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# Relevance of travel time reliability indicators: a managed lanes case study

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## Abstract

Managed lanes operations refer to multiple strategies for recurring congestion control by increasing the road capacity or adapting its configuration to the demand level. As a result, the evaluation of their impacts usually focuses on congestion or safety-related indicators. However, with the growing prosperity, consumers demand higher quality transport services, for which reliable transport networks are central. This paper is focused on the travel time reliability assessment of a managed lane experience from a French motorway. The paper shows results from the field test experience of the hard shoulder dynamic use on the A4-A86 motorway in the east of Paris. Further to the reliability assessment, the paper focuses on the reliability indicators. It particularly shows the weakness of the skew of the distribution of travel time indicator.

*Keywords:* Reliability; Travel 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 for recurring congestion control by increasing the road capacity or adapting its configuration to the demand level. 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 lane width and the temporary or permanent use of the hard shoulder as a running lane.

In France, dynamic use of the hard shoulder dates back to the 1960s with the introduction of reversible lanes (Quai de Seine in Paris, the Olympic Games in Grenoble, the Saint-Cloud Tunnel in Paris) (Nouvier and Lhuillier, 2007). France has two examples of hard-shoulder running schemes. One is on a section of the motorway to the east of Paris, where the hard shoulder is open to cars when traffic becomes saturated. The other is on a section of the motorway leading into Grenoble, where a special lane is open to public transport only when the motorway becomes saturated.

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In this paper we apply a number of indicators for travel time reliability that have been advocated in a range of studies. The 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 descriptions of the French sites where the hard shoulder running (HSR) have been experimented as well as the assessment data. In section 5, travel time reliability results are provided. Based on these results, a discussion regarding the reliability indicators is conducted especially related to the width and skew of the distribution of travel times. Finally, Section 6 draws the main conclusions of this paper.

## 2. Managed lanes assessment

Several service quality indicators have been developed, with a direct impact on network reliability (Cohen et al., 2009). (Goodin et al., 2011) research team developed guiding principles for identification, selection, and communication of performance measures. 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/km)
  - 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
- 
- Until now, however, authors aren't aware of any assessment of the reliability of managed lanes based on the criteria set out in this report.

## 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 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

$$STD = \sqrt{\frac{1}{N-1} \sum_N (TT_i - M)^2} \quad (1)$$

while coefficient of variation is written as

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

where  $M$  denotes the mean travel time,  $TT_i$  the  $i^{\text{th}}$  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. Without any assumption on the travel time distribution shape, there isn't a close relationship between the standard deviation and percentiles. An indicator directly based on percentiles has not this drawback, and does not require making any assumption on the travel time distribution. Therefore, studies have proposed metrics for skew  $\lambda^{skew}$  and width  $\lambda^{var}$  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  $\lambda^{skew}$  indicates higher probability of extreme travel times (in relation to the median). The large values of  $\lambda^{var}$  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

$$\lambda^{skew} = \frac{TT_{90} - TT_{50}}{TT_{50} - TT_{10}} \quad (3)$$

$$\lambda^{var} = \frac{TT_{90} - TT_{10}}{TT_{50}} \quad (4)$$

$$UL_r = \begin{cases} \frac{\lambda^{\text{var}} \cdot \ln(\lambda^{\text{skew}})}{L_r}; & \lambda^{\text{skew}} > 1 \\ \frac{\lambda^{\text{var}}}{L_r}; & \text{otherwise} \end{cases} \quad (5)$$

where  $L_r$  denotes the route length and  $TT_X$  is the  $X^{\text{th}}$  percentile travel time.

Other indicators, especially the *Buffer Index (BI)* appears to relate particularly well to the way in which travelers make their decisions. 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

$$BI = \frac{TT_{95} - M}{M} \quad (6)$$

The Buffer Index 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?". For example, if the average travel time equals 20 minutes and the Buffer Index is 40%, the buffer time equals  $20 \times 0.40 = 8$  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.

A number of other indicators have been proposed in literature. These include:

- *Misery Index*, linked to the relative distance between mean travel time of the 20% most unlucky travelers and the mean travel time of all travelers.
- *Probabilistic indicator*, which is the probability that travel times occur within a specified interval of time related to the median travel time.
- However, we will not consider these in the current paper.

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

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

In the east of Paris, a three-lane urban motorway (A4) and a two-lane urban motorway (A86) share a four-lane 2.3 km long weaving section. 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 was 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 according to the value of the occupancy measured upstream of the common trunk section (hard shoulder opened if occupancy is greater than 20% and closed if less than 15%).

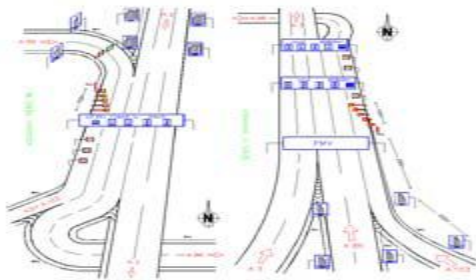


Fig. 1 The weaving section A4-A86 in both senses (additional lanes in red)

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. When this lane is closed, devices pivot leading to the blocking of the hard shoulder. These closure devices 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 barriers were tested between June and October 2004 on a non-traffic experimental site.

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.

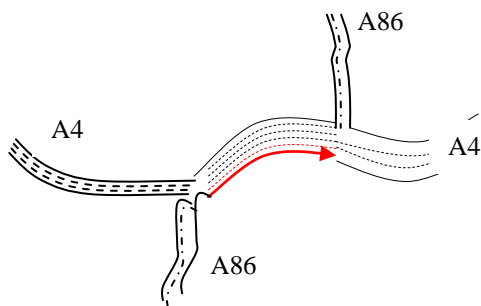


Fig. 2. The weaving A4-A86 section, with the 5<sup>th</sup> lane, upstream and downstream sections, eastbound

Safety has been improved by the installation of automatic incident detection cameras. 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 description

Inductive loops provide traffic flow, occupancy and average speed for each lane. Assessing this road operation requires to consider not only the traffic on the 2.3 km weaving section but also the traffic downstream. 0.7 km downstream stretch has been included in each direction. Data has been analysed for three years (2000-2002) before the implementation of the device and one year (2006) after. Three inductive loops in the eastbound direction (two on the weaving section and one downstream) and four inductive loops in the westbound direction were used for computing the travel times. At each six-minute period of the year 2006 where traffic data were available we associated one period in 2000, 2001, or 2000 with corresponding available traffic data (same month, same day in the week, same hour in the day and six-minute period in an hour). A few traffic data were missing, some others have been disregarded when the recorded average speed appears extreme (higher than 150km/h or lower than 5 km/h).

We will focus on this paper only on 2002 and 2006 data and only to the eastbound part of the motorway. Cleaning the 87600 six-minutes periods data by year (2006 and 2002) we kept 53574 pairs of data.

		Number of pairs of data
“open”	Daylight (*)	7377
	Night	868
Close	Daylight	24864
	Night	20465
Total		53574

(\*) from 7 AM to 8 PM

Table 1 Breakdown of matched periods in {2002, 2006} where correct data were available for the Eastbound direction

The great number of six-minute periods available allows for some confidence in the following analysis.

Note that in 2002, as HSR was not installed, the “open” periods are the periods corresponding to the 2006 periods where HSR was effectively opened. This matching prevents to potential bias if unavailable data in 2006 were not distributed as unavailable data in 2002.

## 5. Findings

The impacts of HSR on the travel time and on travel time reliability are identified with an observational before/after study on the weaving section completed by downstream sections. As Jacques

Chirac, former president of France, launched in 2003 an important campaign for road safety and against speeding, 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. Fortunately, 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. Table 2 shows this increase in travel time between 2002 and 2006 when HSR was closed, and a decrease of travel time (due to the decrease of congestion) when HSR was opened during daylight. Note that HSR was also opened during (limited) nightly periods which were partly congested (HSR leads then to decrease TT) and partly non congested (the speeding campaign leads then to increase TT) – the final result being an increase of average TT.

“Before” means 2002, and “open” means that we simulate the time when it would be opened in 2002 but of course the HSR didn’t exist.

		Travel time			Buffer time			Planning time		
		before	After	<i>Gain</i>	Before	after	<i>Gain</i>	before	After	gain
Open	Daylight	160	137	<b>-14%</b>	86	68	<b>-21%</b>	246	205	<b>-17%</b>
	Night	101	125	<b>24%</b>	94	61	<b>-35%</b>	195	186	<b>-5%</b>

		Travel time			Buffer time			Planning time		
		before	After	<i>Gain</i>	Before	after	<i>Gain</i>	before	after	gain
Closed	Daylight	132	156	<b>18%</b>	112	91	<b>-19%</b>	244	246	<b>1%</b>
	Night	95	115	<b>21%</b>	54	14	<b>-74%</b>	148	129	<b>-13%</b>

*Times are in seconds and correspond to the 3km Eastbound stretch*

Table 2. Impacts of HSR and of the speed reduction campaign on travel time and buffer times

Unreliability decreases between 2002 and 2006 when HSR is open, as shown by the indicators:

- PT (the 95<sup>th</sup> TT percentile) decreases when HSR is open, due to the reduction of congestion. On the contrary PT is stationary when HSR is closed (daylight).
- BT (the difference between the 95<sup>th</sup> TT percentile and the average TT) decreases when HSR is open, due to the decrease of the 95<sup>th</sup> 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<sub>95</sub>; this is less favourable for drivers, but still remains an increase in reliability:

Remark. Due to a decrease of night traffic (not presented in Table 2.), TT reliability is also improved during night, when HSR is closed.

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; indeed when comparing the daily distribution of traffic between off-peak and peak hours (before HSR implementation) to the distribution after, a shift of some traffic from daylight off-peak hours (HSR closed) to peak hours (HSR open) has been observed; 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.

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.

### 5.1. Are skewness and width metrics good indicators for the reliability assessment ?

(Van Lint et al., 2008) present  $\lambda^{\text{Var}}$ , a robust measure for width of travel time. Indeed it is the width of the interval  $[TT_{90}; TT_{10}]$ , where lie travel times of 80% of drivers, divided (for standardisation) by the percentile  $TT_{50}$ . A large width leads to unreliability, forbidding drivers to predict accurately their travel time.

Year	Travel Time (in seconds)		Corresponding speed (km/h)	
	2002	2006	2002	2006
$TT_{90}$	208.3	180.6	51,8	59,8
$TT_{50}$	155.9	124.9	69,3	86,5
$TT_{10}$	88.2	113.8	122,4	94,9
$\lambda^{\text{Var}}$	0.77	0.54		

*This table corresponds to daylight periods when HSR is open*

Table 3. Percentiles of the travel time distribution and  $\lambda^{\text{Var}}$  in 2002 and 2006

Indicator	Open						Closed					
	Daylight			night			daylight			night		
	Before	After	trend	before	after	trend	before	after	trend	before	after	trend
$\lambda^{\text{Var}}$	77%	54%	-	127%	36%	-	127%	83%	-	65%	17%	-
$\lambda^{\text{Skew}}$	77%	549%	+	1267%	421%	-	341%	515%	+	321%	159%	-
$UL_r(1/\text{km})$	26%	31%	+	107%	17%	-	52%	46%	-	25%	3%	-
	Hard shoulder Running effect						Speed limit campaign effect					

Table 4. Effects of HSR and speed limits campaign on skew and width indicators

(Van Lint et al., 2008) argue that during congestion, unreliability of travel time is predominantly proportional to  $\lambda^{\text{Var}}$ . This is not refuted here: the value  $\lambda^{\text{Var}}=0.77$  in 2002 can be considered as large, whereas the value  $\lambda^{\text{Var}}=0.54$  in 2006 is much less, while congestion decreased from 2002 to 2006.

(Van Lint et al., 2008) present also  $\lambda^{\text{Skew}}=(\text{TT}_{90}-\text{TT}_{50})/(\text{TT}_{50}-\text{TT}_{10})$ , a robust measure for the skew of the travel time distribution. They argue that, in transient periods (congestion and dissolve), unreliability is predominantly proportional to  $\lambda^{\text{Skew}}$ . However we cannot have this interpretation of  $\lambda^{\text{Skew}}$  here, since we have computed  $\lambda^{\text{Skew}}$  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  $\lambda^{\text{Skew}}$  is miscellaneous, since the  $\lambda^{\text{Skew}}$  numerator and denominator depend on the location of  $\text{TT}_{50}$  related to the congestion. Different cases may happen. Here, in daylight periods (HSR open) in 2002,  $\text{TT}_{50}=155,9$  seconds was in congestion (speed=69,3 km/h), whereas in 2006,  $\text{TT}_{50}=124,9$  seconds (speed=86,5 km/h) was no more in congestion.

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

In 2006, the not-large  $\text{TT}_{50}$  (congestion concerning less than 50% drivers) implies a small  $\lambda^{\text{Skew}}$  denominator ( $\text{TT}_{50}-\text{TT}_{10}=11.1\text{s}$ ), and implies a  $\lambda^{\text{Skew}}$  numerator ( $\text{TT}_{90}-\text{TT}_{50}=55.7\text{s}$ ) higher than in 2002. Both reasons lead to a very high  $\lambda^{\text{Skew}}$  value (greater than 500% in daylight periods of 2006).

Note that the high skew in 2006 is not mainly due to the right part of the distribution (high travel times) but to the left part (low travel times). The very low  $\lambda^{\text{Skew}}$  denominator ( $\text{TT}_{50}-\text{TT}_{10}=11.1\text{s}$ ) is mainly due to a great speed homogeneity for 40% of drivers who drive in 2006 round the speed limit of 90 km/h (86,5 km/h at  $\text{TT}_{50}$ , 94,9 km/h at  $\text{TT}_{10}$ ). This was not the case in 2002, where the speeds corresponding to  $\text{TT}_{50}$  and  $\text{TT}_{10}$  were respectively 69,3 km/h and 122,km/h;

In summary,  $\lambda^{\text{Skew}}$  seems to be a promising indicator, even computed on a set of inhomogeneous periods, but its evolution must be discussed according to the sense of variation of  $\text{TT}_{10}$ ,  $\text{TT}_{50}$ ,  $\text{TT}_{90}$  and according to the location of  $\text{TT}_{50}$ .

## 6. 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. This paper presents the travel time reliability assessment of a Hard Shoulder Running experiment from a French motorway. Results reveal a positive effect on travel time reliability.

In addition to the reliability assessment of the HSR running, we discuss the ability of five 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. Further to these classical indicators, the paper discusses the robustness of  $\lambda^{\text{Var}}$  and  $\lambda^{\text{Skew}}$  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  $\lambda^{\text{Var}}$  indicator and its robustness to indicate both reliability and congestion. Results from this HSR French experiment show however that the  $\lambda^{\text{Skew}}$  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  $\lambda^{\text{Skew}}$  indicator which depends on this non-congested traffic. The use of this part of the TT distribution as a

component of the  $\lambda^{\text{Skew}}$  definition affects the quality of this indicator: values of  $\lambda^{\text{Skew}}$  reveal more a less a lower TT median value rather than a more reliable traffic. As  $\lambda^{\text{Skew}}$  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.

In the future, the optimization of traffic operations should be developed with respect, among other criteria, to travel time reliability, in its various forms.

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