is a congestion intensity measure rather than a reliability measure" (Pu, 2011).

$$\text{Travel Time Index} = \frac{\text{actual average travel time}}{\text{free-flow travel time}} \quad (3)$$

2. Methodology

2.1 Assuming Lognormal Distributed Travel Times

There is a significant variation in travel time distributions. In literatures, using real-life travel time without fitting any parametric or nonparametric statistical distributions is a frequent approach of developing customized travel time reliability measures to obtain real-life reliability measures. Because of the characteristics of the underlying statistical distribution, some measures developed by this approach could be misleading; moreover, it is hard to depict the relationships between measures which vary on a case-by-case basis by using analytic methods. Hence, developing reliability measures by assuming statistical distribution is a meaningful approach to develop travel time reliability measures. This approach reveals the analytic relationships between the measures in cases which assumed and empirical distribution matches well (Pu, 2011). Acknowledging that reliability measures can derive from multimodal distributions, the first scope is confined to uni-modal travel time distributions to find an appropriate and best fitting simple traditional statistical distribution. The closest traditional statistical distribution is the lognormal distribution that describes the distribution of travel times (Guo et al., 2010). For simplifying, in this study lognormal distribution has chosen as the traditional statistical distribution for travel time and the following steps are all based on this assumption (NIST, 2006). In other words, this paper's results utilize only for lognormal distributed travel times.

The random variable X is distributed lognormal whose logarithm is distributed normally. If Y has a normal distribution with mean μ and variance σ^2 then $Y = \log(x - \theta)$. The general formula for the lognormal distribution probability density function is defined by equation (4), where σ is a shape parameter (and is the standard deviation of the log of the distribution), θ is a location parameter and m is a scale parameter (Balakrishnan, 1999).

$$f(x) = \frac{\exp\left(-\frac{\left(\ln\left(\frac{x-\theta}{m}\right)\right)^2}{2\sigma^2}\right)}{(x-\theta)\sigma\sqrt{2\pi}} \quad x \geq \theta; m, \sigma > 0 \quad (4)$$

2.2 Derivation of New Measure for Travel Time Reliability

There are different ways to calculate travel time reliability, discussed previously. It is derived as a new travel time reliability measure based on planning time index. This measure includes typical delays as well as unexpected delay which are very important for suppliers, shippers and freight carriers to schedule their transport programs. As defined in previous sections, planning time index is a ratio of 95th percentile travel time and free-flow travel time that it is not commonly meaningful in rail transit, so ideal travel time is used instead of free-flow travel time. The total travel time including buffer time is the planning time that calculated as the 90th or 95th percentile travel time (Texas Transportation

Institute and Cambridge Systems, 2009). Planning time index is defined as equation (5) by Pu in 2011 and shows the extra travel time that should be specified in addition to free-flow travel time to arrive on time 95% of the time (Pu, 2011).

$$\text{Planning Time Index} = \frac{95 \text{ percentile travel time}}{\text{Ideal or free-flow travel time}} \quad (5)$$

The ideal travel time is the shortest travel time, which is an ideal passenger travel time without waiting and jam (FHWA, 2007). Minimum travel time is used by finding the shortest path between origin-destination pairs using Dijkstra algorithm. This algorithm is effective to find the shortest path between nodes in graph. In the used transportation network, nodes represent stations and links' travel times are positive edge weights between pairs of stations connected by a direct link. Dijkstra algorithm will find shortest route between one station and all other stations.

2.3 Calculating Reliability Stats

Because of accessing to more information in detail from detectors, reliability measures are more widely discussed nowadays. The study of variation in travel time conditions gets easier utilizing travel information which is obtained directly or estimated from detection systems. Using the traffic management centers' information, the calculation and estimation of all measurement concepts is possible (Lomax et al., 2003). In this paper, the reliability stats are calculated using data collected by monitoring and information systems in freight transportation in Iran. For individual links, the mean and variance of travel time are calculated by equation (6) and (7).

$$T_{T,l} = \frac{1}{n} \sum_{i=1}^n t_i \quad (6)$$

$$\sigma_{T,l}^2 = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - T_{T,l})^2} \quad (7)$$

Assume that rail transit network (graph) G is composed of k lines, expressed as $G = \{l_1, l_2, \dots, l_k\}$. $OD_{m,n}^G$ denotes OD pairs between node m and n in G ; $OD_{m,n}^{l_i}$ denotes OD pairs belongs to line l_i . For fixed OD pairs, it is assumed that travel time distribution obeys lognormal distribution with $f(t)$ probability density function of travel time. Hence, for every OD pairs or route, we need the location and required parameters of lognormal distributed travel time. Route statistics and probability density function are fitted based on statistical measures, e.g., mean and standard deviation. Assuming that for each route, link travel times are independent because each link travel time does not affect on other links. As discussed before, the travel time in each link is distributed lognormal, so it is assumed that in each route travel time is distributed lognormal and calculation of route stats is based on link characteristics. If X is a random variable of sum of independent random variables x_1, x_2, \dots, x_k , the mean and variance of X are calculated as $\mu_X = \mu_{x_1+x_2+\dots+x_k} = \mu_{x_1} + \mu_{x_2} + \dots + \mu_{x_k}$ and $\sigma_X^2 = \sigma_{x_1+x_2+\dots+x_k}^2 = \sigma_{x_1}^2 + \sigma_{x_2}^2 + \dots + \sigma_{x_k}^2$ in sequence and based on these statistics we can calculate the location and scale parameter of route travel time and its' probability density function (Walpole & Mayer, 2012).

2.4 Route Travel Time Reliability

Using the lognormal distribution presented in the previous section, travel time percentiles and thus the reliability can be easily expressed as a function of mean and variance. Here, we concentrate and reintroduce on how the ideal travel time, mean and variation of travel time can be estimated such that studied at (Wu et al., 2014). If the travel times are known, the mean and variances of individual links can be calculated and then the mean and variance of the total route can be achieved by summation. With the mean of total travel time $T_{T,route}$ and the variance of the total travel time for entire route $\sigma_{T,route}^2$, the distribution function (e.g., a lognormal distribution) and required percentile of the total travel time can be determined. In general, the travel time T_T within a link can be considered as a superposition of the free-flow travel time T_f and the delay d within the link. For the individual links, the mean of total travel time $T_{T,l}$ is now considered to be lognormal distributed. Therefore, the variance of the travel time $\sigma_{T,route}^2$ over the entire route is equal to the sum of the variances of all links $\sigma_{T,l}^2$ in case the individual links are independent of each other defined by equations (8) and (9).

$$\sigma_{T,route}^2 = \sum_{i=1}^n \sigma_{T,i}^2 \quad (8)$$

$$T_{T,route} = \sum_{i=1}^n T_{T,i} \quad (9)$$

Where $T_{T,i}$ equals $\frac{1}{n} \sum_{i=1}^n t_{T,i}$ and $t_{T,i}$ is the travel time of link l at time i . The travel time $T_{T,i}$ and its components T_f and d from two adjacent links are not always independent of each other. In particular, the delays d of two adjacent links can be closely correlated with each other. In case of dependent adjacent links, the variance is calculated by equation (10), where $k_{T,i,i+1}$ is the correlation coefficient of the total travel time of two adjacent links. The value of $k_{T,i,i+1}$ is usually very small if only links of sufficient lengths are considered. Normally it can be neglected ($k_{T,i,i+1} \geq 0$) for simplification.

$$\sigma_{T,route}^2 = \sum_{i=1}^n \left(\sigma_{T,i}^2 + 2k_{T,i,i+1} \times \sigma_{T,i} \times \sigma_{T,i+1} \right) \quad (10)$$

Calculation of required percentile travel time of each route $t_{T,95,route}$ is required to its travel time distribution function and in sequence the lognormal probability density function which is defined by the mean $T_{T,route}$ and variance $\sigma_{T,route}^2$. We defined how to calculate these two parameters and will get the value for 95 percentile travel time by using inverse cumulative density function.

The shortest path problem is one of the network flow problems. Here we present the linear programming formulation of the shortest path problem (Taha, 2008). Let $G(V,A)$ a directed graph, c_{ij} link costs or lengths for all $(i,j) \in A$ and path start node $s \in V$, end node $t \in V$, $s \neq t$. x_{ij} is a variable and equal 1 if (i,j) is in the path ($x_{ij}=1$) and 0 otherwise. The main linear program is to minimize $\sum_{ij \in A} c_{ij} \cdot x_{ij}$. The amount of flows for each single node i formulates as subtraction of incoming flow to i from outgoing flow from i ($\sum_j x_{ij} - \sum_k x_{ki}$). In the shortest path, equation (11) satisfies the continuity of path over the selected nodes on the network. More details for this concept and applications are available at (Mahmoudabadi & Seyedhosseini, 2014).

$$\sum_j x_{ij} - \sum_k x_{ki} = \begin{cases} 1, & \text{if } i=s; \\ -1, & \text{if } i=t; \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

There are many algorithms for finding the shortest path between nodes in a graph. Dijkstra algorithm is the fastest known single source shortest path algorithm for arbitrary directed graphs with unbounded non-negative weights and can be used to find the shortest route between one station and all other stations. However, finding a shortest path to any given goal or set of goals is possible with a small modification (Ahuja et al., 1993). As mentioned before, the ideal travel time T_{ideal} is needed to calculate travel time reliability and the ideal travel time is the shortest travel time, which is an ideal passenger travel time without waiting and jam (FHWA, 2007). Dijkstra algorithm is now performed to find the shortest path as is desirable. Finally, the route travel time reliability R_{route} defines as the ratio of ideal travel time and 95th percentile travel time and can be used by equation (12) to further analysis.

$$R_{route} = \frac{\text{Ideal travel time}}{\text{95th percentile travel time}} \quad (12)$$

2.5 Proposed Procedure for Estimating Route Travel Time Reliability

The following procedure is utilized to estimate route travel time reliability as also illustrated in Figure 1. It has been proposed for determining the travel time reliability in a route consisting of more than one links:

- 1) Estimating input parameters for individual links
 - a. travel time of link l at time i : $t_{T,l,i}$
- 2) Estimating output parameters for the links
 - a. Calculating the mean of travel time $T_{T,l}$
 - b. Calculating the variance of travel time $\sigma_{T,l}^2$
- 3) Estimating output parameters for the route consisting of many links
 - a. Determining the ideal travel time for OD pairs

T_{ideal} = The shortest path travel time

- b. Calculating the variance of the shortest path

$$\sigma_{T,route}^2 = \sum \sigma_{T,l}^2 \cdot$$

- c. Determining the percentiles (e.g. $t_{T,90,route}$ or $t_{T,95,route}$) of the travel time.

$t_{T,95,route}$ = Inverse CDF 95% of lognormal distribution

- d. Calculating the reliability of travel time

$$R = \frac{T_{ideal}}{T_{T,95,route}}$$

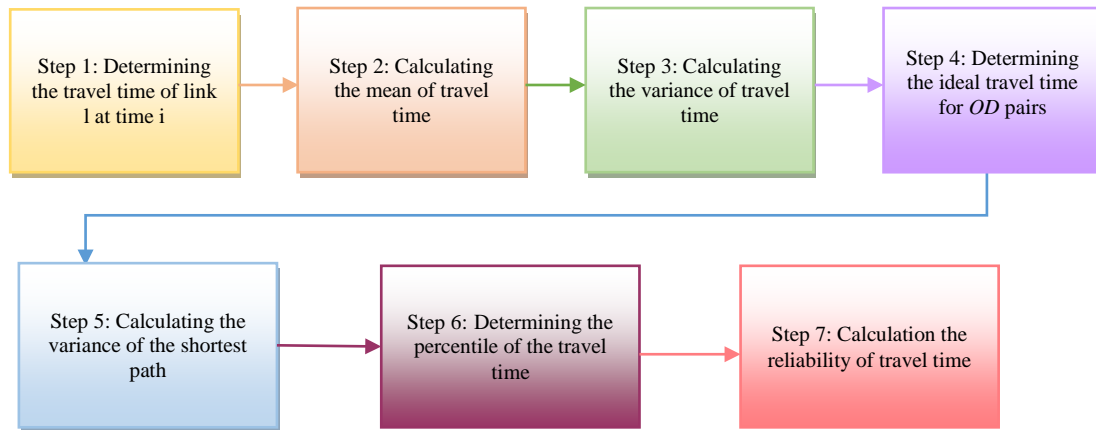


Figure 1. The Proposed Procedure for Estimating the Reliability of Travel Time

3. Numerical Analysis

3.1 Data Description

Travel times during days of three months (2015) are considered on the whole studied rail freight network between all main stations and stations which are located in routes' intersections. Figure 2 depicts a railway system map of Islamic republic of Iran, containing main routes and stations' names. Sixty-one stations have been selected according to their importance and locations and relevant data gathered for all OD pairs. Two types of stations are selected because they are more critical in finding the shortest path between OD pairs. Observed travel times were available from train traffic control centers for every departure during a day between OD pairs and data collected from those centers provide train movement details. Using observed data implies an estimate of the mean travel time for freight trains departing in a certain departure time period. The train traffic control data can obtain the time trains entering and exiting the stations. Sixty-one stations of Iran freight rail transit were selected and numbered as well as relevant data has been received for OD pairs. Since, a large amount of traffic data used to measure travel time reliability by the time of day and day of week (8), we selected data from 90 days in 2015 at the different times of days that fell within this definition.



Figure 2. Railway Map of Case Study Area (Source of Image: <http://www.iranrail.net>)

3.2 Travel Time Reliability Calculation

In order to calculate the defined travel time reliability index of each OD pair, the travel time probability density function is fitted to lognormal distribution. The calculation results are tabulated in Table 1 as a part of analysis results. Following that, route travel time reliability between station 1 to other stations can be compared. Having the 1-4 OD for example, T_{ideal} , $t_{T,95, route}$ and the travel time reliability of this route are 180 minutes, 199 minutes and 0.9 or 90%, respectively.

Table 1. Travel Time Reliability of Some OD Pairs

O-D	T_{ideal} (min)	$t_{T,95, route}$ (minutes)	Estimated Reliability	O-D	T_{ideal} (min)	$t_{T,95, route}$ (minutes)	Estimated Reliability
1-2	151	167.45	0.90	1-11	1995	2118.85	0.94
1-3	282	307.69	0.92	1-12	2012	2135.94	0.94
1-4	180	199.18	0.90	1-13	2054	2178.24	0.94
1-5	771	847.46	0.91	1-14	1697	1810.03	0.94
1-6	1131	1227.71	0.92	1-15	1951	2073.05	0.94
1-7	1371	1475.46	0.93	1-16	1981	2103.45	0.94
1-8	1468	1573.28	0.93	1-17	2017	2140.16	0.94
1-9	1846	1965.22	0.94	1-18	2042	2165.43	0.94
1-10	1972	2095.67	0.94	1-19	2022	2145.17	0.94

As an example, let to consider a route between station 32 and 50 in studied area. The proposed procedure is applied for calculating the reliability of travel time. To calculate reliability, data has been received from RAI (The Railways of the Islamic Republic of Iran). The shortest path between two stations utilizing Dijkstra algorithm is (32-31-28-29-38-39-40-48-49-50) shown in Figure 3. The input parameters and results for illustrative example are given in Table 2. Comparing the values $t_{T,90,route}$ and $t_{T,95,route}$ (or other percentiles) with the ideal travel time T_{ideal} , the reliability of this route is clearly defined and equals to 93% for 95th percentile travel time. The route has an ideal travel time of 1288 min and the 90th and 95th percentile travel time are 1362 and 1384 minutes, respectively.

Table 2. Parameters and Calculation Results for the Example Route

Parameters				Results					
Link i	Length L (km)	$T_{T,i}$ (minute)	$\sigma_{T,i}^2$	T_{ideal} (minute)	$\sigma_{T,route}^2$	$t_{T,90,route}$ (min)	$t_{T,95,route}$ (min)	$R_{90\%}$	$R_{95\%}$
l_1	39.73	43	49	-	-	52.21	55.37	0.824	0.777
l_2	166.19	69	121	-	-	83.47	88.42	0.827	0.780
l_3	240.1	117	256	-	-	138.01	145.01	0.848	0.807
l_4	14.06	12	4	-	-	14.63	15.54	0.820	0.772
l_5	156.27	66	144	-	-	81.81	87.35	0.807	0.756
l_6	117.4	154	256	-	-	174.92	181.63	0.880	0.848
l_7	157.37	206	441	-	-	233.46	242.24	0.882	0.850
l_8	78.5	109	169	-	-	126.03	131.6	0.865	0.828
l_9	541.37	512	1849	-	-	568.07	585.64	0.901	0.874
Total	1510.99	-	-	1288	3289	1362.23	1384.43	0.946	0.93

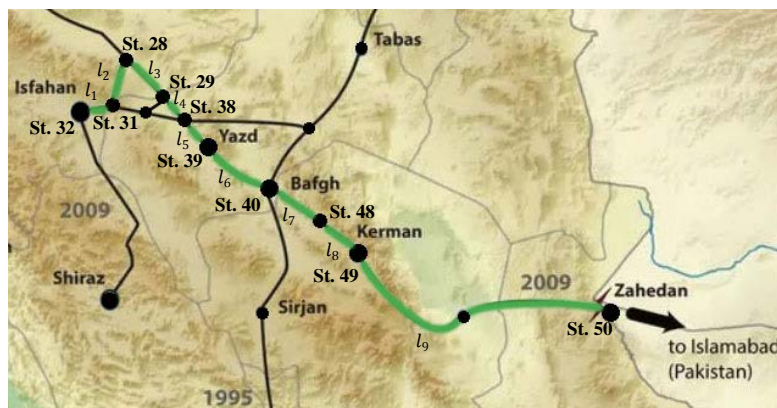


Figure 3. The Shortest Path between Stations 32 (Isfahan) and 50 (Zahedan)

3.3 Route Prioritization Using Reliability Measure

The amount of travel time reliability is used here as the prioritizing measure. Routes which have two major features should be select to improve: a) less than 400 km in length, b) less than 10 links in segments. Routes have been categorized by length and put them into 200 km groups to find out which groups reliability are more critical. The results revealed that routes shorter than 400 kilometers are less reliable than the others as shown in Table 3 and Figure 4 (a). These routes include about 14 percent of all routes in the studied railway network. Figure 4 (b) depicts relationship between route length and travel time reliability. As mentioned, the main notable feature is that apparently the routes reliability increases significantly with route length and between routes which are shorter than 400 km, most of them consist of less than 10 links (Figure 5). So, they should be prioritized under study to improve their reliabilities and get the more reliable network. In other words, some changes are required to tight their travel time variation and gain desired reliability as a critical reliability.

Table 3. Routes Travel Time Reliability Based on Length

Route length (Km)	Number of routes	Portion in total %	Reliability	Route length (Km)	Number of routes	Portion in total %	Reliability
0-200	228	7.3	0.825	1400-1800	411	13.3	0.937
200-400	212	6.8	0.880	1800-2000	351	11.3	0.938
400-600	282	9.1	0.902	2000-2200	226	7.3	0.937
600-800	368	11.9	0.913	2200-2400	101	3.2	0.938
800-1000	386	12.5	0.922	2400-2600	79	2.5	0.939
1000-1200	503	16.3	0.928	2600-2800	37	1.2	0.944
1200-1400	464	15	0.934	2800-3000	10	0.3	0.942

4. Discussion

Previous studies showed the importance of travel time reliability. Measuring accurate travel time reliability is the first step to improve it and ensure travelers' on-time arrivals. In this paper, with the use of a real-life transportation data, a new travel time index for computing travel time reliability in railway freight transportation developed and network performance and its efficiency have been evaluated. Reliability of travel time, in this study, is estimated based on finding the shortest path between origin-destination pairs utilizing Dijkstra algorithm. Based on previous studies, the travel time of a link or route can be considered as lognormal distributed. For estimating the reliability of a whole route consisting of several individual links, the mean and variance of travel time is required. The variance of the total route travel time can be calculated as a superposition of the variances of the individual links. If the mean and the variance for each link can be determined, the reliability of a link or a route can be easily estimated according to the proposed model. The reliability criterion is also defined as the ratio of

the 95th percentile travel time and the shortest path mean travel time as an ideal travel time. The application of the procedure for assessing travel time reliability was demonstrated for a real railway network consisting of several stations and links.

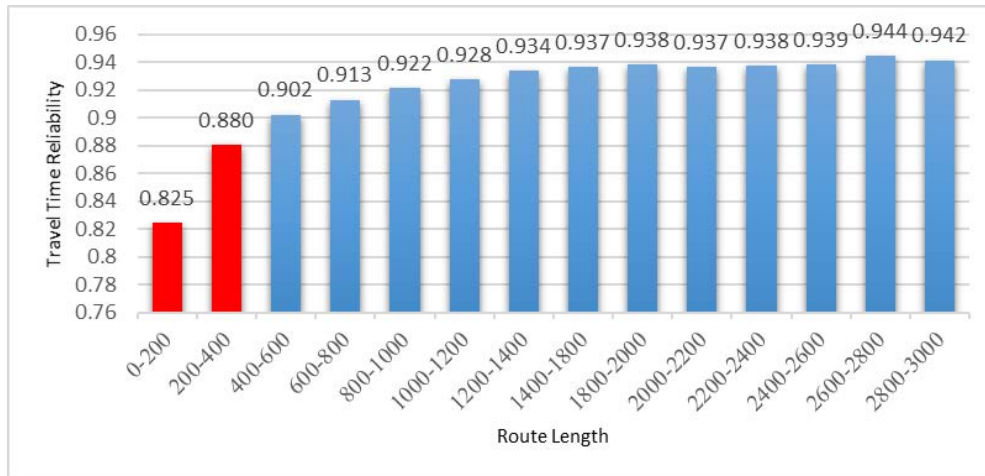


Figure 4 (a). Route Travel Time Reliability Histogram Based on Route Length

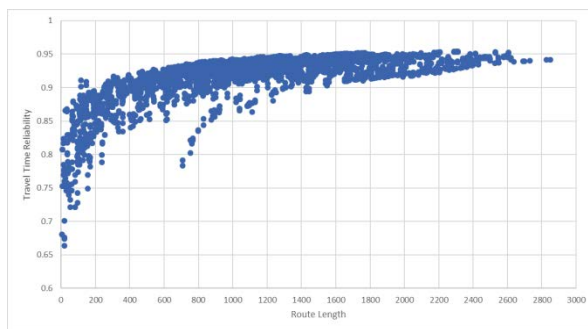


Figure 4 (b). Route Travel Time Reliability Scattered Diagram Based on Route Length

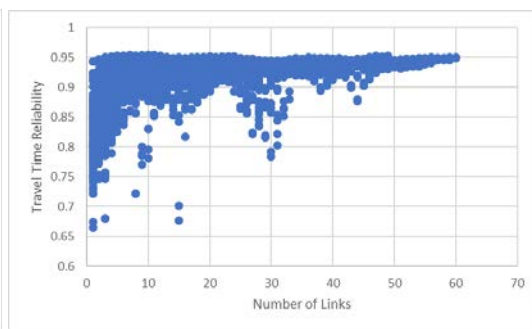


Figure 5. Route Travel Time Reliability Based on Number of Links

There is an outstanding limitation to conduct this research work is to assume travel time distribution log normality while in real cases it may be non-lognormal distributed for example bimodal, Weibull or something else. A distribution that can fit standardize travel time is a suitable distribution that can be used in further studies. Nonetheless, in future studies this paper methodology to calculate travel time reliability could be applied to non-lognormal distributed travel time. In this paper Statistical independence between the links travel time is assumed for simplification. In further researches the assumption of correlation of two adjacent links can give more accurate results and analysis.

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