New Methods for Quality Assessment of Real Time Traffic Information

CONFERENCE PAPER · JANUARY 2014

READS
41

3 AUTHORS:

Gerhard Huber
Universität der Bundeswehr München
3 PUBLICATIONS 0 CITATIONS

Klaus Bogenberger
Universität der Bundeswehr München
41 PUBLICATIONS 267 CITATIONS

Robert L. Bertini
California Polytechnic State University, San L...
180 PUBLICATIONS 1,545 CITATIONS
New Methods for Quality Assessment of Real Time Traffic Information

Gerhard Huber (corresponding author)
University of Federal Armed Forces Munich,
Department of Traffic Engineering
Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany
phone: +49 89 6004 2528
gerhard.huber@unibw.de

Klaus Bogenberger
University of Federal Armed Forces Munich,
Department of Traffic Engineering
Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany
phone: +49 89 6004 2503
klaus.bogenberger@unibw.de

Robert L. Bertini
Portland State University
Department of Civil and Environmental Engineering
P.O.Box 75, Portland, OR 97207-0751, USA
phone: 503-725-4249
bertini@pdx.edu

Accepted for Presentation at the 93rd Annual Meeting of the Transportation Research Board

5214 words + 8 figure(s) + 1 table(s) ⇒ 7464 ‘words’
ABSTRACT
This paper introduces a new concept for the quality rating of traffic information, the technical ground truth (TGT). The TGT enables the identification of quality deficiencies caused by restrictions in data provision and thus contrasts them with real quality shortcomings. For the case of real-time traffic information (RTTI), it is shown how the TGT can be constructed. Additionally, the TGT is used as a basis for computing the squared inverse mean percentage error (SIMPE), a new method envisioned for monitoring the quality of RTTI. This approach is based on the temporal, as well as the spatial location of sources of quality shortcomings. Furthermore, to represent the customers perception of RTTI quality, information about the accuracy of broadcasted travel time estimations is included in the construction of the SIMPE. For this purpose, the travel time difference (TTD) index, a quality evaluation method based on travel times, is described. The construction of the SIMPE is performed in such a way that a statistical analysis based on real measured speed data exhibits significant correlations between the SIMPE and the TTD index. Advantages and disadvantages of the SIMPE are discussed and a comparison to the TTD index is made.
INTRODUCTION
Traffic and traveler information is more important than ever before. Many people are interested in these data, particularly to obtain pre-trip guidance and to reduce their travel times in daily life. With the proliferation of navigation devices, smart phones and numerous ways of data transmission, an enormous amount of traffic data is available at any location, at any time. This fact leads to a tough competitive environment for providers to attract customers. Price is often considered to be crucial for the selection of a traffic information provider, though much is available at no costs. However, customer’s loyalty tends to drop if misinformation becomes more frequent. Hence, providers of traffic data aim to ensure high quality standards. Otherwise, they lose both their reputation and their customers. For this purpose, the first step is to systematically monitor the precision of broadcasted traffic information. This requires the ability to measure data quality. There is a variety of existing quality measures, which are applied in practice. Most of them address incident messages. The objective of this paper is to present a new method for the evaluation of real-time traffic information (RTTI).

STATE OF THE ART QUALITY MEASURING OF TRAFFIC INFORMATION
Methods for rating the quality of traffic information can, in general, be separated into two categories (1): First, methods like the QFCD (quality evaluation based on floating car data) method (2) or the QBENCH (quality benchmark) method (3) use actual vehicle trajectories to evaluate quality, i.e., they are based on microscopic measurements. The second category rates the quality of traffic information by comparing it macroscopically to a spatio-temporal reconstruction of the traffic situation. Such reconstructions are denoted as ground truth. One example is the ASDA/FOTO (automatische Staudynamikanalyse/forecasting of traffic objects) travel time method (4). Here, Kerner’s three phase traffic theory (5) forms the basis for the ground truth. Also the Qualitätskennziffer (QKZ) method (1) compares the spatio-temporal extent of broadcasted jam messages with their ”real” extent according to such a ground truth reconstruction. Both categories have their advantages and disadvantages. Real vehicle trajectories mirror reality as closely as possible, but lack statistical robustness due to the high costs of test drives. A spatio-temporal traffic reconstruction allows a continuous observation of quality. On the other hand, high data resolution is necessary to guarantee an accurate presentation of the real traffic situation.

However, all of these procedures have one aspect in common: they rate the quality of traffic information without taking into account that differences between the ground truth and the broadcasted information are also caused by the limitations of data provision. To clarify this, this problem is explained for the case of RTTI. In this paper, data are denoted as RTTI which are used for displaying the current traffic situation on a road network. The road network is partitioned into road segments and each of these road segments is assigned to a class representing the current state of traffic flow. In this paper, these road segment classes depend only on the current speed and thus are called speed classes. The segments are traditionally colored according to the speed classes and the information is updated every few minutes. An example can be found in Figure 1. It is taken from http://portal.its.pdx.edu/home/expandedSystemsMap/index.php. Consequently, even if the traffic information provider possessed all possible vehicle speed information along a specific road segment, only the corresponding speed class can be broadcasted. Because of this, it may be inappropriate to measure the quality of the broadcasted traffic information due to a comparison with something that is intended to mirror the real traffic situation as precisely as possible. Instead of this, at least from a provider’s perspective regarding internal quality management, it is more reasonable...
to compare the provided traffic data to an approximation of the real traffic situation which takes the aforementioned limitations into account (see Figure 2). This approximation is from here on denoted as technical ground truth (TGT) and forms the basis for the following considerations. The TGT therefore defines the best possible product that a RTTI-provider can deliver. Note that the ground truth, as well as the TGT can be constructed offline. This is much simpler than the online determination of traffic states, which is necessary for producing RTTI. Hence, even if the same data are used as basis for the (technical) ground truth reconstruction and the RTTI production, the (technical) ground truth, in general, mirrors reality more accurately. Consequently, a quality rating using the same data would still be possible, though it is not optimal.

RECONSTRUCTING THE SPATIO-TEMPORAL TRAFFIC STATE FOR REAL TIME TRAFFIC INFORMATION
Throughout this paper, detector data from a 16 kilometers long corridor of the autobahn A99 in Germany is analyzed. The data consist of 80 datasets, each containing speed information for a single day for one driving direction. The speed data is collected by 13 inductive loop detectors at one-minute resolution.

Computing a Spatio-Temporal Ground Truth Using the Adaptive Smoothing Method
For the construction of the TGT, we modify the ”ground truth” that is generated according to (6), i.e., a spatio-temporal speed function $V_{GT}$ is produced using an adaptive smoothing method (ASM) on the basis of point detector data. Figure 2 b) shows an example of a contour plot of $V_{GT}$, which is based on one of the aforementioned datasets. Here, the parameters for the ASM are chosen similarly to (7). Note that it is not necessary for detector data to be used as the basis for the ground truth, also other sensor types are possible. However, to obtain a good approximation of the real traffic situation, which is needed for an appropriate quality rating, a constant high resolution and
FIGURE 2 The Technical Ground Truth for RTTI
quality of the available data should be ensured. For more information, especially about the impact of detector resolution on the quality of estimated travel times, see (8).

**Representation of Real-Time-Traffic-Information by a Contour Plot**

For comparison reasons, RTTI for a single road of the freeway network is transformed into a "contour" plot. To obtain this, one proceeds according to (9). Figure 3 displays the approach for the area marked with a dashed rectangle in Figure 1. One starts with the RTTI-map for a specific time interval, extracts these data and fits it into a spatio-temporal plane. This is done iteratively for any relevant time interval. More formally: let a certain corridor of a road $[x_{start}, x_{end}]$ for a time period $[t_{start}, t_{end}]$ be observed for which RTTI is available. According to the RTTI, speed categories are assigned to road segments $S_i$, which separates $[x_{start}, x_{end}]$, during time intervals $T_j$, which separates the period $[t_{start}, t_{end}]$, $i \in \{1, \ldots, n\}$, $j \in \{1, \ldots, m\}$. As the RTTI is updated regularly, all time intervals $T_j$ have the same length. In Figure 3, the speed categories are denoted with A to E. Each of these speed categories is associated with a speed parameter $v_A$ to $v_E$, i.e., the RTTI assigns either $v_A$, $v_B$, $v_C$, $v_D$ or $v_E$ to each spatio-temporal area $S_i \times T_j$. With $v_{RTTI}(i, j)$ the corresponding speed value for $S_i \times T_j$ is denoted. Using this specification, the spatio-temporal speed function $V_{RTTI}$ can be stated:

$$V_{RTTI}(x, t) := v_{RTTI}(i, j) \quad \forall (x, t) \in S_i \times T_j.$$  

(1)

Here capital letters always refer to functions, whereas small letters refer to values or parameters. $V_{RTTI}$ is a piecewise constant speed function on the RTTI-induced spatio-temporal grid. Such forms of contour plots are here also denoted as grid contour plots.

Returning to the setting in Figure 2, only four speed categories are considered: A (free-flow) to D (heavily congested). To allow visual comparison, the contour plot in Figure 2 d),

**FIGURE 3** Transforming RTTI into a Grid-Contour-Plot
showing $V_{RTTI}$, is based on the same data as Figure 2 b). Note that the function $V_{RTTI}$ in Figure 2 is generated synthetically, but on the basis of real data. The corresponding spatio-temporal grid is also generated synthetically. For this purpose, the 16 kilometers corridor of A99 is (in both directions) partitioned arbitrarily into segments with lengths between 300 meters and around 700 meters. The chosen lengths are oriented on real segment lengths as they are used by traffic information providers. Similarly, the update cycle of the RTTI was simply set to five minutes. The categorization in speed classes for Figure 2 d) is done as follows: class D reaches from 0 to 35 kilometers per hour, class C up to 60 kilometers per hour, class B up to 100 kilometers per hour and all speed values above 100 kilometers per hour are added to speed class A. The associated speed values for each class are given by the arithmetic average of its speed thresholds:

$v_A = 136.5$, $v_B = 80$, $v_C = 47.5$ and $v_D = 17.5$ kilometers per hour. Here, for $v_A$ an upper bound of 173 kilometers per hour is assumed. This means that a navigation device which is based on this RTTI assumes a speed of exactly 17.5 kilometers if speed class D is broadcasted. Note that many RTTI-based navigation or trip planning devices do not only work using speed categories, but using specific speed values for the computation of optimal routes. This means that for a spatio-temporal area $S_i \times T_j$, the function $V_{RTTI}$ cannot only assume one of four values ($v_A$ to $v_D$), but any value. Nevertheless, the corresponding RTTI-based function would still be piecewise constant on a spatio-temporal grid. Thus, all approaches and notations in this paper can be modified for this special case, just by leaving out the categorization of the speed values into speed classes.

The Technical Ground Truth for Real-Time-Traffic-Information

To adapt the ground truth in such a way that restrictions caused by the limited illustration possibilities of RTTI are incorporated, the first step is to identify those limitations. For RTTI, there are three possible sources: The first is the separation of the considered area $[x_{start}, x_{end}]$ into segments. For each segment only one speed class can be broadcasted. The second source of restrictions is the RTTI update rate. Speed changes can only be reflected as soon as a new time interval starts. Keep in mind that here data transmission delays due to technical reasons are not considered. The focus is set solely on limitations of the presentation of the data. The last aspect is the restriction to send only speed classes and not speed values. For example, the data measured by a RTTI provider states a speed of 38 kilometers per hour for certain segment of a highway. According to the speed categorization used in Figure 2, this speed is categorized into speed class C. The speed class C is, as already mentioned, associated with 47.5 kilometers per hour. As one can see, the, in principle, precise information got lost and only an approximation is broadcasted. Now that these restrictions are identified, the TGT for RTTI is constructed in two steps. In a first step $V_{GTTI}$ is discretized in time and space according to the RTTI-induced grid. This is done by computing the harmonic mean of $V_{GT}$ for each cell $S_i \times T_j$:

$$A_{i,j} = \int_{T_j} \int_{S_i} 1 dx dt$$

$$v_{TGT^*}(i, j) = A_{i,j} \cdot \left( \int_{T_j} \int_{S_i} \frac{1}{V_{GT}(x, t)} dx dt \right)^{-1}$$

Note that the harmonic mean is applied instead of the arithmetic mean to avoid systematic bias when computing trajectory-based travel times for $V_{TGT}$ (see Figure 4.10 in (10)). In the sec-
ond step, each resulting speed value $v_{TGT^*}(i, j)$ is assigned to one of the speed categories and $v_{TGT}(i, j)$ assumes the corresponding speed parameter. To continue the example from before, if $v_{TGT^*}(i, j) = 38$ kilometers per hour, then this value is assigned to class C and thus $v_{TGT}(i, j) = v_C = 47.5$ kilometers per hour. The function $V_{TGT}$ is then defined analogously to $V_{RTTI}$ in Equation 1. $V_{GT}$ is essential for the construction of the new quality measure. For part c) of Figure 2, $V_{TGT}$ is constructed according to $V_{GT}$ and $V_{RTTI}$ from Figure 2. This allows direct comparison between these three contour plots.

A NEW QUALITY EVALUATION MODEL FOR REAL TIME TRAFFIC INFORMATION

The new quality evaluation method is constructed particularly for RTTI. It is intended as an objective, customer based indicator that enables a spatio-temporal location of error sources. However, taking limitations of the presentation possibilities of RTTI into account, is the key feature of this approach. This property differs it from former methods. In accordance with Figure 2, this is done by quantifying the difference between $V_{TGT}$ and $V_{RTTI}$, and not between $V_{GT}$ and $V_{RTTI}$. Considering $V_{TGT}$ and $V_{RTTI}$, it can be stated that both functions are piecewise constant on the spatio-temporal plane regarding the same RTTI-induced grid. For comparing these two speed functions, one can calculate the absolute difference of $V_{TGT}$ and $V_{RTTI}$ for each cell of the grid and add all resulting values. Such a procedure can identify temporal and spatial regions of high deviations between $V_{TGT}$ and $V_{RTTI}$. The quality measure, described in this section, accomplishes basically the same. The only modifications are that the differences are not summed up, but are weighted according to the spatial-temporal area of the corresponding cells and that a special metric is used to quantify the difference between $V_{TGT}$ and $V_{RTTI}$ for each cell. So, let $d : \mathbb{R} \times \mathbb{R} \to \mathbb{R}_{\geq 0}$ be any metric and let the spatio-temporal area $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$ be considered. Moreover, let $S_i$ and $T_j$ be defined as before. Then, for the two piecewise constant (regarding to the grid which is defined by $S_i$ and $T_j$, $i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\}$) speed functions $V_{TGT}$ and $V_{RTTI}$, the quality measure $D(d)$ is defined as follows:

$$D(d) := \frac{1}{w} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j} \cdot D_{i,j}(d),$$

with

$$D_{i,j}(d) := d(v_{TGT}(i, j), v_{RTTI}(i, j))$$

$$w_{i,j} := \int_{S_i} \int_{T_j} 1 \, dt \, dx$$

$$w := \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j}$$

To clarify which speed functions are compared, it is written $D(d, V_{TVLR}, V_{RTTI})$. Weighting the deviations according to the areas of the cells results in a quality measure that focuses on the spatio-temporal extent of errors. Other approaches might also be reasonable, e.g., weight a cell $S_i \times T_j$ according to the number of vehicles that are located on the road segment $S_i$ at any time of the time interval $T_j$. For this, certainly, additional data would be needed. Also the selection of the metric provides many possibilities. To decide which metric is the best depends on what objectives
are pursued: If one wants to penalize especially high differences between $V_{\text{GT}}$ and $V_{\text{RTTI}}$, then a metric with exponential or quadratic growth should be chosen. If the quality measure should allow higher deviations at higher speeds, then relative metrics might be useful. As already mentioned, the intention is to construct the new measure in such a way that it takes the customer’s perception of quality into account. This is done by choosing a metric $d_m$ which leads to high correlations between $D(d_m)$ and a quality measure that is especially intended for this purpose, the travel time difference (TTD) index (9).

The Travel Time Difference Index
The intention of the TTD index is to construct a customer-oriented quality measure for RTTI. Hence, as adequate information about travel times is the key element of interest for most users of RTTI-based services, the TTD index refers to travel times. For its construction, two ingredients are necessary: a specific set of starting times $t_1, ..., t_N$ and for each of these starting times a pair of two virtual travel times. Before one can explain how the starting times are chosen, the travel times are calculated. For this purpose, let the spatio-temporal speed function $V$ on $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$ be considered. For some starting time $t_s$, the travel time for driving from $x_{\text{start}}$ to $x_{\text{end}}$, with speeds given by $V$, can be computed by solving the ordinary differential equation

$$\frac{dx}{dt} = V(x(t), t)$$

with initial condition $x(t_s) = x_{\text{start}}$ and termination condition $x(t_s + t(t_s)) = x_{\text{end}}$ (compare section 19.6 in (10)). Here, $t(t_s)$ denotes the resulting travel time. Several approaches for solving Equation 8 can be found in (11). In this paper, the piecewise constant trajectory method, denoted as PCSB in (11), is used. Note that van Lint introduced the computation of travel times according to a speed function that is constructed using the ASM as a filtered speed-based trajectory method (FSB). In the case of piecewise constant (referred to the spatio-temporal plane) speed functions, as e.g. $V_{\text{RTTI}}$, the corresponding ordinary differential equation can be solved analytically if the PCSB is applied. This does not hold for general speed functions. In order to be able to generate trajectories which lie partially outside of $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$, the speed function $V$ is extended:

$$V(x, t) := v_{\text{free}} \quad \forall(x, t) \notin [x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}],$$

where $v_{\text{free}}$ is a parameter representing the speed during free-flow. It is important for the construction of the TTD index that the two functions which are compared are extended using the same free-flow speed. In accordance with Figure 2, the TTD index, since it should represent the customer’s view, compares the functions $V_{\text{GT}}$ and $V_{\text{RTTI}}$. The reason for this is that $V_{\text{GT}}$ usually is more similar to the real situation than $V_{\text{GT}}$. First, a pair of two travel times for the starting time $t_{\text{end}}$ is computed. One travel time, by solving Equation 8 for $V = V_{\text{GT}}$, the second travel time by doing the same for $V_{\text{RTTI}}$. The resulting travel times are denoted with $t_{\text{GT}}(t_{\text{end}})$ and $t_{\text{RTTI}}(t_{\text{end}})$, respectively. Then, by working backwards along the time axes in five minute steps, new starting times are added. For each of these new starting times, an additional pair of travel times is computed in the same way as it was done for $t_{\text{end}}$. One proceeds until the resulting pair of trajectories does not cross the area $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$ any more. This guarantees that the TTD index covers the total area $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$. The starting times are denoted chronologically, i.e., the first starting time is denoted with $t_1$, the second with $t_2$, up to $t_N = t_{\text{end}}$. Note that $t_1 < t_{\text{start}},$
since the corresponding trajectory does lie completely outside of $[x_{\text{start}}, x_{\text{end}}] \times [t_{\text{start}}, t_{\text{end}}]$. As a consequence, since $v_{\text{free}}$ is chosen equally for extending $V_{\text{GT}}$ and $V_{\text{RTTI}}$, it holds:

$$t_{\text{GT}}(t_1) = t_{\text{RTTI}}(t_1) = \frac{x_{\text{end}} - x_{\text{start}}}{v_{\text{free}}}.$$  \hfill (10)

Analogously, it can be argued that

$$t_{\text{GT}}(t_{\text{end}}) = t_{\text{GT}}(t_N) = t_{\text{RTTI}}(t_N) = \frac{x_{\text{end}} - x_{\text{start}}}{v_{\text{free}}}.$$  \hfill (11)

Hence, the travel times for the starting times $t_1$ and $t_N$ cannot explain any difference between $V_{\text{GT}}$ and $V_{\text{RTTI}}$ and thus, they are not taken into account for the TTD index. This can be observed schematically on the left side of Figure 4, whereas trajectories computed according to $V_{\text{RTTI}}$ of Figure 2 are displayed on the right side. Now, in a final step, the gathered information about differences of travel times is aggregated into one single value. This is done by forming the mean squared error of the relative travel time deviations between $t_{\text{GT}}$ and $t_{\text{RTTI}}$ for the starting times $t_2, ..., t_{N-1}$:

$$\text{TTD} := \frac{1}{N-2} \sum_{i=2}^{N-1} \left( \frac{t_{\text{GT}}(t_i) - t_{\text{RTTI}}(t_i)}{t_{\text{GT}}(t_i)} \right)^2.$$  \hfill (12)

Including the compared speed functions in the notation, e.g. $\text{TTD}(V_{\text{GT}}, V_{\text{RTTI}})$, increases clarity. The power of two in Equation 12 weights high errors overproportionally. This is done, as high errors are supposed to affect customer’s experience of quality drastically, whereas minor errors might not even be noticed. Dividing through $t_{\text{GT}}(t_i)$ normalizes the TTD index with regard to the distance between $x_{\text{start}}$ and $x_{\text{end}}$. The idea is that doubling the considered part of the highway, also doubles the differences between $t_{\text{GT}}$ and $t_{\text{RTTI}}$ if constant RTTI-quality is assumed. Since the TTD index should not depend on the size of $x_{\text{end}} - x_{\text{start}}$, the denominator $t_{\text{GT}}(t_i)$ is necessary. Note that dividing through $N - 2$ does, in principle, the same for the considered time span $t_{\text{start}}$ to $t_{\text{end}}$. In Figure 5, the example of Figure 2 is continued with $v_{\text{free}} = 136.5$ kilometers per hour. The top part shows travel times $t_{\text{GT}}$, $t_{\text{TGT}}$ and $t_{\text{RTTI}}$ depending on the starting times of the correspond-
FIGURE 5  Comparison of travel times for $V_{GT}$, $V_{TGT}$ and $V_{RTTI}$

ing virtual trajectories. Note that this allows the TTD index to compare any of the functions $V_{GT}$, $V_{TGT}$ and $V_{RTTI}$. Consequently, the TTD index cannot only be used to approximately quantify the customers experience of RTTI-quality, i.e., $TTD(V_{GT}, V_{RTTI})$ is computed, but also to follow the idea to incorporate technical restrictions and compare $V_{TGT}$ with $V_{RTTI}$. At the bottom of Figure 5, the corresponding (absolute) deviations are shown. It is remarkable that $t_{RTTI}$ lies for several starting times closer to $t_{GT}$ than $t_{TGT}$. The resulting $TTD(V_{GT}, V_{RTTI})$ index is 0.0056. To give an idea of what this values means, it is analyzed how the TTD index develops if a constant relative relation $f > 0$ between $V_{GT}(x, t)$ and $V_{RTTI}(x, t)$ is assumed:

$$V_{GT}(x, t) := f \cdot V_{RTTI}(x, t) \quad \forall (x, t) \in [x_{start}, x_{end}] \times [t_{start}, t_{end}].$$

(13)
Then it can be stated for an appropriate set of starting times $t_i$:

$$TTD(V_{GT}, V_{RTTI}) := \frac{1}{N-2} \cdot \sum_{i=2}^{N-1} \left( \frac{t_{GT}(t_i) - t_{RTTI}(t_i)}{t_{GT}(t_i)} \right)^2 = (14)$$

$$= \frac{1}{N-2} \cdot \sum_{i=2}^{N-1} \left( \frac{x_{end}^i - x_{start}^i}{\bar{v}_{GT}(t_i)} - \frac{x_{end}^i - x_{start}^i}{\bar{v}_{RTTI}(t_i)} \right)^2 \approx (15)$$

$$\approx \frac{1}{N-2} \cdot \sum_{i=2}^{N-1} \left( \frac{x_{end}^i - x_{start}^i}{f \cdot \bar{v}_{RTTI}(t_i)} - \frac{x_{end}^i - x_{start}^i}{\bar{v}_{RTTI}(t_i)} \right)^2 = (16)$$

$$= \frac{1}{N-2} \cdot \sum_{i=2}^{N-1} (1 - f)^2 = (17)$$

Here with $\bar{v}_{GT}(t_i)$ the average speed for the trajectory through $V_{GT}$ starting at $t_i$ is denoted. Note the $\approx$-sign. It is necessary because the free-flow speed $v_{free}$ is for both functions $V_{GT}$ and $V_{RTTI}$ the same and thus Equation 13 cannot hold for $(x, t) \notin [x_{start}, x_{end}] \times [t_{start}, t_{end}]$. Consequently, a TTD index of 0.0056 corresponds roughly to a constant relative speed relation $f$ of

$$0.0056 = TTD(V_{GT}, V_{RTTI}) = TTD(f \cdot V_{RTTI}, V_{RTTI}) = (1 - f)^2 = (18)$$

$$f = 1 - \sqrt{0.0056} = 92.52\% = (19)$$

### The Squared Inverse Mean Percentage Error

For finding a metric with a high correlation with the TTD index, any metric could be considered. In this paper the following selection of metrics is analyzed: The absolute error (AE), the relative squared error (RSE), the absolute percentage error (APE) and the squared percentage error (SPE):

$$d_{AE}(x, y) = |x - y| = (20)$$

$$d_{RSE}(x, y) = \frac{(x - y)^2}{x} = (21)$$

$$d_{APE}(x, y) = \left| \frac{x - y}{x} \right| = (22)$$

$$d_{SPE}(x, y) = \left( \frac{x - y}{x} \right)^2 = (23)$$

Moreover, to each of these four metrics $m \in \{AE, RSE, APE, SPE\}$ a modified version "Im" is constructed:

$$d_{Im}(x, y) := d_m(\frac{1}{x}, \frac{1}{y}) = (24)$$

The basic idea for this modification is that the TTD index is based on travel times, whereas $D(d_m)$ compares speeds. $d_{Im}$ respects the inverse relation between speeds and travel times. If $D(d_{Im})$ is considered, an "I" is added to the abbreviation $m$, i.e., the modified metric of AE is denoted with IAE and so on. The correlations of these altogether eight versions of $D(d_m)$ with the TTD index are analyzed on the basis of the 80 datasets of the A99 which were described previously. For each of these sets, the ground truth is computed by applying the ASM. Here, in order to reduce the com-
Huber, Bogenberger, Bertini

**TABLE 1** Upper bounds of speed classes [km/h]

<table>
<thead>
<tr>
<th>classification</th>
<th>D</th>
<th>C</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>35</td>
<td>60</td>
<td>100</td>
<td>173</td>
</tr>
<tr>
<td>C2</td>
<td>20</td>
<td>35</td>
<td>85</td>
<td>173</td>
</tr>
<tr>
<td>C3</td>
<td>48</td>
<td>90</td>
<td>131</td>
<td>173</td>
</tr>
<tr>
<td>C4</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>173</td>
</tr>
<tr>
<td>C5</td>
<td>50</td>
<td>85</td>
<td>123</td>
<td>173</td>
</tr>
<tr>
<td>C6</td>
<td>15</td>
<td>22</td>
<td>38</td>
<td>173</td>
</tr>
<tr>
<td>C7</td>
<td>97</td>
<td>113</td>
<td>125</td>
<td>173</td>
</tr>
<tr>
<td>C8</td>
<td>42</td>
<td>102</td>
<td>118</td>
<td>173</td>
</tr>
<tr>
<td>C9</td>
<td>30</td>
<td>70</td>
<td>110</td>
<td>173</td>
</tr>
<tr>
<td>C10</td>
<td>25</td>
<td>55</td>
<td>95</td>
<td>173</td>
</tr>
</tbody>
</table>

Computational effort, the basic version of the ASM is not performed, but a sped-up version utilizing fast Fourier transformations instead. This reduces computation times up to a factor of 100, whereas the loss of quality is negligible. For notational reasons, the function representing the ground truth for the kth dataset is denoted with \( V^k_{GT} \), \( k \in \{1, \ldots, 80\} \). The RTTI-induced grid is the same as for parts c) and d) in Figure 2. In order to achieve more robust results, the correlations are not only computed for one type of speed categorization, but for ten. In Table 1 an outline of these speed classifications can be found. For each speed class of each classification, its upper speed boundary is listed. The upper bound for class A is always set to 173 kilometers per hour, since this is the highest value of \( v^k_{TGT*}(i, j) \) computed for the considered data. The listed speed classifications are chosen arbitrarily. Some are related to real classification schemes, other are constructed according to the distribution of speeds within the considered datasets. The representative speed parameter for each speed class of each classification is defined as the arithmetic mean of the borders of the class, e.g. for the classification scheme C1 it holds \( v_D = \frac{35+0}{2} = 17.5 \) kilometers per hour. There may be alternatives, but this is usually done in practice. Note that C1 is used for Figure 2.

It seems reasonable to compute the TTD index and \( D(d_m) \) on the basis of the same two speed functions, i.e., to compare \( TTD(V_1, V_2) \) with \( D(d_m, V_1, V_2) \). Since \( D(d_m) \) can only be applied to piecewise constant speed functions, \( V_{GT} \) cannot be taken into account. Moreover, sufficient RTTI-data was not available. Hence, \( V_{RTTI} \) is discarded. Thus, only two functions remain: \( V_{TGT} \) and \( V_{TGT*} \) (compare Equation 3). Consequently, for each dataset \( k \) and each speed classification

![FIGURE 6 Scheme describing the computation of correlations](image-url)
c, speed functions $V^k_{TGT}(c)$ and $V^k_{TGT*}$ are computed. Note that $V^k_{TGT*}$, in contrast to $V^k_{TGT}(c)$, depends not on the speed classification, but still on the RTTI-induced grid. Now, to obtain the correlations between the TTD index and $D(d_m), m \in \{AE, IAE, RSE, IRSE, \ldots \}$, for each speed classification $c$, all 80 values $TTD(V^k_{TGT*}, V^k_{TGT}(c))$, $k \in \{1, \ldots, 80\}$, are stored into one vector $TTD^c_{vec}$. The same is done for the values $D(d_m, V^k_{TGT*}, V^k_{TGT}(c))$. This means that altogether ten vectors $TTD^c_{vec}$ and eighty vectors $D(d^c_m)_{vec}$ are computed. An overview of the resulting correlations between $TTD^c_{vec}$ and $D(d^c_m)_{vec}$ is provided in Figure 7. For each of the eight metrics, the ten correlation values resulting from the different speed classification schemes are displayed. If one considers the triangle on the left top of Figure 7, it states that the correlation of $TTD^C_{vec}$ and the $D(d_{AE})^C_{vec}$ is about 0.95. The three dashed rectangles mark metrics leading to high correlations with the TTD index: AE, ISPE and IAPE. All three of them might be used. However, here the ISPE is chosen, since it is - at least when considering its formula - closely related to the TTD index as it is the (inverse) mean squared error of the differences between the cell-speeds and the TTD index is the mean squared error of the relative travel time differences. The corresponding quality measure $D(d_{ISPE})$ is from here on denoted as the Squared Inverse Mean Percentage Error (SIMPE). Note that Figure 7 contains some surprising results: Even though the TTD index, as well as all stated measures $D(d_m)$ quantify the differences between $V^k_{TGT*}$ and $V^k_{TGT}(c)$, there are several metrics that lead to very low correlations with the TTD index. Even all “good” metrics show correlations less than 0.4. This observation reveals that the TTD index and the SIMPE provide different information and thus leaving out one of these measures may imply a significant loss of information. Considering $V_{RTTI}$ and $V_{GT}$ of Figure 2, the resulting $SIMPE(V_{TGT}, V_{RTTI})$ is 0.0807. A plot of the corresponding errors $D_{i,j}(d_{ISPE})$ assigned to each cell can be found in Figure 8. For illustration, the errors are categorized into one of three classes. The thresholds for the classes are 0.0225

![FIGURE 7 Correlations resulting from computations](image)

Note: The figure shows a scatter plot with correlations between different metrics and the TTD index. The plot is divided into three dashed rectangles, each highlighting metrics with high correlations: AE, ISPE, and IAPE. The ISPE is chosen due to its close relation with the TTD index.
FIGURE 8  SIMPE-Plot: spatio-temporal view of $d_{ISPE}(v_{TGT}(i,j), v_{RTTI}(i,j))$

and 0.36. If one considers the cell which is on the left top, i.e., at kilometer 16 at 7:30, a SIMPE between 0.0225 and 0.36 is calculated. The reason for this can be found by looking at Figure 2: in part c) the corresponding cell is assigned to class B, whereas in part d) it is assigned to class A. Using that $v_A = 136.5$ kilometers per hour and $v_B = 80$ kilometers per hour, the exact SIMPE of this cell is

$$
\left( \frac{1}{80} - \frac{1}{136.5} \right)^2 = 0.1713
$$

The interpretation of the thresholds, as well as of the SIMPE can be done similarly to the TTD index, by assuming $V_{TGT} = f \cdot V_{RTTI}$ and plugging this into the definition of the SIMPE:

$$
SIMPE(V_{TGT}, V_{RTTI}) = \frac{1}{w} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j} \cdot d_{ISPE}(v_{TGT}(i,j), v_{RTTI}(i,j)) = \frac{1}{w} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j} \cdot d_{ISPE}(f \cdot v_{RTTI}(i,j), v_{RTTI}(i,j)) = \frac{1}{w} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j} \cdot \left( \frac{1}{f \cdot v_{RTTI}(i,j)} - \frac{1}{v_{RTTI}(i,j)} \right)^2 = \frac{1}{w} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} w_{i,j} \cdot (1 - f)^2 = (1 - f)^2.
$$

Comparing these equations to the approximation done for the TTD index (see equations 14 to 17), the only difference is that for the SIMPE the resulting formula is analytical. This similarity emphasizes the strong relation between the SIMPE and the TTD index. Hence, according to Equation
19, a SIMPE of 0.0807 corresponds to a constant relative speed relation $f$ of

$$f = 1 - \sqrt{0.0807} = 71.59\%.$$  \hspace{1cm} (30)

The threshold 0.0225 is equivalent to $f = 85\%$, and 0.36 to $f = 60\%$.

**Comparison of the SIMPE and the TTD index**

Both measures, the TTD index and the SIMPE, are constructed especially for the evaluation of RTTI-quality, both measures use the same ground truth reconstruction scheme and both measures penalize primarily large errors. Nevertheless, there are crucial differences: The TTD index is computed on the basis of virtual travel times, whereas the SIMPE quantifies the spatio-temporal extent of quality shortcomings. Consequently, the TTD index sets its focus on the most important quality criterion for customers, namely the accuracy of travel time estimations. However, quality measures that are based on travel times usually have inevitable disadvantages: during the computation of the TTD index, one generates a set of pairs of trajectories. Comparing the corresponding travel times for each of these pairs provides the possibility to roughly locate the origins of high values of the TTD index - at least temporarily. Since only travel times are considered, a spatial identification of error sources is not possible. Even worse is the fact that similar travel times do not imply similarity between the compared speed functions. For example, spatio-temporal areas where $V_{RTTI}$ overestimates speeds may neutralize areas where $V_{GT}$ is higher. Consequently, the resulting $TTD(V_{GT}, V_{RTTI})$ index might not indicate quality deficiencies. The SIMPE does not suffer from this issue. However, the SIMPE is a very abstract measure. This fact makes it more suitable for an internal analysis of the RTTI quality, in particular, as it is especially constructed for comparing the TGT with the RTTI. Furthermore, the SIMPE can only compare speed functions which are piecewise constant on the same spatio-temporal grid. The TTD index is not bounded to this restriction. This allows to compute $TTD(V_{GT}, V_{RTTI})$ and hence to quantify the customer’s perspective of quality shortcomings very closely. Taking all this into account, the TTD index is suited best for evaluating the perception of customers. The SIMPE, on the other hand, is the appropriate choice for an internal quality management. The optimal case for a RTTI provider is to use both quality measures for reaching an exhaustive understanding of the sources and the consequences of potential quality deficiencies.

**CONCLUSIONS AND WAY FORWARD**

A new concept for the evaluation of the quality of traffic information has been introduced. The crucial part of this concept, the TGT allows the identification of quality deficiencies caused by the limited possibilities of delivering traffic data. Hence, in contrast to former quality measuring methods, a more accurate rating of the true quality of traffic information is achievable. The paper explains in detail how the aforementioned aspects, especially the TGT, can be implemented for RTTI. The key idea is the transformation of RTTI into a contour plot-like form. The quality measure SIMPE for RTTI is also described. The SIMPE is derived as an independent index which provides the ability to locate errors temporarily and spatially. It also incorporates the impact of quality shortcomings on travel time estimations, providing an indicator of customer’s perception of RTTI quality. This last aspect is achieved by including information delivered by the TTD index into the SIMPE’s construction.

Reconsidering this research, some disadvantages of the SIMPE should also be mentioned.
The derivation of the measure is quite complex and the resulting formula very abstract. This complicates a direct interpretation of the resulting SIMPE values. Furthermore, for the stated ground truth construction, substantial data is necessary. This requirement may cause problems for implementing the SIMPE on arterial resolution. Another aspect is that the SIMPE is only able to compare piecewise constant speed functions. Due to this fact, the SIMPE cannot measure the difference between $V_{GT}$ and $V_{RTTI}$. Therefore, the approximation of the customer’s point of view may be more inaccurate than for other quality measures which can take $V_{GT}$ into account. The last aspect leads to the suggestion of combining the SIMPE with the TTD index to get an overall understanding of the sources of RTTI quality shortcomings and their impact on the customer’s perception. This conclusion is amplified further by the strong fluctuations of the correlations between the TTD index and the SIMPE, showing both measures provide different information.

REFERENCES


