JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2016; 3 (6): 520–530

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

Travel time reliability with and without the dynamic use of hard shoulder: Field assessment from a French motorway

*Neila Bhouri**, *Maurice Aron*, *Gerard Scemama*

IFSTTAR/COSYS/GRETTIA Laboratory, Université Paris-Est, Marne-la-vallée 77447, France

ARTICLE INFO

Article history:
Received 12 October 2015
Accepted 3 January 2016
Available online 9 November 2016

Keywords:
Travel reliability
Travel time
Managed lanes
Hard shoulder
Recurrent congestion
Traffic management assessment

ABSTRACT

Traffic management aims to ensure a high quality of service for most users by decreasing congestion and increasing safety. However, uncertainty regarding travel time decreases the quality of service and leads end-users to change their routes and schedules even when the average travel time is low. Indicators describing travel time reliability are being developed and should be used in the future both for the optimization and the assessment of active traffic management operation. This paper describes a managed lane experience on a motorway weaving section in France – hard shoulder running operation in rush hours. The paper is focused on travel time reliability indicators and their use for reliability assessment. It provides some discussions about the advantages and drawbacks of reliability indicators under different traffic conditions. It particularly shows the difference between using buffer times and buffer indexes. The paper also discusses the difficulty of interpreting the skew of travel time distribution for travel reliability.

1. Introduction

Managed lanes (e.g., dynamic peak hour lanes, additional lanes, high occupancy vehicles lanes, bus lanes) take a growing importance in traffic operations. This topic is becoming more and more important to tackle recurring congestion. Various practices have already been done in several European countries.

Managed lanes' operations refer to multiple strategies increasing the road capacity or adapting its configuration, in order to favour one transportation mode (bus, taxis, high occupancy vehicles), or for recurring congestion. In this last case, typically, the increase of capacity was obtained through a redefinition of the transverse profile within the roadway limits. Several technical alternatives are possible, such as the reduction of lanes width and the temporary or permanent use of the hard shoulder as a running lane.

* *Corresponding author*. Tel.: +33 1 81668689.
E-mail addresses: neila.bhouri@ifsttar.fr (N. Bhouri), mauraron@gmail.com (M. Aron), gerard.scemama@ifsttar.fr (G. Scemama).
Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2016.01.008

In France, dynamic reversible lanes (according to the commuter traffic direction) have been introduced since the 1960s (Quai de Seine in Paris, the Olympic Games in Grenoble, the Saint-Cloud Tunnel in Paris) (Nouvier and Lhuillier, 2007). A static hard shoulder running (HSR) operation has been implemented on a motorway weaving section (A3-A86 motorway) with a likely negative impact on safety, because of higher speeds even at peak hours. Then a dynamic HSR operation has been implemented on another motorway weaving section (A4-A86 motorway), only at rush hours, without any negative impact on safety. The objective of this paper is first to demonstrate the impact of this operation on travel time reliability. The second objective is to clarify the use of the indicators' cases according to traffic conditions and to their evolution from the period "before" to the period "after" the installation of the management operation. In Section 2, the standard traffic impact assessment of any management strategies is described. Section 3 is dedicated to the description of the travel time reliability approaches and in particular the introduction of the definitions of a number of reliability indices used. Section 4 gives the descriptions of the French site where the hard shoulder running (HSR) has been experimented as well as the assessment data. In Section 5, data quality is discussed and a method for replacing abnormal speed measures is given. In Section 6, travel time reliability results are provided. Based on these results, a discussion about the reliability indicators is conducted especially related to the width and skew of the distribution of travel times (Section 6). Finally, some conclusions of this paper are given in Section 7.

2. Managed lanes assessment

Several service quality indicators have been developed, with a direct impact on network reliability (Cohen et al., 2009). Impact assessments for dynamic use of the hard shoulder have focused on the general indicators.

- Volume of traffic, i.e. total distance covered by vehicles (veh/km);
- Total time spent in traffic (veh·h);
- Volume of congestion (h·km). This indicator describes the size of traffic jams. It is obtained by multiplying the length of roadway – reduced to one lane of saturated traffic by the length of time during which traffic is saturated;
- Impact on capacity;
- Improvement in traffic levels of service (LoS);
- Average journey speed;
- Reduced congestion;
- Environment impact;
- Number of accidents by traffic type/scenario (Aron et al., 2007);
- Socioeconomic aspects.

Goodin et al. (2011) research team developed guiding principles for identification, selection, and communication of performance measures. We are aware of two managed lanes reliability assessment in relation with HSR.

The first one is a simulation, validated by field operation, in order to make a pre-evaluation. The travel time reliability is based on the criteria set out in this report. Mehran and Nakamura (2009) estimated that reliability as a function of demand, capacity, weather conditions and accidents and pre-evaluated the impact of HSR for the Tokyo-Nagoya Expressway.

The second one is a field operation. The travel time reliability is based on its variability. On M42 motorway, HSR was experienced with other active traffic management operations. It leads to a reduction in the variability of journey times. According to the scenario, this reduction reaches 27% and 34% on week days (DFT, 2008) or 22% (Ogawa et al., 2010).

3. How to measure reliability

When monitoring reliability, it is important to distinguish between network operator perspective and user perspective. For the network operator, the focus is network quality (what is provided and planned). While for the user, the focus is how the variability of travel time is experienced (Bhouri et al., 2013).

Several definitions for travel time reliability exist and many different relevant indicators have been proposed. Quality of service from the customer point of view was discussed, with the proposition of indicators that reflect their needs in terms of punctuality and reliability (BTCE, 1996). Other indicators are also summarized (OECD/ITF, 2010). Here we use the same breakdown as presented in previous studies and divide these measures into four categories listed below (Lomax et al., 2003; Van Lint et al., 2008).

(1) Statistical range methods;
(2) Buffer time methods;
(3) Tardy trip measures;
(4) Probabilistic measures.

3.1. *Statistical range methods*

Standard deviation (STD) and the coefficient of variation (COV) show the spread of the variability in travel time. They can be considered as cost-effective measures to monitor travel time variation and reliability, especially when variability is not affected by a limited number of delays and when travel time distribution is not much skewed. Standard deviation is defined as

$$\mathrm{STD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\mathrm{TT}^{i} - \mathrm{M}\right)^{2}} \quad (1)$$

while coefficient of variation is written as

$$\mathrm{COV} = \mathrm{STD}/\mathrm{M} \quad (2)$$

where M is the mean travel time, TT^i is the ith travel time observation, N is the number of travel time observations.

When the travel time is not directly measured, Rakha and Zhang (2005) related time-mean speed (recorded by dual loop detectors) to space-mean speed and then they related space-mean speed variability to travel time variability for estimating STD and travel speed confidence limits.

Fosgerau et al. (2008) proposed a theoretical economic model as the basis for defining and valuing travel time variability.

De Jong et al. (2009) based the monetary values of reliability on STD and multiplied by the monetary value of 1 min standard deviation.

A further consideration to use the standard deviation as a reliability indicator derives from recent studies that recommends defining travel time reliability as the standard deviation of travel time when incorporating reliability is included in cost-benefit assessment (HEATCO, 2006). As a result, standard deviation is used to measure reliability in few countries where guidelines for cost-benefit assessment include reliability (New Zealand Transport Agency, 2008).

Both standard deviation and coefficient of variation indicate the spread of travel time around some expected value must be taken with caution because the travel times distributions are often asymmetric, due to congestion, and thus far from the Gaussian distribution. Then the coefficients linking the width of the confidence intervals to the standard deviation are no more valid, such as the value "1.96 × standard deviations" for the 95% confidence interval. Therefore, studies have proposed metrics for skew (λ^{skew}) and width (λ^{var}) of the travel time distribution (Van Lint et al., 2008).

3.2. *Buffer time methods*

The wider or more skewed the travel time distribution the less reliable travel times. In general, the larger λ^{skew} indicates higher probability of extreme travel times (in relation to the median). The large values of λ^{var} indicate that the width of the travel time distribution is largely relative to its median value. Previous studies have found that different highway stretches can have very different values for the width and skewness of the travel time and propose another indicator (UL_r) which combines these two and removes the location specificity of the measure (Van Lint et al., 2008). Skewness and width indicators are defined as

$$\lambda^{\text{skew}} = (\text{TT}_{90} - \text{TT}_{50})/(\text{TT}_{50} - \text{TT}_{10}) \tag{3}$$

$$\lambda^{\text{var}} = (\text{TT}_{90} - \text{TT}_{10})/\text{TT}_{50} \tag{4}$$

$$\text{UL}_\text{r} = \begin{cases} \lambda^{\text{var}} \cdot \ln(\lambda^{\text{skew}})/L_\text{r} & \lambda^{\text{skew}} > 1 \\ \lambda^{\text{var}}/L_\text{r} & \text{otherwise} \end{cases} \tag{5}$$

where L_r is the route length, TT_X is the Xth percentile travel time.

Other indicators, especially the buffer index (BI) appears to relate particularly well to the way in which travellers make their decisions (Bhouri and Kauppila, 2011). Buffer time (BT) is defined as the extra time a user has to add to the average travel time so as to arrive on time in 95% of the situation. It is computed as the difference between the 95th percentile travel time (TT_{95}) and the mean travel time (M). The BI is then defined as the ratio between the buffer time and the average travel time

$$\text{BI} = (\text{TT}_{95} - M)/M \tag{6}$$

The buffer time is useful in user assessments of how much extra time has to be allowed for uncertainty of travel conditions. Hence it answers simple questions such as "How much time do I allow for uncertainty of travel condition?" or "When should I leave?". The BI gives the percentage of time wasted for counterbalancing uncertainty, independently from the duration of the trip. For example, if the average travel time equals 20 min and the BI is 40%, the buffer time equals 20 × 0.40 = 8 min. Therefore, to ensure on-time arrival with 95% certainty, the traveler should allow 28 min for the normal trip of 20 min.

Planning time (PT) is another concept used often. It gives the total time needed to plan for 95% on-time arrival as compared to free flow travel time. The planning time index (PTI) is computed as the 95th percentile travel time (TT_{95}) divided by free-flow travel time ($\text{TT}_{\text{free-flow}}$).

For example, if PTI = 1.60 and $\text{TT}_{\text{free-flow}} = 15$ min, a traveler should plan 24 min in total to ensure on-time arrival 95% certainty. Because these indicators use 95% value of the travel time distribution as a reference of the definitions, they more explicitly take into account the extreme travel time delays.

3.3. *Tardy trip measures*

Tardy trip measures indicate unreliability impacts using the amount of trips late. Indeed, if travelers only use the average trip time for their travel plans, they will be late for half of their destinations and early for the other half (in round numbers).

A misery index (MI) calculates the relative distance between mean travel time of the 20% most unlucky travelers and the mean travel time of all travelers. It is defined as

$$\text{MI} = \left(\text{M}_{|\text{TT}^i > \text{TT}_{80}} - \text{M}\right)\Big/\text{M} \tag{7}$$

3.4. *Probabilistic measures*

Probabilistic indicators (Pr) calculate the probability that travel times occur within a specified interval of time. Probabilistic measures are parameterized in the sense that they use a threshold travel time, or a predefined time window, to differentiate between reliable and unreliable travel times. Probabilistic measures are useful to present policy goals, such as the Dutch target for reliability, according to which at least 95% of all travel time should not deviate more than 10 min from the median travel time (Van Lint et al., 2008). This can be presented by the following equation

$$\text{Pr}(\text{TT}^i \geq \beta + \text{TT}_{50}) \geq 95\% \tag{8}$$

which calculates the probability that travel times do not deviate by more than β min from the median travel time. Parameter β can be given any value. For example, $\beta = 10$ min for routes less than 50 km in the Netherlands is used in this paper.

BTs are useful for users as they indicate the time they have to add to their average travel time or to their free-flow (PT) to avoid being late to their destinations.

Pr such as STD, COV, λ^{skew}, and λ^{var} are not understandable by all users but they are useful for operators who can specify some targets so that only small part of people can have unreliable travel time. Also indexes, BI, PTI, MI are ratios (without any unit), thus they are comparable whatever the length of the trip. Therefore they are useful for traffic operators who will tend to minimize them.

FHWA (2010) considers that the most effective methods of measuring travel time reliability are 90th or 95th percentile travel times, buffer index, and planning time and frequency that congestion exceeds some expected threshold.

4. Dynamic use of hard shoulder on the French A4-A86 motorway

4.1. *Section TC A4-A86: dynamic use of the hard shoulder*

The two-lane urban motorway ring (A86) round Paris and the three-lane west-east urban motorway (A4) share a four-lane 2.3 km long weaving section in the east of Paris. At this place the A86 ring is north-south and the A4 motorway is also locally north-south, due to the constraint of the nearby river "Marne". As the traffic flows of the two motorways are added, traffic is particularly dense in some hours on the weaving section (Fig. 1), renowned as the greatest traffic bottleneck in Europe. Until summer 2005, 280,000 vehicles using this stretch of road every day used to form one of the worst bottlenecks in French history, with over 10 h congestion per day and tailbacks regularly averaging 10 km. Traffic would be saturated by 6:30 a.m. and the situation would not revert to normal until 8:30 p.m.

A HSR experiment has been launched in July 2005. It gives drivers access at peak times to an additional lane on the hard shoulder where traffic is normally prohibited. The size of the traffic lanes has been adjusted. From the standard width of 3.50 m, they have been reduced to 3.20 m.

The opening and closure of this lane are activated from the traffic control centre in principle according to the value of the occupancy measured upstream of the common trunk section, open if occupancy is greater than 20% and close if less than 15%. In fact, traffic operators made the decision for opening/closing the system based on a set of criteria, including occupancy.

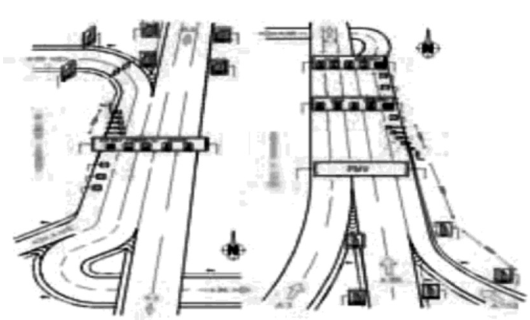

Fig. 1 – Weaving section A4-A86 (additional lanes in dotted red).

Daily statistics in the duration of HSR during working days in 2006 show an average of 5 h use inward Paris and 4 h use eastward out of the city. On Saturdays, the hard shoulder is open for an average of 4 h inward Paris and 3 h 45 min in the opposite direction. On sundays it is open in both directions for 3 h 20 min.

Moveable safety barriers are installed on the right side of the additional lane. The barriers rotate for closing this lane (hard shoulder). These moveable barriers are installed at several key locations at the section so that drivers can see them whatever their positions are and thus dissuaded from using the lane (Fig. 2). The width of the hard-shoulder has been increased to 3 m and the width of the other lanes has been reduced from the standard 3.5 m–3.2 m.

Automatic incident detection cameras have been installed for monitoring overall safety. Safety has been improved by the installation of cameras. In the event of accident when the lane is open, stationary vehicles on the hard shoulder lane can be detected, leading to the closure. Additional safety is provided by speed control radars on the A4 motorway in both traffic directions.

4.2. *Data collection*

Assessing this HSR road operation requires to consider not only the traffic on the 2.3 km weaving section but also the traffic downstream. Although data were available on a 8 km-long stretch (in each direction) here we only analyse a 3 km long stretch in the eastbound direction (2.3 km on the weaving section, 0.7 km on the downstream). Inductive loops provide traffic flow, occupancy and average speed for each lane every 6 min.

Data has been analysed for three years (2000, 2001, and 2002) before the experiment and one year after 2006. Four inductive loops in the eastbound direction (three on the weaving section, respectively 200 m, 800 m and 1500 m after the beginning of the 2.3 km weaving section; and one inductive loop 200 m downstream) were used for computing the travel times presented here.

4.3. *Traffic trend between the periods of 2000–2002 and 2006*

The level of the traffic volume exerts influence on the travel time and its reliability. When analyzing the travel time reliability for two sets of years, the traffic volume trend in between must be taken into account. Table 1 gives the vehicles-kilometres by year for the 2.3 km weaving section (both ways).

We are using a different period here for the day later for the reliability assessment. This difference doesn't affect our analysis as we are comparing the same periods for the years before and after HSR opening.

The total traffic decreased by 2% between periods of 2000–2002 and 2006 and traffic increased during night by 7%, which is corresponding to a change in drivers' behaviour. Although difficult to estimate without using a simulation model, these traffic variations are not very high, their impact on travel time should be rather low.

In turn, a modification of the travel time reliability may have an impact on the traffic level, because a part of drivers

Fig. 2 – Weaving A4-A86 section, eastbound with 5th lane, open and closed.

are sensitive to traffic conditions that some trips are advanced, postponed or rerouted. In the case of a before-after assessment of a new traffic management system, it is easy to describe what happen in terms of traffic volume or its distribution during the day. The following table provides (for daylight only) the breakdown of vehicles-kilometres in opened and closed HSR.

In 2000, 2001 and 2002, HSR was not installed and the open periods are the periods corresponding to the periods in 2006 where HSR was effectively opened. The correspondence between these periods is made on calendar principles.

At each six-minute period of the year 2006 where traffic data was available we associated the period in 2000, 2001, or 2002 (with available traffic data) which is characterized by the same six-minute period in an hour, same hour in the day, same day in the week and approximately same date in the year. This matching prevents to potential bias if unavailable data in 2006 were not distributed as unavailable data in 2002.

The small increase in 2006 of the part that drivers driving during rush hours (20.1% in 2006 against 19% in 2000–2002) correspond to a shift in 2006 of some drivers toward rush hours (now less congested).

This analysis contributes to a better understanding of the link between the driver choice and the travel time reliability. This should be helpful for building and calibrating a driver behaviour model based on the travel time reliability and such a model is required for pre-evaluations.

4.4. *Weather condition and the variable day-to-day traffic flow*

Some factors, other than the HSR operation, may affect travel time reliability significantly such as the weather condition and the variable day-to-day traffic flow.

Table 1 – Day and night vehicles-kilometres by year on the weaving section in both directions.

Year	Day	Night	Total
2000–2002 average annual (AA)	168,168,200	31,961,163	200,129,363
Trend 2006 (Tr)	161,438,429	34,374,817	195,813,246
Tr/AA (%)	96	107	98

Note: for tables concerning the vehicles-kilometres, missing data are reconstituted and day is defined from 5 a.m. to 9 p.m.

Rain has not been added in the assessment model, however we checked that rain frequency was the same in 2000–2002 and in 2006, thus the lack of the rain variable does not result in any bias in the assessment. Rain occurrence was estimated by combining the six-minute records of a pluviometer and the hourly description of actual weather by a meteorologist. The yearly rain duration is quite the same in 2000–2002 (7.3% of the year) and in 2006 (7% of the year).

The day-to-day traffic flow variations have not been added in the assessment but this lack does not result in any bias, since complete years have been compared (Bhouri and Aron, 2014).

5. Travel time computation and quality

5.1. *Travel time computation*

Although data generally seems very good, some are missing, inaccurate or irrelevant. It is crucial to ensure that this does not distort the mean travel time, nor the queues in its distribution.

Anomalies in traffic data are identified from given thresholds. Some data are impossible such as occupancy greater than 100%, six-minute mean speed greater than 200 km/h, six-minute flow (by lane) greater than 400 vehicles. In these cases data for the corresponding period and lane is cancelled then considered as missing.

When this occurs, for a given period and lane in 2000, data is substituted, when possible, by 2001 or 2002 data of another period corresponding (in 2001 or 2002) to the same period in the hour, the same hour, the same day in the week, and approximately the same date. This process is also applied for reconstituting 2001 missing data (from 2000 to 2002 data), and 2002 missing data (from 2000 to 2001 data).

The travel time for the route is then computed from the four consecutive traffic stations as follows.

(1) At each traffic station, for each lane, the travel time is the ratio of the length of the stretch covered by the traffic station, divided by the six-minute mean speed for the lane. However this travel time is considered as an outlier (thus missing for the following) if the mean speed (for the lane) is lower than 2 km/h or higher than 150 km/h.
(2) At each traffic station, the average travel time over the lanes is the weighted sum of the non-missing travel

times of the different lanes. Each lane travel time is weighted by the proportion of the traffic flow circulating on this lane (over the total traffic flow for the period). This process requires that at least the speed on one lane is relevant (equal or greater or equal to 2 km/h and less or equal to 150 km/h).

(3) The travel time of the route constituted by the four consecutive stretches is the sum of the travel times of the stretches. This requires that the process described in the previous paragraph succeeds for the four stretches.

A comparison between travel times in 2006 and 2002, for instance is possible for all couples of periods where this whole process succeeded both in 2006 and in 2002. The frequency of success is high in absolute value which is 53,574 periods out of the 87,600 periods of the year, even if missing or irrelevant data are not rare and in percentage, the frequency of success is 61% = 53,574/87,600.

Except for the HSR open night periods for which few periods are recorded (about 140 six-minute periods), the amount of data used allows for some confidence in the following analysis.

5.2. *Data quality: missing data*

The previous paragraph indicates that missing data is frequent. However this does not imply any bias on travel time distribution, if the distribution of the missing data is independent from the traffic condition distribution. We checked for instance that there was no major breakdown for the 2.3 km eastbound weaving section with the four traffic sensors equipping. Indeed, a breakdown in months of high traffic for instance should make bias the travel time distribution, because the traffic flow and the travel time varies according to the month of the year (Fig. 3), related to the average annual travel time (day and night).

5.3. *Data quality: possible method for replacing speed outliers*

Thresholds for discarding very high or very low speed data impact the travel time distribution and have therefore an influence on data accuracy. As usually described in statistics tests, two types of influence occur, in falsely rejecting a very low (but right) or in not rejecting a very low (and false) speed. A complementary study is currently being made in order to replace outlier speeds by a function of the ratio (flow/occupancy) (Cassidy and Coifman, 1997). which examined the relationship between occupancy and speed and set a few equations. An analogous work is presented here to decide if an outlier speed must or not be rejected.

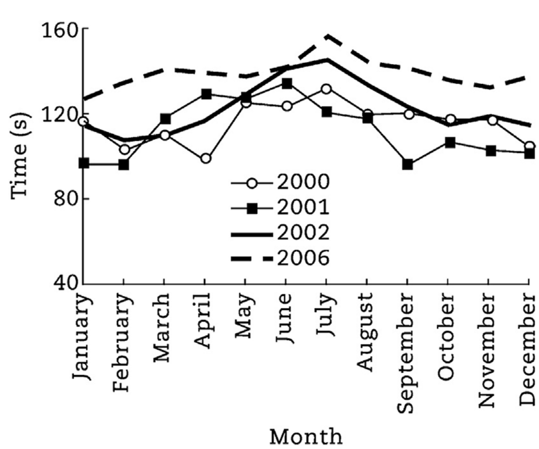

Fig. 3 – Average travel time for 3 km route according to month and year.

L_i is the length in metres of vehicle "i" (enlarged by the length of the magnetic loop constituting the sensor), V_i is its speed (i m/s), o^p is the occupancy for the 6 min (360 s) period p. o^p s given by

$$o^p = \sum_{i=1}^{q^p} (L_i/V_i)/360 = \sum_{i=1}^{q^p} \left[L_i/(100V_i')\right] \tag{9}$$

where q^p is the six-minute flow, V_i' is the speed in km/h of vehicle i, thus $V_i' = 3.6\ V_i$.

Assuming that on a given lane, the length of a vehicles is constant ($L_i = L$ for any vehicle i on the motorway lane), the occupancy is then given by the following relationship.

$$o^p = \sum_{i=1}^{q^p} \left[L_i/(100V_i')\right] = (L \cdot q^p)/(100V'^p) \tag{10}$$

where V'^p is the harmonic mean of the speed for period p for the given lane $1/V'^p = (1/q^p)\sum_{i=1}^{q^p} 1/V_i'$

This allows computing L

$$L = (100o^p \cdot V^p)/q^p \tag{11}$$

This length (by lane) is identified on a set P of periods p, excluding speed outliers. Weight every period p by the proportion of traffic flow for period p out of the set P. This leads to the weight $(q^p)/\sum_{\pi=1}^{P} q^{\pi}$

Then,

$$L = \left(100 \sum_{p=1}^{P} o^p \cdot V'^p\right) \Big/ \sum_{p=1}^{P} q^p \tag{12}$$

This gives an enlarged length L of 6 m on the slow lane and 5 m on other lanes.

When there is no access or exit ramp on the motorway stretch, the vehicle average length (over the lanes) does not change from one position on the motorway to the other one. Thus the consistency of the information given by two successive traffic stations can be checked by matching the average lengths derived from Eq. (12).

Reversing Eq. (12), a recorded speed for period p suspected to be an outlier can be replaced by

$$V''^p = (L \cdot q^p)/(100o^p) \tag{13}$$

where V''^p is also a harmonic mean. Using a harmonic mean speed in the travel time computation is correct, allowing building arithmetic means in travel time which deal with the inverse of the speeds.

In France, traffic detectors, in general, provide the average harmonic speeds, which is suitable for identifying L from Eq. (11) (Hombourger, 2011). In places where traffic detectors provide arithmetic speed average, L would be overestimated, because the arithmetic mean is always greater

Table 2 – Daylight vehicles-kilometres according to HSR status (both directions) on weaving section.

Year	Daylight vehicles-kilometres			
	Open	Closed	Total	Open part
2000–2002 average annual	31,868,274	136,299,926	168,168,200	$19.0\% = \frac{31,868,274}{168,168,200}$
2006	32,473,118	128,965,311	161,438,429	$20.1\% = \frac{32,473,118}{161,438,429}$

than the harmonic mean. However, the difference between these two means would very small. The difference can be computed when an assumption on the variations of individual speeds during period p is given. For instance if the individual speeds are uniformly distributed between $0.83\overline{V}^P$ and $1.17\overline{V}^P$, where $\overline{V}^P$ is the arithmetic mean, it is not difficult to derive the distribution of the inverse of speed, and, after an integration, to compute the inverse of the harmonic mean. L will be overestimated by 1%, thus the speed will also be overestimated by 1% (Eq. (13)).

The accuracy of Eq. (11) to Eq. (13) is based on three points, first, on the assumption that the length of the vehicles are the same (on the same lane); second, on the accuracy of the occupancy; its depends of the calibration of the sensor and of the record format.

The available occupancy is a percentage which is up to two decimal points. If, during period p, there is a five-metre long vehicle at the speed of 25 m/s (90 km/h), it occupies the sensor during 0.2 s and the six-minute occupancy will be 0.2/360 = 0.06%. An error of 0.01% on occupancy (for instance 0.05% instead of 0.06%) leads to a speed of 100 km/h using Eq. (13). If there are N vehicles circulating during the period, the same error (0.01%) for all vehicles implies an average speed of 100 km/h (Eq. (13)). This gives an idea about the accuracy of the speed derived from the occupancy. A more complete study will allow refining the relation between speed and occupancy.

Note also, that it is not easy to estimate the accuracy of the equipment. As traffic measure equipment is periodically updated, measurement accuracy may change. This fact may mitigate certain results.

5.4. *Building the travel time distribution*

At each six minute period, a travel time is experienced by a number of drivers, which is equal to the traffic flow during the six-minute period. The individual travel times are not measured, only the mean travel times by period are estimated. The question here is what statistical unit we should consider, the vehicle or the period of time.

(1) If the statistical unit is the time period, the distributions related to the offer are that traffic operators have to be guaranteed, for instance to offer a travel time less than a certain threshold during 95% of the year. This distribution is understood by drivers, who have to avoid traveling during the 5% of time periods when traffic conditions are the worst.
(2) If the statistical unit is the user, the distribution is the combination of the offer and the traffic demand. This will tend to be the distribution of the drivers' travel times, if travel times are homogeneous during a period. This distribution is preferred by the community. It is often used for the before-after assessment, where a weighting of each period by the corresponding traffic flow corresponds to the wasted time.

In Table 3 during day periods, the weighted distribution elements are higher. This is because high travel time corresponds generally to a high traffic flow and therefore will be weighted by a high number of vehicles. During night the traffic flow is generally very low. The link between travel times and traffic flows is not so clear and the previous relationship is not established. Indeed, by night, traffic is generally fluid and a high travel time might correspond to a high percentage of trucks in the traffic.

Nevertheless, we think that the reliability analyses from both distributions are parallel. We used the time period as the statistical unit of the travel time distribution, which is more relevant for users and operators.

6. Reliability analysis

Impacts of HSR on the travel time and on its reliability are identified with an observational before-after study on the weaving section completed by downstream sections. Analyses are conducted on both the HSR and the speed limit campaign. Indeed, Jacques Chirac, former president of France, launched an important campaign for road safety and against speeding in 2003. Therefore, it is necessary to study the impact of this campaign on speed, thus on travel time, in order not to confound the impacts of HSR and of the speed reduction campaign. The speed reduction, which is synonymous of an increase in travel time, was important only at off-peak, when HSR was not opened. We can assume that, during peak hours, speeding was very limited in the "before" period, since the average speed was very low.

6.1. *Global evaluation*

The HSR effect may be split in two components.

(1) A direct effect on travel time reduction and on travel time variance reduction.
(2) An indirect effect on the daily traffic distribution. Indeed when comparing off-peak and peak hours before and after HSR implementation a shift of some traffic from daylight off-peak hours (HSR closed) to peak hours (HSR open) has been observed (Table 2). Daylight traffic increased by 2% at peak hours, and decreased by 5% at off-peak hours. This shift might be due to the better traffic conditions when HSR is open. We assume that some drivers willing to drive during peak hours, were,

Table 3 – Non-weighted and weighted average travel times according to year and period in day.

Year and period	Weighted distribution	Distribution of average travel times by six-minute periods	Difference
2001, night	95.7	101.1	−4.4
2001, day	121.1	120.1	1.0
2001	116.3	113.5	2.8
2002, night	92.7	94.6	−1.9
2002, day	138.8	138.2	0.6
2002	130.1	123.0	7.1

during the "before" period, constrained to drive during off-peak, in order to avoid very bad peak-hour traffic conditions. Because of HSR and the resulting decrease of congestion, more drivers chose to circulate at peak hours, and less at off-peak periods. Reductions of travel time and of its variance are resulted at off peak. However, we cannot prove this assumption. In any case, the impact of this shift, if it is really due to HSR, leads to a smaller reduction of congestion, and a smaller increase in travel time reliability. If that assumption was false, increase in reliability would be even more.

Without the indirect effect, the travel time reduction during peak hours as well as the travel time increase during off-peak, would have been more. However it is no use to try to distinguish the part of each component in the travel time reduction or in the travel time variance reduction, because the drivers experienced the global results of these two components.

Fig. 4 shows the average, median and standard deviation of travel time for years 2000 and 2002 before the HSR and the year 2006 after the HSR. It shows results when the HSR is open and closed in days or nights. We can notice that travel time increases in 2002 as compared with the year 2000 for all the situations (night and day). For the day period, we can easily see the positive impact of the HSR, as the average travel time is reduced when the HSR is open, which means that the HSR reduced the congestion as there is one more lane for the circulation (Bhouri and Aron, 2013).

For day periods when HSR is closed, we notice an increase of travel time.

(1) Generally these periods were off-peak; then the better speed enforcement led to increase travel times.
(2) There are some rush hours in 2006 where HSR was unavailable, for instance it was in maintenance in August 2006. At these periods, there was a small traffic increase leading to the travel times increase.

We notice that for the night period, the average travel time, as well as the median increases in 2006 as compared with the two years before HSR (2000 and 2002) when the HSR is closed. This travel time increase when traffic condition is fluid (closed by night) is due to the speed limit campaign. This campaign also induced more homogeneous speeds in 2006 (nights) – the standard deviation is lower in 2006. We also notice an increase

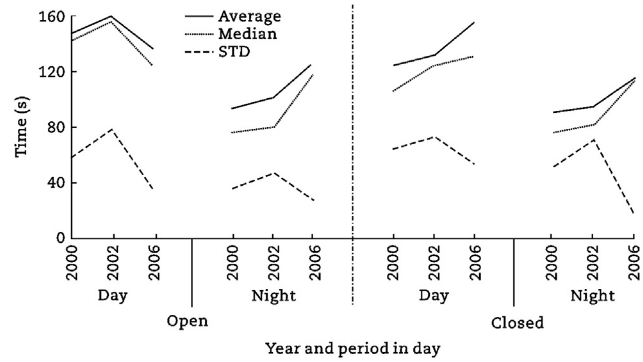

Fig. 4 – Impacts of HSR and of speed reduction campaign on travel time.

of travel time for the opened HSR during the limited nightly periods. HSR was sometimes opened in the morning, during night, before the beginning of the congestion, for avoiding or delaying it. At these periods in 2000–2002, travel time was low due to speeding, and higher in 2006 due to traffic enforcement, without any HSR effect. This can be confirmed when looking at Fig. 5. We can see that the BT and the PT are reduced. This means that it is not the extreme value of travel time which increases but the average, which means that travellers more respect the speed limit. We can notice for all situations a decrease of STD which means less dispersion and more reliable travel time of traffic in 2006 compared with 2000 and 2002.

We can see from Fig. 5, that all travel time indicators increase in 2002 compared with 2000. Unreliability, decreasing happened between 2002 and 2006 when HSR is open, as shown by the indicators. PT decreases when HSR is open, due to the reduction of congestion. On the contrary this PT is stationary when HSR is closed in daylight.

BT (the difference between the TT_{95} percentile and the average travel time) decreases when HSR is open, due to the decrease of the TT_{95}, although the average travel time also decreases.

Note that BT also decreases when HSR is closed (daylight) and this is due to the increase in travel time average and not in any decrease in TT_{95}. This is less favourable for drivers, but still remains an increase in reliability.

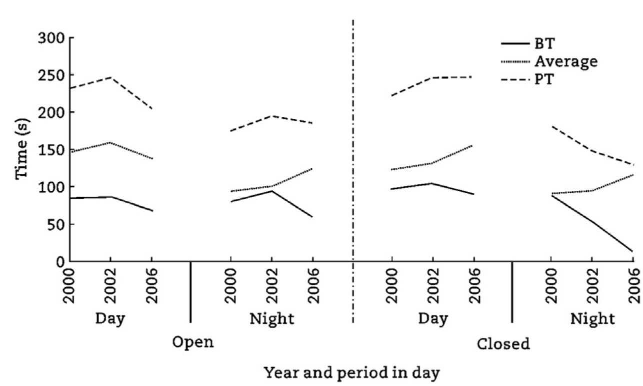

Fig. 5 – Impacts of HSR and of speed reduction campaign on travel time and BT.

The decreases of PT and BT in 2006 during night, when HSR is closed, is likely due to the speed enforcement campaign, which induced more homogeneous speeds in 2006 than in 2000 and 2002, thus an improve in travel time reliability.

6.2. *Buffer times and buffer indexes*

In the following we use only data from 2002 for the before period. Fig. 6 gives the PT, the free flow and PTI. Note that the PTI is a percentage and therefore not in the same scale as PT and free-flow, and it is drawn here just to show the difference in changes between it and the PT. As one can see on Fig. 6, PTI decreases outstandingly in 2006 for the four situations which are day, night, open, and close. However PT remains stable for the day-closed situation, and it decreases slightly for the night-open situation and decreases more notably for the other two situations. We can easily notice that the decrease in PTI is due to the rise of the free-flow. The rise in free-flow is only due to the speed-limit campaign and isn't influenced by traffic conditions (congestion or fluid). We can conclude here that.

(1) When comparing the situation in 2002 and 2006, the decrease of PTI was misleading for users because the PT did not always decrease.
(2) PTI remains as a good reliability indicator, if used for the same year. It shows the ratio between lucky drivers (at free-flow) and users who want to arrive in time in 95% uses.

Comparing the evolution of BT and BI (Fig. 7), we can see that both have the same evolution between 2002 and 2006. This is because the average travel time depends also on the congestion not on the free-flow. In 2002, the average speed corresponds to a congested traffic conditions only for the day-open period where average travel time is equal to 160 s, with a speed of 67.5 km/h.

In 2006, during night, day, and closed periods, the decrease of BI is more important than the decrease of BT. This difference is due to the increase of average travel time for these periods. In 2006, during day open periods, the decrease of BI is less important that the decrease of BT, due to the average travel time decrease at these periods.

If we define reliability in time by the BT, the BI still remains in this example a good reliability indicator. If we prefer defining reliability in percentage of time by the BI, BT still remains in this example a good reliability indicator.

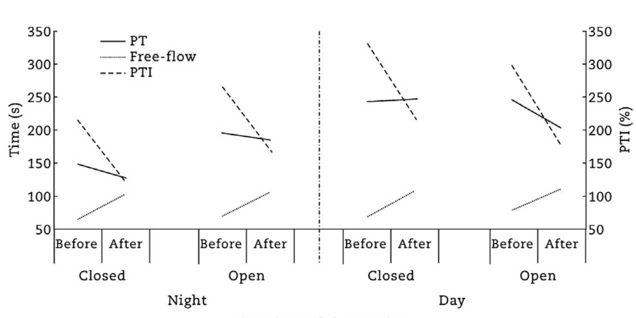

Fig. 6 – Evolution of PT and PTI.

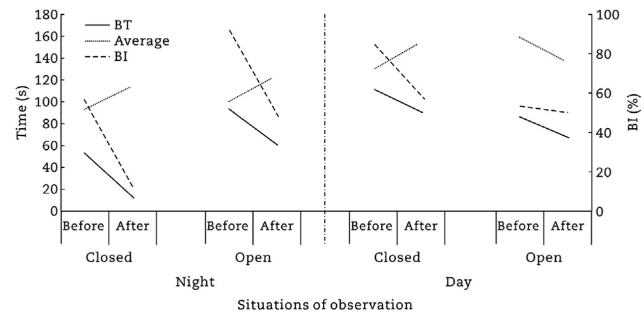

Fig. 7 – Evolution of BT and BI.

6.3. *Tardy trip measures and probabilistic indicator*

Tardy trip measures indicate unreliability impacts using the amount of trips late. A MI calculates the relative distance between mean travel time of the 20% most unlucky travelers and the mean travel time of all travelers. Fig. 8 shows that the evolution of the MI is very close to that of the BI when HSR is closed. The MI is more improved than the buffer when the HSR is open, especially for the day period (the more important one). This means that, HSR improves noticeably the reliability of travel time of very unlucky travelers.

The probabilistic indicator gives a different point of view. We can see from Fig. 8 that the probability that experienced travel time does not deviate by more than 20% more than the median travel time, remains stable (very slight rise), round 20%, for the open day period and decreases for other periods. The slight rise for the open day period is the inverse of the tendency of the BI and MI evolution. This slight rise comes from a decrease of the median, thus the value ($1.2TT_{50}$) corresponds to a shorter travel time, more frequently exceeded. Unlucky drivers are not less in 2006 than in 2002 (20%). In the MI definition which is also in this case, the value of Pr (travel time > $1.2TT_{50}$), these 20% unlucky drivers are less miserable in 2006 (MI from 54% to 41%).

6.4. *Are skewness and width metrics good indicators for the reliability assessment ?*

Van Lint et al. (2008) presented λ^{var} and λ^{skew} as robust measure is for width and skew of travel time. They argued that during congestion, unreliability of travel time is

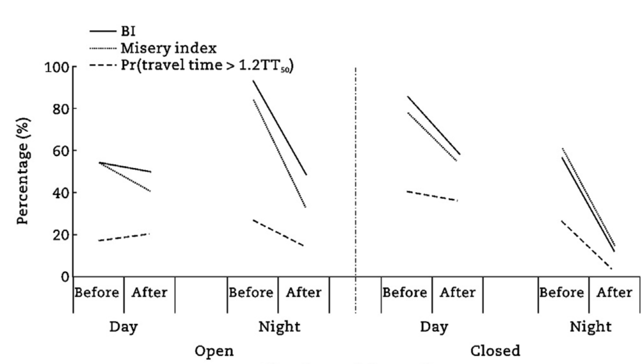

Fig. 8 – Misery index and probabilistic indicator.

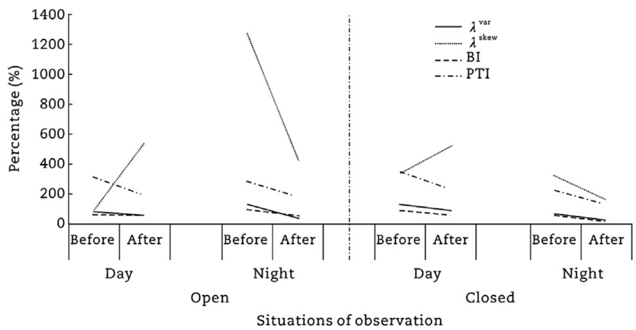

Fig. 9 – Evolution of width and skewness indexes for years 2002–2006 before and after HSR opening.

predominantly proportional to λ^{var}. This is not refuted here (see Fig. 9). The value $\lambda^{var} = 0.77$ in 2002 can be considered as large, whereas the value $\lambda^{var} = 0.54$ in 2006 is much less, while congestion decreased from 2002 to 2006. They also argued that in transient periods (congestion and dissolve), unreliability is predominantly proportional to λ^{skew}. However we cannot have this interpretation of λ^{skew} here, since we have computed λ^{skew} for all opened HSR periods, which include transient periods, congested and not congested periods. We say that on this large set of periods, the interpretation of λ^{skew} is miscellaneous, since the λ^{skew} numerator and denominator depend on the location of TT_{50} related to the congestion. Different cases may happen. Here, in daylight periods (HSR open) in 2002, $TT_{50} = 155.9$ s was in congestion (speed was 69.3 km/h), whereas in 2006, $TT_{50} = 124.9$ s (speed was 86.5 km/h) was no more in congestion.

In 2002, the large TT_{50} (due to congestion for half drivers) implies a large λ^{skew} denominator $TT_{50}-TT_{10} = 67.7$ s, and a relatively low λ^{skew} nominator $TT_{90}-TT_{50} = 52.4$ s, despite of congestion. Both reasons lead to a not so high λ^{skew} value (0.77).

7. Conclusions

Reliability is a new dimension for assessing traffic operations and is as important as the traditional factors such as road capacity, safety, equipment and maintenance costs, etc. This paper presents the travel time reliability assessment of a HSR field test from a French motorway. Field tests provide large amounts of data which is necessary for any assessment. The first concern is the quality of data.

In this field test, travel time is estimated from speeds which are measured by inductive loops. Data analysis shows the accuracy of data. However, some outlier speeds are identified. The paper gives a method to replace them from occupancy and flow.

The statistical unit on which is computed the travel time may be either a time period of six minutes or the vehicle, and this leads, because weights are different, to two travel time distributions. We show in this paper that there isn't a large numerical difference issued from the two methods. We used the time distribution which is closer to the users understanding.

In order to distinguish between the HSR effects and other concomitant aspects, traffic analyses have been performed with regard to day and night periods and to the peak and off-peak periods.

Results reveal a positive effect of HSR on travel time reliability. In addition to the reliability assessment of the HSR, we discussed in this paper the ability of different indicators to accurately reveal the travel time reliability improvement. Results show that lower PT increases driver satisfaction.

Perhaps it's easier to attain that a smaller BT implies a better reliability, even if the PT does not decrease. Results show that the comparison between PTI from different years may be misleading to travellers. In this field test example, reduction in PTIs is because of the increase in free-flow time and not of a decrease of the PT. Increase in free flow time is due to a greater respect of the motorway speed limit imposed by a control-sanction campaign. Further to these classical indicators, the paper discusses the robustness of λ^{var} and λ^{skew} indicators proposed by Van Lint et al. (2008) to measure respectively the width and the skew of travel time distribution. It shows the effectiveness of the λ^{var} indicator and its robustness to indicate both reliability and congestion. Results from this HSR French experiment show that the λ^{skew} indicator is not always suitable for the reliability assessment. Indeed, two factors impact traffic in this experiment which are the HSR implementation and the speed limit campaign, supported by the automatic speed control systems.

The speed limit affects traffic only for non-congested periods and hence when HSR isn't open. However it affects the denominator of the λ^{skew} indicator which depends on this non-congested traffic. The use of this part of the travel time distribution as a component of the λ^{skew} definition affects the quality of this indicator. Values of λ^{skew} reveal more a lower TT_{50} value rather than a more reliable traffic. As λ^{skew} isn't an effective indicator for reliability assessment, the combined indicator of width and skew, the ULR indicator is also affected and cannot therefore be considered as an effective indicator.

All results here come from empirical data. It should be useful to systematically match the results of a before-after assessment like this presented here, with those obtained by pre-evaluation, in order to understand the deviations between both studies, and thus improve our understanding of the phenomenon and on the models. In the future, the optimisation of traffic operations should be developed with respect, among other criteria, to travel time reliability, in its various forms.

Acknowledgments

We acknowledge Vincent Chagnaud (A7 Conseil), Francis Papon (IFSTTAR; AME/DEST Laboratory) and the anonymous referees for their help and accurate proofreading.

REFERENCES

Aron, M., Morin, J.M., Seidowsky, R., et al., 2007. From traffic indicators to safety indicators. In: Application for the Safety

Assessment of an ITS Activothere Traffic Management Experiment, 14th ITS World Congress, Beijing, 2007.
Bhouri, N., Aron, M., 2013. Reliability benefits of active traffic management: a managed lanes case in a French urban motorway. In: TRB 92nd Annual Meeting, Washington DC, 2013.
Bhouri, N., Aron, M., 2014. Isolating different factors affecting travel time reliability in an observational before/after study. In: EWGT-Euro Working Group on Transportation, Sevilla, 2014.
Bhouri, N., Haj-Salem, H., Kauppila, J., 2013. Isolated versus coordinated ramp metering: field evaluation results of travel time reliability and traffic impact. Transportation Research Part C: Emerging Technologies 28 (3), 155–167.
Bhouri, N., Kauppila, J., 2011. Managing highways for better reliability-assessing, reliability benefits of ramp metering. Transportation Research Record 2229, 1–7.
BTCE, 1996. Quality of Rail Freight Service: The Customer Perspective. Working Paper 96. Australian Government Publishing Service, Canberra.
Cassidy, M.J., Coifman, B., 1997. Relation among average speed flow and density and analogous relation between density and occupancy. Transportation Research Record 1591, 1–6.
Cohen, S., Princeton, J., Hounsell, N., et al., 2009. Case Studies Identification and Assessment, Task 2.4: Local Main Road Networks. Available at: http://www.nearctis.org/home/resources-desk/deliverables/ (Accessed 2 February 2016).
De Jong, G., Kouwenhove, M., Kroes, E., et al., 2009. Preliminary monetary values for the reliability of travel times in freight transport. European Journal of Transport and Infrastructure Research 9 (2), 83–99.
DFT, 2008. Advanced Motorway Signalling and Traffic Management Feasibility Study: A Report to the Secretary of State for Transport. Department for Transportation, Washington DC.
FHWA, 2010. Travel Time Reliability: Making it there on Time, all the Time. Available at: http://www.ops.fhwa.dot.gov/publications/tt_reliability/TTR_Report.htm (Accessed 2 February 2016).
Fosgerau, M., Hjorth, K., Brems, C., et al., 2008. Travel Time Variability–Definition and Valuation. Danish Department of Transport, Copenhagen.
Goodin, G., Burris, M., Lomax, T., et al., 2011. Operational Performance Management of Priced Facilities. Texas Transportation Istitute, College Station.
HEATCO, 2006. Developing Harmonised European Approaches for Transport Costing and Project Assessment, Deliverable 5, Proposal for Harmonized Guidelines. European Commission, Sixth Framework Programme 2002-2006. Available at: http://heatco.ier.uni-stuttgart.de/ (Accessed 2 February 2016).
Hombourger, E., 2011. Guide Méthodologique sur l'observatoire des Vitesses en lle-de-France MEDDTL. Available at: http://www.driea.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/Methodologieobservatoire_de_vitesse_Vfinale_cle51b387.pdf (Accessed 2 February 2016).
Lomax, T., Schrank, D., Turner, S., et al., 2003. Selecting Travel Reliability Measures. Texas Transportation Institute, Arligton.
Mehran, B., Nakamura, H., 2009. Implementing travel time reliability for evaluation of congestion relief schemes on expressways. Transportation Research Record 2124, 137–149.
New Zealand Transport Agency, 2008. Amendment No 2. Economic Evaluation Manual, vol. 1. ARRB Group Limited, Vermont South.
Nouvier, J., Lhuillier, J.P., 2007. La gestion dynamique des voies. Historique et perspectives. Revue Generale des Routes et des Aerodromes 861, 39–43.
OECD/ITF, 2010. Improving Reliability on Surface Transport Networks. OECD, Paris.
Ogawa, M.J., Arlow, A.J., Meekums, R.J., et al., 2010. M42 active traffic management monitoring and evaluation: results from hard shoulder running up T60 Mph Mott Mac Donald. In: International Conference on Road Transport Information and Control (RTIC), London, 2010.
Rakha, H., Zhang, W., 2005. Estimating traffic stream space-mean speed and reliability from dual and single loops detectors. Transportation Research Record 1925, 38–47.
Van Lint, J.W.C., Van Zuylen, H.J., Tu, H., 2008. Travel time unreliability on freeways: why measures based on variance tell only half the story. Transportation Research Part A: Policy and Practice 42, 258–277.

Neila Bhouri, PhD in transport and automatic control, is a researcher at IFSTTAR (The French Institute of Transport, Planning and Networks). Her research fields are related to multimodal urban and freeway traffic control strategies and transport network analysis, mainly reliability analysis of road traffic flow and public transport systems. She has worked as an associate professor of automatic control and given lectures on transport control and plan in various engineering schools (EIVP and ENPC (France), Naval academy, ENIT, ISTLS (Tunisia) …). She also acts as an expert in national and international committees (OECD/ITF, …).

Maurice Aron, graduated in Statistics, was, before retiring in 2016, with Université Paris-Est, IFSTTAR/COSYS/GRETTIA, the French Institute for Transportation. He developed traffic models (simulation, forecasts, road safety).

Gerard Scemama is a senior researcher at GRETTIA. He developed the ClaireSITI multimodal supervisory system which is currently implemented in operational context in Toulouse and Brussels near the STIB multimodal public transport operator (bus, metro and tram) and also in a laboratory environment at IFSTTAR in Paris, dealing with both real and simulated data. The ClaireSITI multimodal platform gathers real-time and multi-sources. A number of national research projects have used this equipment.