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FIELD TEST FROM A FRENCH MOTORWAY

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ABSTRACT

Traffic management aims to ensure a high quality of service for most users, by decreasing congestion and increasing safety. However, uncertainty regarding travel times decreases the quality of service and leads end-users to modify their plans whatever the average travel time. e. Indicators describing travel time reliability are being developed and should be used in the future both for the optimization and for 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 at rush hours. The paper focuses on travel time reliability indicators and on their use for reliability assessment. It provides some discussions on the advantages and drawbacks of reliability indicators under different traffic conditions. It particularly shows the difference between using whether buffer times whether buffer indexes. The paper also discusses the difficulty of interpreting the skew of travel time distribution for travel reliability.

Keywords: Reliability; *T*ravel time; Managed lanes; Hard shoulder; Recurrent congestion; Assesment

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1. INTRODUCTION

Managed lanes (e.g., dynamic peak hour lanes, additional lanes, HOV lanes, bus lanes) play an increasing role in traffic operations. This topic is becoming more and more important to tackle recurring congestion. Various practices are already initiated 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 is 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.

In France, dynamic reversible lanes (according to the commuter traffic direction) have been introduced from the 1960s (Quai de Seine in Paris, the Olympic Games in Grenoble, the Saint-Cloud Tunnel in Paris) (Nouvier and Lhuillier, 2007). A static High 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, and second, thanks to the discussion on the use of the indicators, to clarify the use cases of the indicators according to the traffic conditions and to their evolution from the period "before" to the period "after" the installation of the management operation This paper is organized as follows; 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 (in vehicle/km)
- Total time spent in traffic (in vehicle*hour)
- Volume of congestion (in 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 & 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, Hard Shoulder Running 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 on network quality (what is provided and planned) while for the user, the focus is on how the variability of travel time is experienced (Bhouri & al. , 2011).
Several definitions for travel time reliability exist and many different relevant indicators have been proposed. Here we use the same breakdown as presented in previous studies and divide these measures into four categories as in (Lomax *et al*., 2003) and (Van Lint *et al*., 2008):

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

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 (2). Standard deviation is defined as:

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

while coefficient of variation is written as

$$COV = \frac{STD}{M} \tag{2}$$

where M denotes the mean travel time, TT_i the i^{th} travel time observation and N the number of travel time observations.

A further consideration to use the standard deviation as a reliability indicator derives from recent studies that recommend defining travel time reliability as the standard deviation of travel time when incorporating reliability into 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 but must be taken with caution because the travel times distributions are often (due to congestion) asymmetric and thus far from the Gaussian distribution. Then the coefficients linking the width of the confidence intervals to the standard deviation (as the value "1.96 x standard deviations" for the 95% confidence interval) are no more valid. Therefore, studies have proposed metrics for *skew* λ^{skew} and *width* λ^{var} of the travel time distribution (Van Lint *et al*., 2008).
The wider or more skewed the travel time distribution the less reliable travel times are. In general, the larger λ^{skew} indicates higher probability of extreme travel times (in relation to the median). The large values of λ^{var} in turn indicate that the width of the travel time distribution is large 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) that combines these two and removes the location specificity of the measure (Van Lint *et al*., 2008). Skewness and width indicators are defined as**:**

$$\lambda^{skew} = \frac{TT_{90} - TT_{50}}{TT_{50} - TT_{10}} \tag{3}$$

$$\lambda^{var} = \frac{TT_{90} - TT_{10}}{TT_{50}} \tag{4}$$

$$Ul_r = \begin{cases} \dfrac{\lambda^{\text{var}}.\ln(\lambda^{skew})}{Lr}; & \lambda^{skew} \succ 1 \\ \dfrac{\lambda^{\text{var}}}{Lr}; & otherwise \end{cases} \tag{5}$$

Where L_r denotes the route length and TT_X is the X^{th} percentile travel time.
Other indicators, especially the *Buffer Index (BI)* appears to relate particularly well to the way in which travellers make their decisions (18). 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 95% of the time. It is computed as the difference between the 95th percentile travel time (TT_{95}) and the mean travel time (M). The Buffer Index is then defined as the ratio between the buffer time and the average travel time

$$BI = \frac{TT_{95} - M}{M} \tag{6}$$

The Buffer Time is useful in users' assessments of how much extra time has to be allowed for uncertainty in travel conditions. It hence answers simple questions such as "How much time do I need to allow?" or "When should I leave?". The Buffer Index gives the percentage of time wasted for counterbalancing uncertainty, independently of the duration of the trip. For example, if the average travel time equals 20 minutes and the Buffer Index is 40%, the buffer time equals 20 × 0.40 = 8 minutes. Therefore, to ensure on-time arrival with 95% certainty, the traveler should allow 28 minutes for the normal trip of 20 minutes.
Planning Time (PT) is another concept used often. It gives the total time needed to plan for an on-time arrival 95% of the time 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 ($TT_{\text{free-flow}}$)

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

3- 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 to half their destinations and early to 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

$$MI = \frac{M_{|TT_i > TT_{80}} - M}{M} \tag{7}$$

Where TT_{80} is the 80^{th} percentile travel time.

4 - 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 minutes from the median travel time" (Van Lint *et al.*, 2004). This can be presented by the following equation

$$Pr\left(TT_i \geq \beta + TT_{50}\right) \tag{8}$$

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

Buffer Times are useful for users as they indicate a time they have to add to their average travel time (Buffer Time) or to their free-flow (Planning Time) in order to not being late to their destinations. Probabilistic indicators 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 such that only x% of people can have unreliable travel time. Also indexes, such as BTI, 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.

4. DYNAMIC USE OF HARD SHOULDER ON THE FRENCH A4-A86 MOTORWAYY

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 at some hours on the weaving section, 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 hours' congestion a 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 hard shoulder running (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 3.2 m.

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

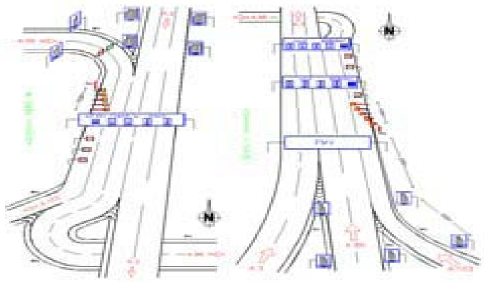

Fig. 1 The weaving section A4- A86 (additional lanes in dotted red)

Daily statistics on the duration of hard-shoulder running on working days in 2006 show an average of 5 hours' use inward Paris and 4 hours' use eastward out of the city. On Saturdays, the hard shoulder is open for an average of 4 hours into Paris and 3 hours 45 minutes in the opposite direction. On Sundays it is open in both directions for 3 hours 20 minutes.

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 on the section so that drivers can see them whatever their position and are thus dissuaded from using the lane (Figure 2). The width of the hard-shoulder has been increased (to 3m) and the width of the other lanes reduced from the standard 3.5m to 3.2m.

Fig. 2. The weaving A4-A86 section, eastbound with the 5th lane, open and closed

Automatic incident detection cameras have been installed for monitoring overall safety All safety has been improved by the installation of. In the event of an incident or 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 8km-long stretch (in each direction) we analyse here only a three-km long stretch in the Eastbound direction (2.3 on the weaving section, 0.7 km downstream). Inductive loops provide traffic flow, occupancy and average speed for each lane every six minutes.
Data has been analysed for three years (2000, 2001 and 2002) before theexperiment and one year (2006) after. Four inductive loops in the eastbound direction (three on the weaving section , respectively 200 meters, 800 meters and 1,500 meters after the beginning of the 2.3 km weaving section; and one inductive loop 200 meters downstream) were used for computing the travel times presented here.

4.3 Traffic trend between 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.
The following table gives the vehicles- kilometres by year for the 2.3 km weaving section (both ways).

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

	Day	Night	Total
2000-2002 average annual	168 168,200	31 961,163	200 129,363
2006	161 438,429	34 374,817	195 813,246
Trend 2006/{2000—2002}	96%	1 07%	98%

For tables concerning the vehicles-kilometres, missing data are reconstituted and day is defined from 5 h AM to 9 PM
Note that we are using a different period here for the day than later for the reliability assessment. This difference doesn't affect our analysis as we are comparing the same periods for the before and after years.

The total traffic decreased by 2% between 2000-2002 and 2006; traffic increased during night by 7%, this corresponding to a change in drivers' behavior. These traffic variations are not very high, their impact on travel time, although difficult to estimate without using a simulation model, 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 are sensitive to traffic conditions – 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 happened (in terms of traffic volume or of its distribution during the day).The following table provides (for daylight only) the breakdown of vehicles-kilometres in "opened" and "closed" HSR.

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

	Daylight vehicles-kilometres			
Years	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 -	$20{,}1\% = \frac{32{,}473{,}118}{161{,}438{,}429}$

Note that in 2000, 2001 and 2002, HSR was not installed; the "open" periods are the periods corresponding to the 2006 periods where HSR was effectively opened. The correspondence between the 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 of 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 – such a model being required for pre-evaluations..

5. TRAVEL TIME COMPUTATION AND QUALITY

5.1 Travel Time Computation

Although data seem generally 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, as an occupancy greater than 100%, a 6 minute mean speed greater than 200 km/h, a 6 minute flow (by lane) greater than 400 vehicles. In these cases data for the corresponding period and lane are cancelled then considered as missing.
When this occurs, for a given period and lane in 2000, data are 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 and 2002 data), and 2002 missing data (from 2000 and 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 6 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 (53,574 periods) out of the 87,600 periods of the year, even if missing or irrelevant data are not rare: 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

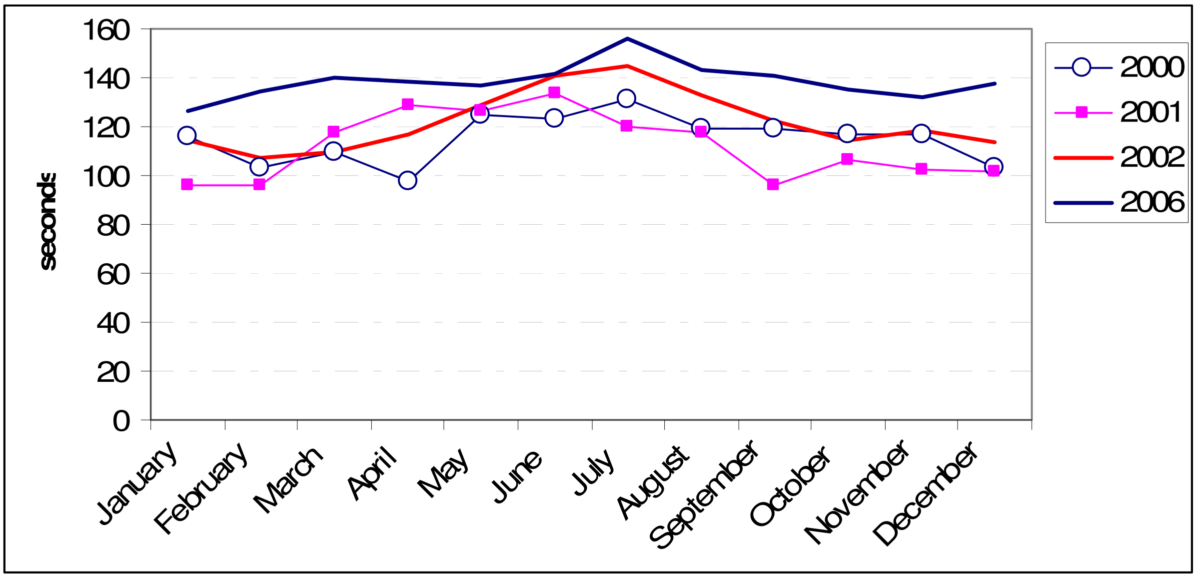

Figure 3. Average travel time for the 3km route according to the month and the year

The previous paragraph indicates that missing data are 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 for the four traffic sensors equipping the 2.3 km eastbound weaving section, there was no major breakdown. Indeed, a breakdown in months of high traffic for instance should bias the travel time distribution, because the traffic flow and the travel time vary according to the month of the year –see figure 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 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 & Coifman, 1997) examined the relationship between occupancy and speed and set a few equations.An analogous work is presented here for deciding if an oulier speed must or not be rejected.

Let us name L_i the length in meters of vehicle "i" (enlarged by the length of the magnetic loop constituting the sensor), V_i its speed (in m/s), and "o^p" the occupancy for the 6 minute (360 seconds) period "p". o^p s given by:

$$o^p = \frac{\sum_{i=1}^{q^p} L_i/V_i}{360} = \frac{1}{100}\sum_{i=1}^{q^p} L_i/V'_i \tag{9}$$

Where q^p is the 6 minute flow, V'_i is the speed in km/h of vehicle i, thus $V'_i = 3.6 \times V_i$

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

$$o^p = \frac{1}{100}\sum_{i=1}^{q^p} L/V'_i = \frac{L \times q^p}{100 \times V'^p} \tag{10}$$

Where V'^p is the harmonic mean of the speed for period p for the given lane: $\frac{1}{V'^p} = \frac{1}{q^p}\sum_{i=1}^{q^p} 1/V'_i$

This allows computing $L = \frac{100 \times o^p \times V'^p}{q^p}$ (11)

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

$$L = \frac{100 \times \sum_{p=1}^{P} o^p \times V'^p}{\sum_{p=1}^{P} q^p} \tag{12}$$

This gives an (enlarged) length L of 6 m on the slow lane and of 5.0 m on other lanes.

When there is no access or exit ramp on the motorway stretch, the vehicles' length average (over the lanes) does not change from one position on the motorway to another. Thus the consistency of the information given by two successive traffic stations can be checked by matching the average lengths derived from equation (12).
Reversing equation (12), a recorded speed for period p suspected to be an outlier can be replaced by

$$V''^p = \frac{L \times q^p}{100 \times o^p} \tag{13}$$

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 times (which deal with the inverse of the speeds).

In France, traffic detectors, in general, provide the harmonic speeds average, which is suitable for identifying L from formula (11) (E; Hombourger, 2011), In places where traffic detectors provide arithmetic speed average , L would be over-estimated, because the arithmetic mean is always greater then 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 $1.17\,\overline{V}^P$ ($\overline{V}^P$ being 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 (by formula 13) will also be over-estimated by 1%.

The accuracy of relations (11) to (13) is based:

- 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 format of the record.

The available occupancy is a percentage (up to two decimal points). If, during period p, there is a 5-meter long vehicle at the speed on 25m/s (90 km/h), it occupies the sensor during 0.2 seconds; the 6 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, using formula (13) to a speed of 100 km/h. If there are N vehicles circulating during the period, the same error (0.01%) for all vehicles implies an average speed (given by formula 13) of 100km/h. 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 changes. 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 (equal to the traffic flow during the six minutes).The individual travel times are not measured, only the mean travel times by period are estimated. The question here is what statistical unit should we consider, the vehicle or the period of time?

1) If the statistical unit is the time period, the distributions related to the “offer” that traffic operators have to guarantee – 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 where traffic conditions are the worst
2) When 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 4 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; a high travel time might correspond to a high percentage of trucks in the traffic.

Table 4. Non weighted and weighted average travel times according to the year and the period in the day

	Weighted distribution	distribution of average travel times by 6-minute periods	Difference
2001, night	95,7	101,1	-4,4
2001, day	121,1	120,1	1
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	7,1

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 in 2003 an important campaign for road safety and against speeding. 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. Happily, 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:

- A direct effect on travel time reduction and on travel time variance reduction,
- 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 (se Table 2); daylight traffic increased by 2% at peak hours, and decreased by 5% at off-peak. This shift might be due to the better traffic conditions when HSR is opened. We assume that some vehicles willing to drive during peak hours, were, during the period "before", constrained to drive during off-peak, in order to avoid very bad peak-hour traffic conditions. Thanks to HSR and to 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 result 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, thus to a smaller increase in travel time reliability. If that assumption were false, increase in reliability would be even better

Without the "indirect" effect, the travel time reduction during peak hours as well as the travel time increase during off-peak, would have been larger. 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 result of these two components.

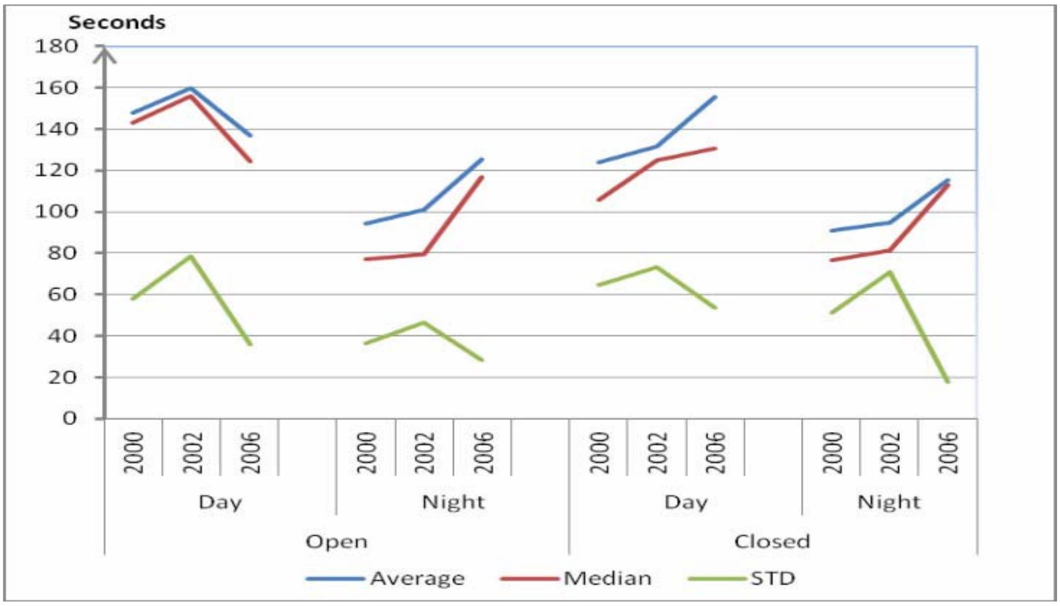

Figure 4. Impacts of HSR and of the speed reduction campaign on travel time

Figure 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 on days or nights. We can notice that travel time increases on 2002 as compared with the year 2000 for all the situations (night, day). For the day period, we can easily see the positive impact of the HSR, as the average TT is reduced when the HSR is open, which means that the HSR reduced the congestion as there is one more lane for the circulation.

For day periods where HSR is closed, we notice an increase of travel time:

- Generally these periods were off-peak; then the better speed enforcement led to increase travel times,
- 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 increase the travel times.

We notice that for the night period, the average TT (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 TT increase when traffic condition is fluid (closed by night) is due to the speed limit campaign. This campaign induced also more homogeneous speeds in 2006 (nights) – the standard deviation is lower in 2006. We notice also an increase of TT for the opened HSR during the limited nightly periods. HSR was sometimes opened on 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 figure 5. We can see that the buffer time and the planning time are reduced: this means that it is not the extreme value of travel time which increases but the average, which means that travellers respect more the speed limit.
We can notice for all situations a decrease of the standard deviation (STD) which means less dispersion and more reliable travel time of traffic in 2006 compared with 2000 and 2002.

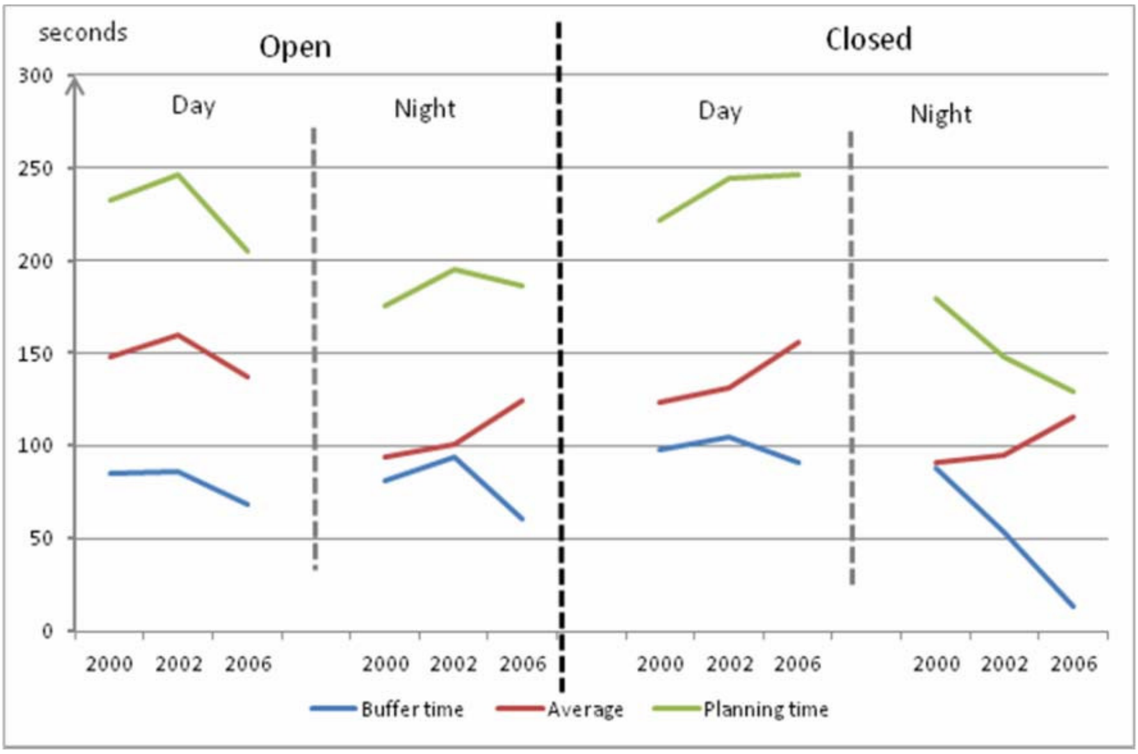

Figure 5. Impacts of HSR and of the speed reduction campaign on travel time and buffer times

One can see on figure 5, that all TT indicators increase in 2002 as compared with 2000. Unreliability, , decreases 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 (daylight).

BT (the difference between the 95th TT percentile and the average TT) decreases when HSR is open, due to the decrease of the 95th TT percentile, although the average TT also decreases. Note that BT also decreases when HSR is closed (daylight)- this is then due to the increase in TT average and not in any decrease in TT_{95}.; this is less favourable for drivers, but still remains an increase in reliability:

Remark. 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, 2002), thus an improve in TT reliability. .

6.2 Buffer times and buffer indexes

In the following we use only data from 2002 for the before period.

Figure 6 gives the planning time (PT), the free flow and the planning time index (PTI). Note that the PTI is a percentage and therefore not in the same scale as PT and Free-flow, it is drawn here just to show the difference in changes between it and the PT. As one can see on figure 6, PTI decreases outstandingly in 2006 for the four situations (Day, Night, Open, Close). However PT remains stable for the "Day-closed" situation, it decreases slightly for the (Night-open situation) and decreases more notably for the two other situations. We can notice easily 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

- When comparing the situation in 2002 and 2006, the evolution of PTI (which decreased) is misleading for users because the PT did not always decrease

-PTI remains 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.

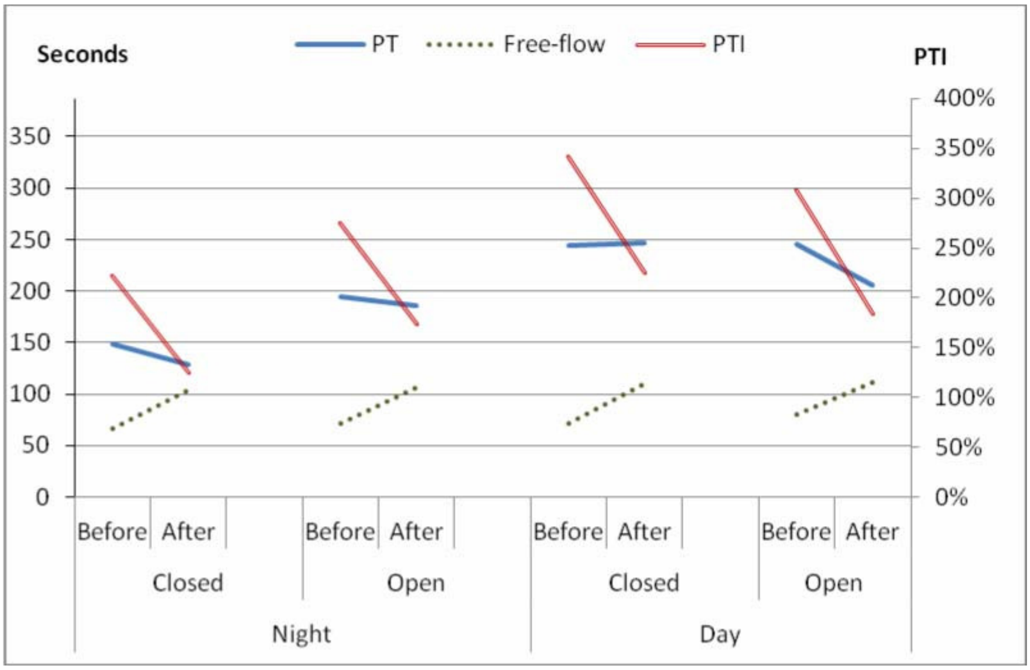

Figure 6. Evolution of the PT and PTI

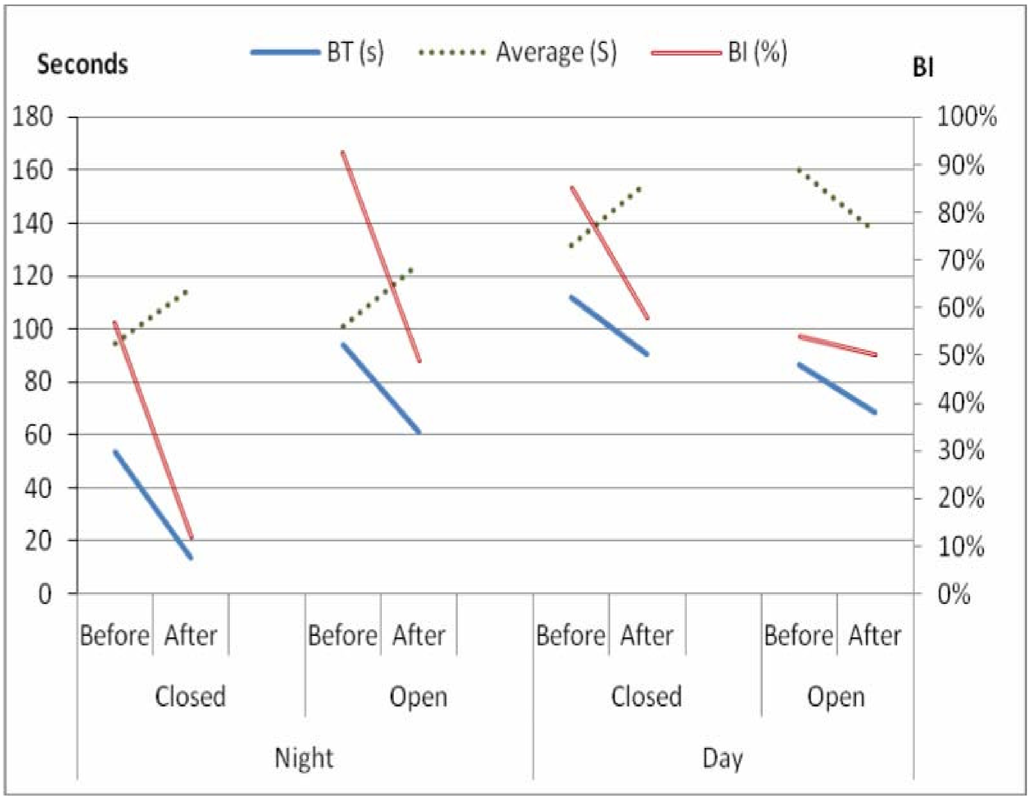

Figure 7. Evolution of the BT and BI

Comparing the evolution of buffer time (BT) and buffer time index (BI) which is equal to the BI divided by the average travel time, 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 the Free-flow).

In 2002, the average speed corresponds to a congested traffic conditions only for the day_open period where average TT is equal to 160 seconds, meaning a speed of 67.5 km/h

In 2006; during night and during day, closed periods, the decrease of BI is more important than the decrease of BT. This difference is due to the increase of average TT 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 TT decrease at these periods.

If we define "reliability" in time by the buffer time (the extra time which must be added to the average) the buffer index still remains in this example a good reliability indicator. If we prefer defining "reliability" in percentage of time by the buffer index; buffer time still remains in this example a good reliability indicator.

6.3 Tardy trip measures and probabilistic indicator

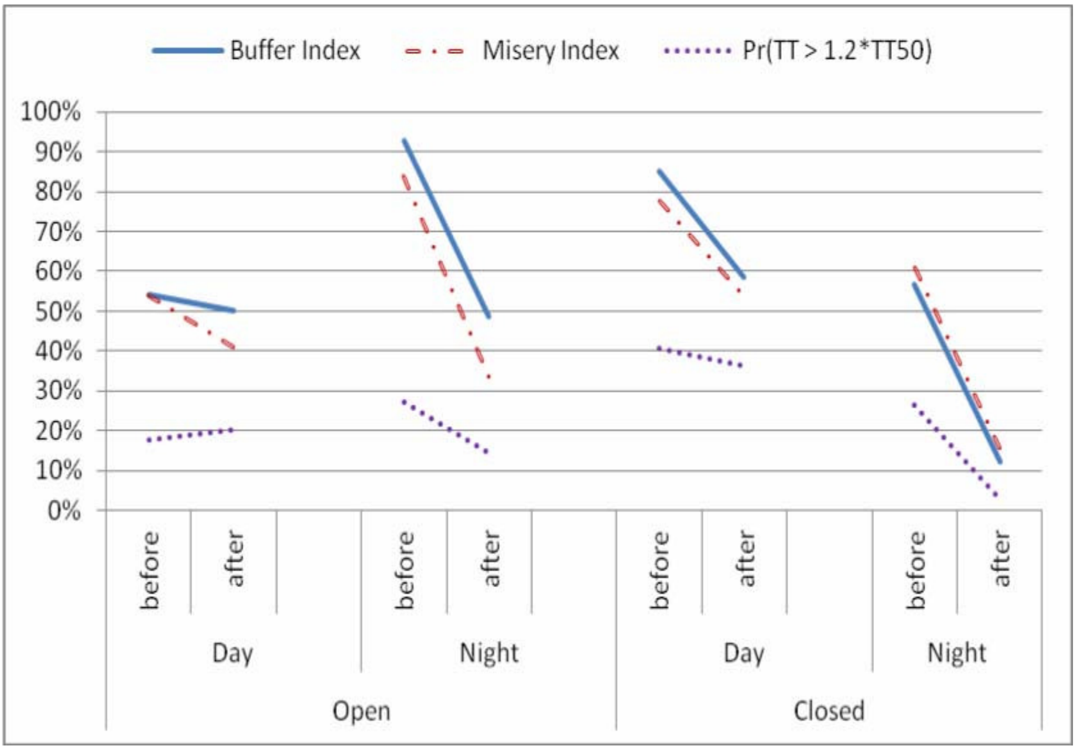

Figure 8. Misery index and probabilistic indicator

Tardy trip measures indicate unreliability impacts using the amount of trips late. 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. Figure 8 shows that the evolution of the Misery index is very close to that of the buffer index when HSR is closed. The Misery index is more improved than the buffer when the HSR is open, especially for the day period (the more important one). That 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 on figure 8 that the probability that experienced TT do not deviate by more than **20%** more than the median TT, 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 buffer and misery index evolution;. This slight rise comes from a decrease of the median, thus the value (1.2 x median) corresponds to a shorter travel time, more frequently exceeded. Unlucky drivers are not less many in 2006 than in 2002 (20%, as well in the Misery Index definition which is also in this case, the value of $Pr(TT>1.2*TT_{50})$, but these 20% unlucky drivers are less miserable in 2006. (MI passes 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 for width and skew of travel time. They argued that during congestion, unreliability of travel time is predominantly proportional to λ^{Var}. This is not refuted here: the value λ^{Var} =0.77 in 2002 can be considered as large, whereas the value λ^{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 seconds was in congestion (speed=69,3 km/h), whereas in 2006, TT_{50}=124,9 seconds (speed=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})= 67.7s, and a relatively low λ^{Skew} nominator (TT_{90}-TT_{50})= 52.4s, despite of congestion. Both reasons lead to a not so high λ^{Skew} value (0.77).

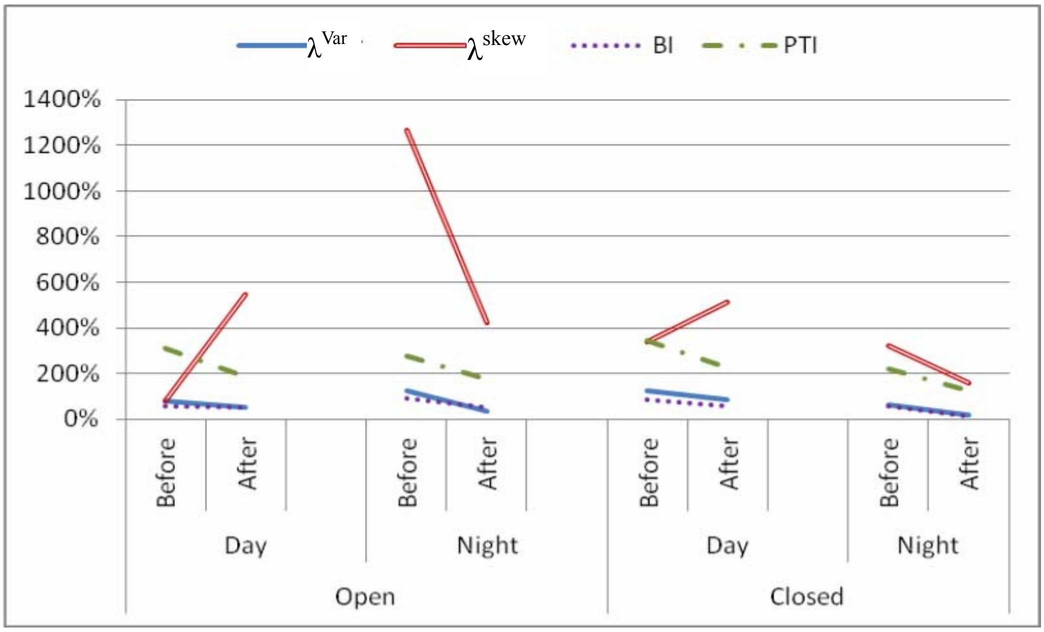

Figure 9. Evolution of the width and skewness indexes for the years 2002-2006 before and after the HSR opening.

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 Hard Shoulder Running field test from a French motorway.
Field tests provide large amounts of data which are 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 were 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, this leading, because weights are different, to two TT distribution. 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 TT reliability.
In addition to the reliability assessment of the HSR running, we discussed in this paper the ability of different indicators known to accurately reveal the travel time reliability improvement. Results show that lower Planning Time increases driver satisfaction. Perhaps easier to attain, a smaller Buffer Time implies a better reliability, even if the Planning Time does not decrease. Results show that the comparison between planning time index from different years may be misleading to travellers. In this field test example, reduction in PTIs was due to the increase in free-flow time and not to a decrease of the planning time. 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 TT 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 however that the λ^{Skew} indicator is not always suitable for the reliability assessment. Indeed, two factors impact traffic in this experiment: on one hand the HSR implementation and on the other hand 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. It affects however the denominator of the λ^{Skew} indicator which depends on this non-congested traffic. The use of this part of the TT distribution as a component of the λ^{Skew} definition affects the quality of this indicator: values of λ^{Skew} reveal more a lower TT median 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.

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