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A Median-Based Misery Index for Travel Time Reliability

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Abstract

Travel time reliability is vital for both road agencies and road users. Expected travel time reliability can be used by road agencies to assess the state of a transportation system, and by road users, to schedule their trips. Road network deficiencies, such as insufficient traffic flow capacity of a road segment or poor road design, have a negative impact on the reliability of travel times. Thus, to maintain robust and reliable travel times, the detection of road network deficiencies is vital. By continuously analyzing travel times and using appropriate travel time reliability measurements, it is possible to detect existing deficiencies or deficiencies that may eventually occur unless necessary actions are taken. In many cases, indices and measurements of travel time reliability are related to the distribution of the travel times, specifically the skewness and width of the distribution. The current paper introduces a median-based misery index for travel time reliability. The index is robust and handles travel times that follow a skewed distribution well. The index measures the relative difference between the slow travel speeds and the free-flow travel speed. The index is inspired by the median absolute deviation, and its primary application is to detect routes or road segments with potential road network deficiencies. To demonstrate the applicability of the index, we conducted an empirical case study using real travel speed data from the European route E4 in Sweden. The results from the empirical case study indicate that the index is capable of detecting road segments with slow travel speeds regardless of the travel speed distribution.

Keywords: Travel time reliability; travel speed index; travel speed

1. Introduction

Travel time is an important performance measure of the state of a transportation system and it plays a fundamental role for the society from a broad perspective [1, 2]. For example, the uncertainty in travel times may account for 15% of time costs on an urban road [3]. This means that, given the extensive resources and time spent on the daily transportation of both persons and goods, the uncertainty in travel times may incur considerable economic costs to society. Road users are likely to be less tolerant of unexpected delays, and therefore select on average longer trips

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with more reliable travel times [4, 5]. Thus, travel time reliability can be utilized by road users to plan their trips to reach their destinations on time or with tolerable delays. As the number of vehicles on the roads is increasing, it has become more important to predict and detect congestion, bottlenecks, and other road network deficiencies that may influence the travel times negatively. Therefore, to maintain or improve the traffic state, it is important to detect routes or road segments where delays or high deviations in travel times occur. Travel time reliability refers to how consistent the travel times are from day-to-day or during different periods of the day, based on the prior experiences of individual road users or from historical observations [6, 7]. Day-to-day variations in travel time are influenced by travel demand, weather conditions, congestion, and road work, among other variables [8, 9]. Travel time reliability can be evaluated in different ways, but in general, all travel time reliability measures can relate to the distribution of travel times and the properties of this distribution: The wider the distribution of the travel times, the less reliable the travel times are [8, 9].

Data to evaluate travel time reliability can be sourced from, for instance, loop detectors, probe vehicles, Bluetooth devices, and GPS records [10]. Modern vehicles are increasingly connected, either directly by built-in navigation systems in the vehicles or indirectly by other devices such as mobile phones and GPS units. This renders it possible to continuously collect various types of traffic data in a cost-effective way over time and across large geographic regions without any additional measurement devices. Travel speed is a common descriptor of the traffic state, and it can be extracted from GPS data [11]. According to the kinetic theory of traffic flow, travel time variability negatively correlates with the travel speed (the variability of travel times increases as the mean travel speed decreases), which means that travel speeds can indirectly be used to analyze the reliability of travel times [12].

The travel time index is a straight-forward measure of travel time reliability and is the ratio between the mean travel time and the free-flow travel time [13]. However, empirical studies show that travel time reliability, is to a large extent, correlated to the variance of travel times, and travel time reliability measures can be determined from the day-to-day distribution of travel times [14, 9]. For travel times that follow a symmetric (i.e., normal) distribution, it has been suggested that the standard deviation can be used to model an expected travel time window around the mean travel time to encompass 68% or 95% of the trips using one or two standard deviations [15, 6]. When travel times follow a skewed distribution, it is more appropriate to use percentiles [3]. A straight-forward approach to measuring travel time reliability is to use the 90^{th}-percentile or 95^{th}-percentile, which estimates the delay during the heaviest trafficked days [16, 13]. Examples of measures using percentiles include the planning index and buffer index. The planning index is the ratio between the travel time for a given percentile and the free-flow travel time, and the buffer index is the relative difference between the mean travel time and the travel time for a given percentile [17, 18]. For instance, based on the 95^{th}-percentile, the planning index is a measure of how much longer the total travel times are than the free-flow travel time for 95% of the trips. The buffer index is the additional travel time (above the mean travel time) required for 95% of the trips.

As the travel time index and buffer index include mean travel time, their values can be misleading when the distribution of travel times is strongly skewed. Instead, it is suggested to use the coefficient of variation as a replacement for many of the established measures and indicators used today [13]. Furthermore, when travel times follow a skewed distribution, it is suggested that mean travel time should be replaced by the median travel time when computing the buffer index. Another robust measure to evaluate the travel time reliability is dmp90, which is defined as the difference between the 90^{th}-percentile and the median travel time [19]. It is also argued that it is important to capture both the skewness and width of the distribution of the travel times [8, 9]. The Florida Department of Transportation defines the travel time reliability as the percentage of trips that takes no longer than some acceptance level. Their model uses a threshold level (expected arrival time plus some additional delay) and calculates the probability that the travel time will be less than the threshold value [20]. Another measure of the travel time reliability is the misery index (MI), which measures the relative difference between a portion of the worst trips and the mean travel time [21, 13]. The index gives a measure of how much the longest travel times exceed the mean travel time [6]. For example, the MI can be computed by taking the difference between the longest 20% of travel times and the mean travel time and dividing it by the mean travel time.

The novel contribution of this paper is a new median-based MI (MMI) to assess the traffic state. The index provides a measure of difference between the relatively slow travel speeds and the free-flow travel speed along a route or a road segment. The index may be used as a tool to analyze travel time reliability or to detect road segments with deficiencies that may negatively impact the travel times. To demonstrate the applicability of the proposed index, we provide an empirical case study using travel speed data from a 2+1 road in Sweden.

The remainder of the paper is organized as follows. In Section 2 we present and discuss the proposed MMI. Section 2 also includes a discussion of free-flow travel speed, and how the proposed index relates to the MI. An empirical case study using high-resolution travel speed data acquired from GPS devices is provided in Section 3. Finally, Section 4 provides concluding remarks and avenues for future research.

2. Median-Based Misery Index for Travel Time Reliability

2.1. Median-based Misery Index

The purpose of the proposed MMI is to quantify the difference between the relatively slow travel speeds and the free-flow travel speed. The index can be used to detect road segments or routes with road network deficiencies, and it may serve to support decision-making when prioritizing improvements or investments in transportation systems. The index is inspired by the median absolute deviation (MAD), which is a statistical measure of the variability of a sample data set [22]. For a univariate data set $X = \{X_1, X_2, \dots, X_n\}$, whose median is denoted by $\widetilde{X}$, the MAD is defined as

$$\text{MAD} = \text{median}\left(\left|\widetilde{X} - X_i\right|\right), \quad i = 1, 2, \dots, n. \tag{1}$$

The MAD is the median of the absolute values of the deviations from the median of the sample data set. In the proposed index, the median of the deviations between the relatively slow travel speeds and the free-flow travel speed is instead used. Hence, let X denote the set of relatively slow travel speeds during some period with respect to the free-flow travel speed, denoted by X_{free}. The proposed MMI is defined as

$$\text{MMI} = \text{median}\left(\frac{X_i - X_{\text{free}}}{X_{\text{free}}}\right), \quad i = 1, 2, \dots, n \tag{2}$$

which is the median of the relative deviations from the relatively slow speeds and the free-flow travel speed. Note the absence of the absolute value in Eq. (2). On the one hand, if MMI is small (and either positive or negative), then the relatively slow travel speeds are close to the free-flow travel speed, which indicates that the traffic conditions are satisfactory for road users who want to reach their destination as efficiently as possible. On the other hand, if MMI is negative and closer to -1, then a non-trivial number of travel speeds are significantly slower than the free-flow travel speed. This may indicate a deficiency related to capacity or the road design.

This research supports the use of percentiles to identify relatively slow travel speeds, where travel speed observations below a specified percentile value, e.g., the 20^{th}-percentile or 25^{th}-percentile, are relatively slow. The index in Eq. (2) is defined in terms of travel speed; however, the index can also be defined in terms of travel time by considering the relatively longest travel times and the free-flow travel time.

Many different methods exists to define the free-flow travel speed. For instance, the free-flow travel speed can be expressed as *"the mean speed of passenger cars under low to moderate flow rates that can be accommodated on a uniform roadway under prevailing roadway and traffic conditions"* or *"the speed vehicles can travel under no restrains during actual road conditions"* [23, 24]. The free-flow travel speed can be measured during off-peak hours of the day when the traffic flows are low or moderate. The posted speed limit of the road segment can also be used as the free-flow travel speed.

2.2. Relation to the Misery Index

The MMI and MI both focus on the slowest travel speeds (trips with longest travel time). Using travel speeds, the MI can be defined as

$$\text{MI} = \frac{\overline{X}_{20} - \overline{X}}{\overline{X}}, \tag{3}$$

where $\overline{X}_{20}$ is the mean travel speed for the slowest 20% of the trips and $\overline{X}$ is the overall mean travel speed [6]. Other suggested percentages to use for the slowest trips are as low as 0.5% [13].

As previously discussed, measurements using the mean travel speed may give misleading results if the travel speeds follow a skewed distribution. For demonstration, Fig. 1 and Fig. 2 show histograms of travel speeds from two example road segments where the travel speeds follow a symmetric and skewed distribution, respectively. The light-red shaded region of the histogram shows the 20% slowest travel times. The vertical lines in the figures show the values of the mean travel speed of the 20% slowest travel speeds $\overline{X}_{20}$, the mean travel speed $\overline{X}$, and free-flow travel speed X_{free}. The vertical lines labeled α are the median values among the slowest 20% travel speeds. The width of the horizontal lines is $|\alpha - X_{\text{free}}|$ and $|\overline{X}_{20} - \overline{X}|$ which is proportional to the absolute values of MMI and MI by the factors X_{free} and $\overline{X}$. Given that the free-flow travel speed is 100 km/h for the road segments, the MI values are −0.13 and −0.14, and the MMI values are −0.14 and −0.25 for the distributed travel speeds that are symmetrical and skewed, respectively. Thus, the MI does not highlight that a large number of the travel speeds are below the free-flow travel speed in the example shown in Fig. 2 because the difference between the two MI values is very small.

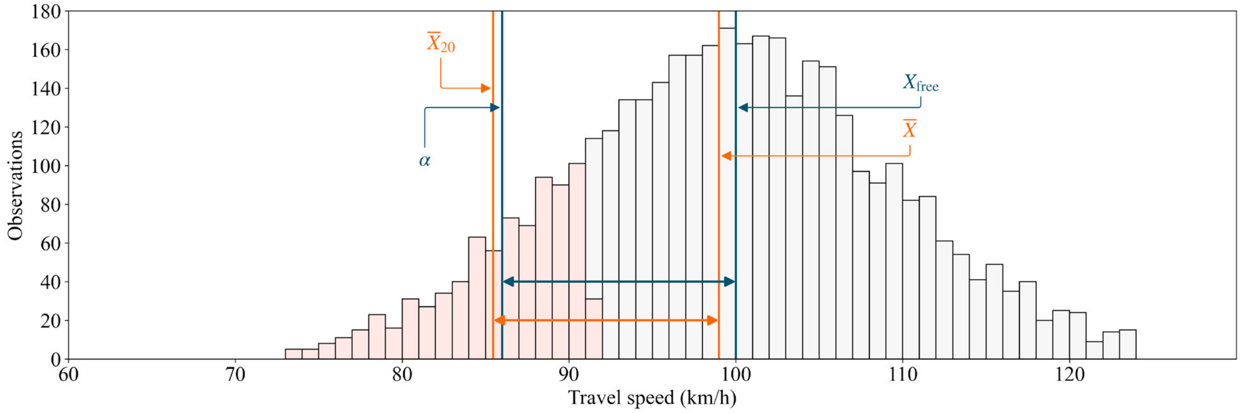

Fig. 1. Symmetrically distributed travel speed observations. The MI and MMI of the travel speed data set are −0.13 and −14.0 respectively. The light-red shaded region shows the 20% slowest travel speed.

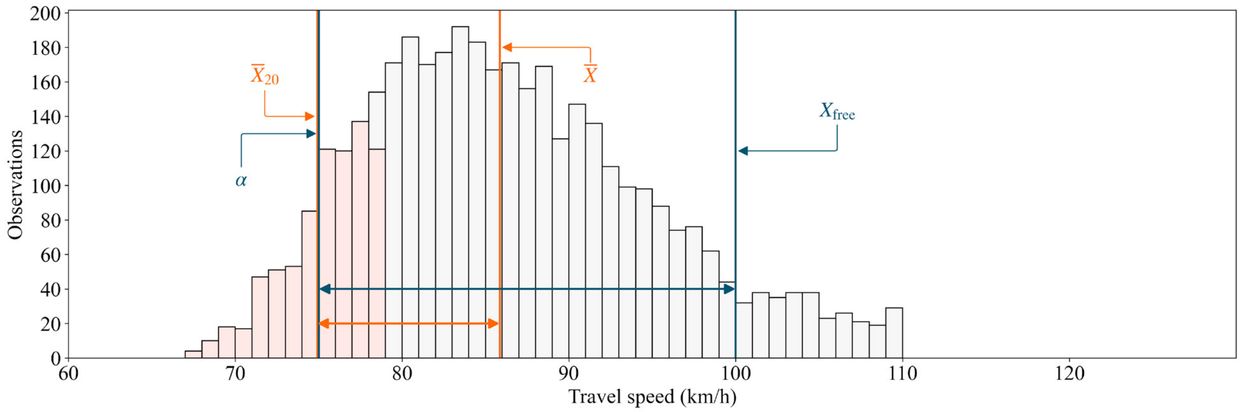

Fig. 2. Skewly distributed (positive) travel speed observations. The MI and MMI of the travel speed data set are −0.14 and −0.25 respectively. The light-red shaded region shows the 20% slowest travel speed.

3. Empirical Study of Median-Based Misery Index

3.1. Scenario and Data Description

Travel speed data from the European route E4 between Gävle and Söderhamn in Sweden were used in the empirical study. The 2+1 road studied had two lanes in one travel direction and one lane in the opposite travel direction, alternating every few kilometers. The road had a wire rope safety barrier to protect vehicles from the oncoming traffic. A 2+1 road can serve as an alternative for two-lane roads when the traffic flow is insufficient to justify a four-lane road, or as a safety countermeasure for two-lane highways [25, 26]. The length of the road was approximately 72 km and consisted of 82 road segments in each travel direction. The length of the road segments was, on average, slightly below one kilometer. There were four different types of road segments along the studied road: (A) one-lane, (B) two-lane, (C) two lanes that merged to a single lane, and (D) a single lane that split into two lanes. A diagram of a 2+1 road is illustrated in Fig. 3.

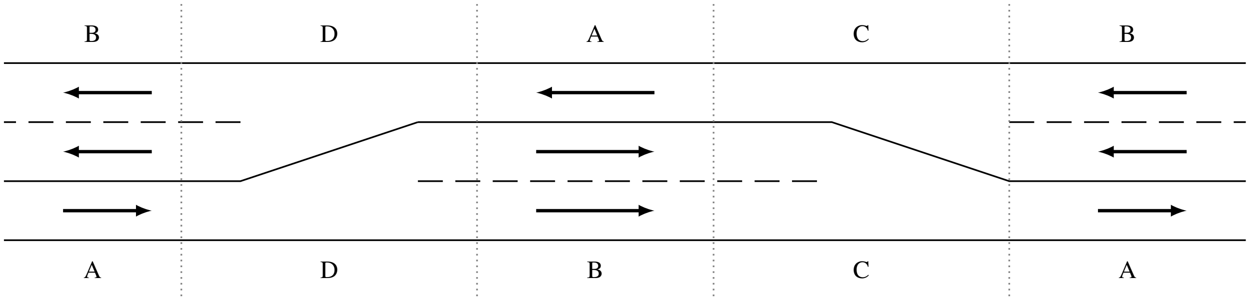

Fig. 3. A diagram of a 2+1 road showing the transition from one lane to two lanes and vice versa. The arrows show the vehicle travel direction.

The travel speed data were obtained from the Stress database (provided by the Swedish Transport Administration [Trafikverket]), and consisted of travel speed records with one-minute resolution during 2020 for each road segment. The travel speed records were produced by a rolling mean over a five-minute period. This means that the computation of the MMI is based on mean values rather than actual travel speeds of individual vehicles. Because there was only one measurement per road segment, it was assumed that the travel speed was constant for the entire road segment. The travel speed data were preprocessed by removing outliers from the data sample using the interquartile range (IQR) method before finding the slowest travel speeds. The IQR is defined as the difference between the upper quartile, Q_3 and the lower quartile Q_1 of observations, i.e., IQR = $Q_3 - Q_1$, and the travel speeds that are lower than $Q_1 - 1.5$IQR, or higher than $Q_3 + 1.5$IQR, are treated as outliers and are not included in the computations of the index [27]. When computing the index, travel speed records from 07:00 to 18:00 were used, and the 20% slowest travel speeds were considered relatively slow travel speeds. The posted speed limit was used as free-flow travel speed.

3.2. Results

The purpose of the index was to detect road segments where the difference between the slow travel speeds and the free-flow travel speed was large. This may indicate the presence of road segment deficiencies which can be related to the capacity of the road segment or to the design of the road. The studied road had 23 type-A road segments, 15 type-B road segments, 23 type-C road segments, and 23 type-D road segments in each travel direction. Fig. 4 illustrates how the MMI and MI vary over the individual road segments in the southbound and northbound travel directions, respectively. The circle and asterisk markers show the road segments with the lowest and highest MMI. Table 1 shows the min, max, mean, and median values of the MMI for the different types of road segments in each travel direction. From Fig. 4 and Table 1 it is clear that MMI is in general slightly lower for one-lane road segments than for the other types of road segments and that MMI decreases when the road transitions from two lanes to a single lane (the MMI is higher on type-C road segments compared with their following type-A road segments). This behavior is not captured by the MI and it may indicate that one-lane road segments have a negative influence on the travel speed and, consequently, on the travel times along the road. A likely explanation for this is that the wire rope safety barrier renders it impossible to overtake other vehicles on one-lane road segments. For instance, a heavy truck which is regulated to travel at a maximum speed of 90 km/h on motorways and semi-motorways in Sweden, may force the other vehicles to drive at the same travel speed or slower on a one-lane road segment.

To compare road segments with different values of MMI we, analyzed the two road segments with the lowest and highest MMI in the southbound travel direction. The road segments are marked in Fig. 4 in the upper plot with a dot (the first type-A road segment) in the beginning of the road and an asterisk (type-D road segment) toward to the end of

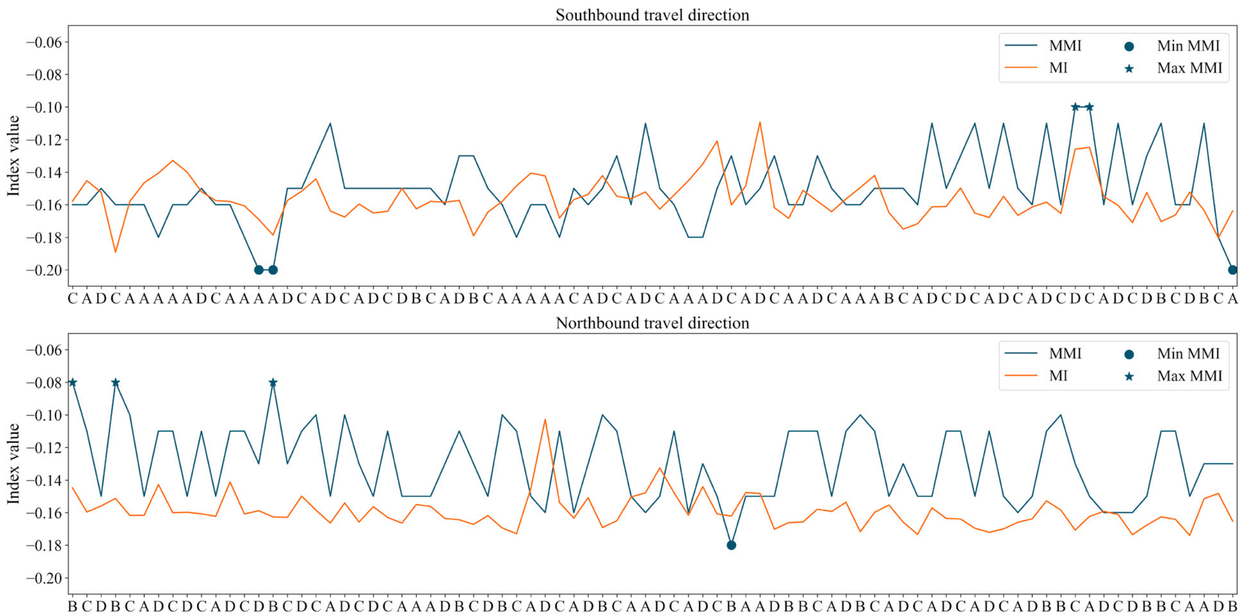

Fig. 4. Plot illustrating how the MMI and MI vary over the individual road segments in the southbound and northbound travel directions. The markers indicate the road segments with the lowest and highest MMI.

Table 1. Min, max, mean, and median values for MMI for all types of road segments in the southbound and northbound travel directions.

Road segment type	Southbound travel direction				Northbound travel direction			
	Min	Max	Mean	Median	Min	Max	Mean	Median
A (one-lane road segment)	−0.20	−0.13	−0.17	−0.16	−0.16	−0.13	−0.15	−0.15
B (two-lane road segment)	−0.15	−0.11	−0.13	−0.13	−0.18	−0.08	−0.11	−0.11
C (merge of two lanes)	−0.18	−0.10	−0.15	−0.15	−0.16	−0.1	−0.12	−0.11
D (split into two lanes)	−0.16	−0.10	−0.13	−0.13	−0.16	−0.1	−0.13	−0.13

the road. Fig. 5 and Fig. 6 show the histograms of travel speeds for the two road segments where the light-red shaded regions show the 20% slowest travel times

The posted speed limit of both road segments is 100 km/h. As the 20% slowest travel speed ranged from 60 to 85 km/h for road segment A, and from 76 to 93 km/h for road segment D, it is reasonable to postulate that the traffic state is worse along the one-lane segment. This is also indicated by the MMI for the road segments (−0.20 against −0.10). Thus, the index conveys that the performance of the road is improved when the slow travel speeds are closer to the free-flow travel speed.

Furthermore, it can be seen in Fig. 4 that not all sequences of one-lane road segments have an MMI as low as −0.20. This indicates that these road segments of the lowest MMI should be investigated further as being probable bottlenecks. The MMI can thus be used to single out the segments that require the most improvements. By detecting and eliminating road network deficiencies the travel times can be improved for all road users traveling along the road.

4. Conclusions and Avenues for Future Research

Travel time reliability is an important indicator of the performance of a transportation network, and it plays an important role for road users in particular and for society in general. This paper presented a MMI to assess the performance of the road segments. The proposed index measures the difference between the relatively slow travel speeds and the free-flow travel speed. In other words, the index provides a measure of *"how slow are the worst*

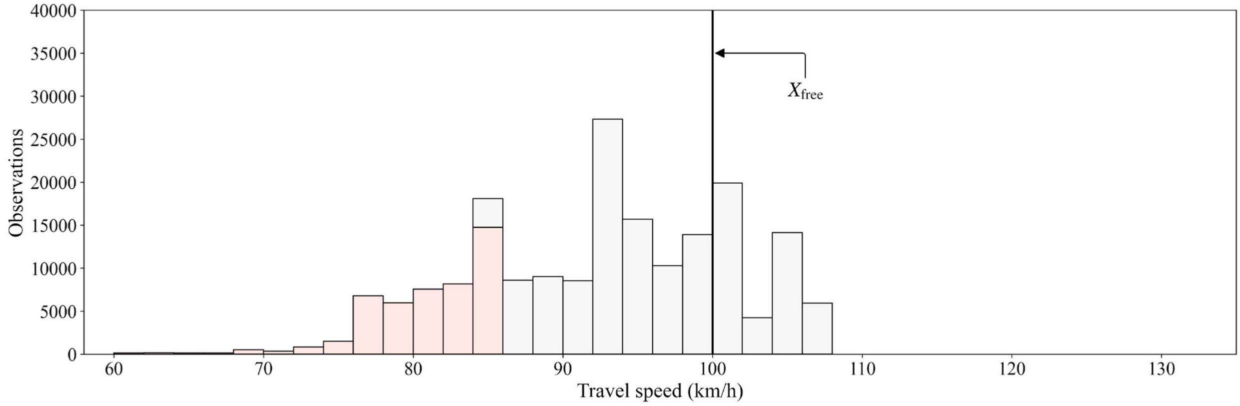

Fig. 5. Histogram of travel speeds from a one-lane road segment with MMI −0.20. The light-red shaded region shows the 20% slowest travel speed.

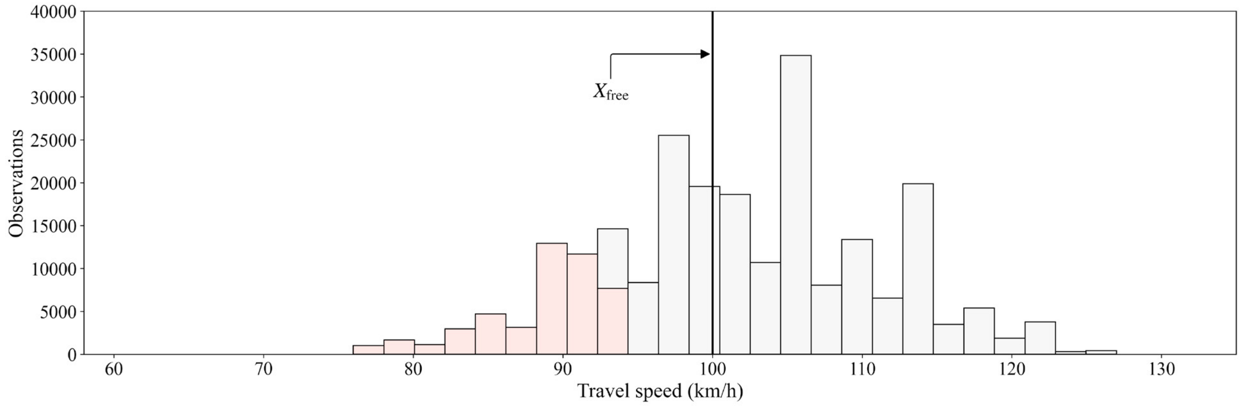

Fig. 6. Histogram of travel speeds from a road segment where one lane splits into two lanes with MMI −0.10. The light-red shaded region shows the 20% slowest travel speed.

trips compared to the free-flow travel speed?". The index is robust and efficient to compute, and is inspired by the median absolute value. In the empirical case study, where we used travel speed data from a road in Sweden, the index highlighted road segments with potential road network deficiencies. The results also demonstrated that one-lane road segments may affect travel times negatively. Future research may include how the index can be used to inform road users in real time about the prevailing conditions along their trip or to study how MMI varies over time to identify peak periods and obtain further important insights into the traffic state. A third avenue of potential future research is to investigate the correlation between the traffic flows and our the index proposed in this research.

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References

[1] C. Carrion, D. Levinson, Value of travel time reliability: A review of current evidence, Transportation Research Part A: Policy and Practice 46 (2012) 720–741.

[2] F. Zheng, J. Li, H. van Zuylen, X. Liu, H. Yang, Urban travel time reliability at different traffic conditions, Journal of Intelligent Transportation Systems 22 (2018) 106–120.
[3] M. Fosgerau, A. Karlström, The value of reliability, Transportation Research Part B: Methodological 44 (2010) 38–49.
[4] B. Hellinga, L. Fu, Route selection considering travel time variability, in: 6th World Congress on Intelligent Transport Systems, Toronto, Ontario, 1999, pp. 1–8.
[5] E. A. I. Bogers, H. J. van Zuylen, The importance of reliability in route choice in freight transport for various actors on various levels, in: Proceedings of the European Transport Conference, Strasbourg, France, 2004, pp. 1–13.
[6] T. Lomax, D. Schrank, S. Turner, R. Margiotta, Selecting travel reliability measures, Texas Transportation Institute, Cambridge Systematics Inc., 2003.
[7] Z. Ma, H. N. Koutsopoulos, L. Ferreira, M. Mesbah, Estimation of trip travel time distribution using a generalized Markov chain approach, Transportation Research Part C: Emerging Technologies 74 (2017) 1–21.
[8] J.W.C. van Lint, H. J. van Zuylen, Monitoring and predicting freeway travel time reliability: Using width and skew of day-to-day travel time distribution, Transportation Research Record 1917 (2005) 54–62.
[9] J. van Lint, H. J. van Zuylen, H. Tu, Travel time unreliability on freeways: Why measures based on variance tell only half the story, Transportation Research Part A: Policy and Practice 42 (2008) 258–277.
[10] C. Kamga, M. A. Yazıcı, Temporal and weather related variation patterns of urban travel time: Considerations and caveats for value of travel time, value of variability, and mode choice studies, Transportation Research Part C: Emerging Technologies 45 (2014) 4–16.
[11] S. Kim, B. Coifman, Comparing INRIX speed data against concurrent loop detector stations over several months, Transportation Research Part C: Emerging Technologies 49 (2014) 59–72.
[12] I. Prigogine, R. Herman, Kinetic theory of vehicular traffic, Elsevier, New York, 1971.
[13] W. Pu, Analytic relationships between travel time reliability measures, Transportation Research Record 2254 (2011) 122–130.
[14] S. Zhu, G. Jiang, H. K. Lo, Capturing value of reliability through road pricing in congested traffic under uncertainty, Transportation Research Part C: Emerging Technologies 94 (2018) 236–249. ISTTT22.
[15] J. Bates, J. Polak, P. Jones, A. Cook, The valuation of reliability for personal travel, Transportation Research Part E: Logistics and Transportation Review 37 (2001) 191–229. Advances in the Valuation of Travel Time Savings.
[16] Texas Transportation Institute and Cambridge Systems, Inc, Travel time reliability: Making it there on time, all the time., https://ops.fhwa.dot.gov/publications/tt_reliability/brochure/index.htm, 2017. Accessed: 2022-06-08.
[17] K. Lyman, R. L. Bertini, Using travel time reliability measures to improve regional transportation planning and operations, Transportation research record (2008) 1–10.
[18] Cambridge Systematics, Cost-effective performance measures for travel time delay, variation, and reliability, volume 618, Transportation Research Board, 2008.
[19] T. C. Lam, K. A. Small, The value of time and reliability: measurement from a value pricing experiment, Transportation Research Part E: Logistics and Transportation Review 37 (2001) 231–251. Advances in the Valuation of Travel Time Savings.
[20] H. Al-Deek, E. B. Emam, New methodology for estimating reliability in transportation networks with degraded link capacities, Journal of Intelligent Transportation Systems 10 (2006) 117–129.
[21] N. Bhouri, M. Aron, J. Kauppila, Relevance of travel time reliability indicators: A managed lanes case study, Procedia - Social and Behavioral Sciences 54 (2012) 450–459. Proceedings of EWGT2012 - 15th Meeting of the EURO Working Group on Transportation, September 2012, Paris.
[22] P. J. Rousseeuw, C. Croux, Alternatives to the median absolute deviation, Journal of the American Statistical association 88 (1993) 1273–1283.
[23] Transportation Research Board, Highway Capacity Manual, Washington, DC, 2000.
[24] A. P. Silvano, K. L. Bang, Impact of speed limits and road characteristics on free-flow speed in urban areas, Journal of transportation engineering 142 (2016) 04015039.
[25] M. Romana, M. Martin-Gasulla, A. T. Moreno, 2+1 highways: Overview and future directions, Advances in Civil Engineering 2018 (2018).
[26] T. Bergh, M. Remgård, A. Carlsson, J. Olstam, P. Strömgren, 2+1-roads recent Swedish capacity and level-of-service experience, Transportation Research Procedia 15 (2016) 331–345. International Symposium on Enhancing Highway Performance (ISEHP), June 14-16, 2016, Berlin.
[27] V. Chandola, A. Banerjee, V. Kumar, Anomaly detection: A survey, ACM computing surveys 41 (2009) 1–58.