Analysing the Impact of Traffic Flow on Free Speed Distributions on Motorways

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Free speed (FS) is the speed that drivers would adopt if they were not influenced by the presence of other drivers. It is an important parameter in simulation analysis, and the difference between FS and actual speed driven (AS) could be useful as a performance measure for quality of service of traffic flow on motorways. This study's objective is to investigate if and how FS changes with traffic flow. We use raw pulse detector data and the Modified Kaplan-Meier estimation method to derive free speed distributions (FSD) at three motorway sections in Japan under various flow conditions. FS is also compared with AS, and with free-flowing vehicles' speed (FFS). Results showed that in most cases, an increase in flow rate only led to a slight decrease in FS. FS was also significantly different depending on the lane driven in, with the lane with more large vehicles in its traffic stream having lower FS by more than 15km/h.

Key Words : *free speed distribution, traffic flow rate, free flow speed, headway*

1. INTRODUCTION

Free speed (FS) can be defined as the speed that drivers would adopt if they were not influenced by the presence of other vehicles[1]. Because of its variability from driver to driver, in the analysis of a given roadway, it would be more realistic to consider the distribution of free speed, rather than individual free speeds. These free speed distributions (FSD) are important in the field of traffic engineering for the modelling of traffic flows, and as inputs for microsimulation analysis.

The importance of FSDs led to several research efforts being made in order to facilitate their estimation.

Botma[2] reviewed several methods of estimating the FSD such as estimating it from speeds at low flows, extrapolating towards low flows in case only high flows were observable, simulation based methods, and so on. Finding several limitations to these methodologies, Botma proposed the use of censored observations in which not only the "free vehicles" are used in the estimation of FSD, but the constrained vehicles whose speed would be known to be below their free speed, could also be used in FSD estimation by determining to which extent the vehicles were constrained.

The concept of censored observations was later used by Hoogendoorn[3] to modify the Kaplan-Meier[4] survival function estimate and provide a method of estimating FSD by simply using the observed speeds and headways of vehicles.

Given that each driver is assumed to have a unique free speed, and that their choice of free speed could be influenced by the prevailing roadway and traffic conditions, it stands to reason that a comparison between the FSD and the actual speed distribution (ASD) could provide insights on the perception of the quality of service (QOS) by the drivers.

Suzuki *et al.*[5] provided a detailed analysis of the factors that influence FSD. Their findings showed that free speed was dependent on the gradient, speed limit, time of day, weekday or holiday, vehicle type, and lane.

To investigate the possibility of using FSD in estimating the QOS on motorways, it is important to understand its response to traffic conditions.

In this study, we investigate the variation of FSD by flow rate. In addition, we compare FSD to ASD, and to the distribution of speeds of vehicles that are deemed to be free-flowing (FFS-D) by the definition of the "following condition" in the Highway Capacity Manual, HCM 6th Edition[6]. Furthermore, based on the observations of different driving conditions on motorways in Japan, we investigate the variation in FSD by lane.

2. METHODOLOGY

(1) Data collection methods

For the type of analysis conducted in this study, two types of data were necessary: the spot speed of vehicles, and their corresponding headways. Vehicle length was used to classify the vehicle as either a small vehicle (length <7m) or a large vehicle (length ≥7m) since the analysis was separated by vehicle type.

Raw pulse data collected by Central Nippon Expressway Company using double loop detectors was used in this study. Data at three cross-sections on three motorways in Japan collected over two-day, daytime periods on clear non-holiday weekdays was used. **Table 1** shows some basic geometric characteristics of the three sites.

Sites 1 and 2 were chosen for comparison because of the similar characteristics such as speed limit, gradient, and location relative to an interchange. The difference in curve radius at the sites was not considered because earlier work by Suzuki *et al*.[5] indicated that its impact on free speed was minimal compared to other variables.

(2) Analysis methods

a) Hourly flow rate

The flow conditions were computed every five minutes, and the equivalent hourly flow rate calculated. Based on these values, the flow rates were aggregated into groups with flow rate ranges of 200 veh/h starting from 0 – 199 to 1800 – 1999 veh/h. These aggregated data groups were then used in the rest of the analysis.

b) Free-flowing vehicle speed (FFS)

The HCM 6th Edition[6] defines the following state as "a condition in which a vehicle is following its leader by no more than three seconds". Using the same threshold, we define free-flowing vehicles as having a headway of more than 3 seconds, and their speeds are obtained as the "free-flow speed", and denoted by FFS. This is different from the HCM definition of free-flow speed – the speed measured at low volumes.

c) Free speed distribution (FSD)

The estimation of FSD is based on the work by Hoogendoorn[3], in which they modified the original Kaplan-Meier[4] survival analysis method in order to also make use of censored observations.

This method has the advantage of being able to include the free speeds of vehicles with shorter headways, which would be excluded from the computation of free speed if headway were the only criterion for the distinction between following and free-flowing vehicles. A brief description of the methodology follows.

First, the observed headways are used to develop a composite headway model that includes both the constrained and unconstrained components of the total headway distribution. Such a model was proposed by Buckley[7], and **Eq. 1** shows its probability density function *f(t)*:

$$f(t) = \phi g(t) + (1-\phi)h(t) \tag{1}$$

where *g(t)* and *h(t)* are the constrained and unconstrained components, respectively, and ϕ is the proportion of the constrained vehicles.

We can define $g_1(t) = \phi g(t)$ and $h_1(t) = (1-\phi)h(t)$, and re-write **Eq. 1** as $f(t) = g_1(t) + h_1(t)$

For sufficiently large headways beyond a given value, T, vehicles can be assumed to be free-flowing, with their headways taking an exponential form given by **Eq. 2**, and applicable for $t>T$.

$$f(t) = h_1(t) = A\lambda e^{-\lambda t} \tag{2}$$

The parameter A in **Eq. 2** is known as the normalisation constant, and is given by $A = (1-\phi)/B$ where

$$B = \int_0^\infty \lambda e^{-\lambda t} \int_0^t g(s)\,ds\,dt \tag{3}$$

Referring to the work by Wasielewski[8] and Hoogendoorn[3], the headway distribution of free-flowing vehicles can be estimated by **Eq. 4**.

$$h_1(t) = \frac{A\lambda e^{-\lambda t}}{\phi} \int_0^t \left[f(s) - h_1(s) \right] ds \tag{4}$$

Table 1 Geometric characteristics of the study locations.

Site	Expressway	Speed limit (km/h)	Location (KP)	Gradient (%)	Curve radius (m)
1	Higashi Meihan	80	EB 69.200 [0.90 km d/s of Suzuka IC]	0.60	R-2000
2	Chuo	80	EB 328.320 [0.67 km d/s of Tajimi IC]	0.70	L-1200
3	Shin Meishin	100	EB 35.500 [2.50 km d/s of Tsuchiyama SA]	2.00	R-14991

Note: EB = Eastbound, d/s = downstream, IC = interchange, SA = service area, L/R = Left/Right curve

Parameters A and λ can be estimated by **Eq. 5** and **Eq. 6**.

$$\hat{\lambda} = \left[\frac{1}{m} \sum_i (t_i - T) \right]^{-1} \quad (5)$$

$$\hat{A} = \frac{m}{n} e^{\hat{\lambda} T} \quad (6)$$

where m is the number of headway observations greater than T $(t_i > T)$ and n is the total number of observed headways.

Eq. 4 can now be transformed to the form

$$\hat{h}_1(t) = \hat{A}\hat{\lambda} e^{-\lambda t} \left\{ 1 - \frac{1}{\hat{\phi}} \int_t^\infty \left[\hat{f}(s) - \hat{h}_1(s) \right] ds \right\} \quad (7)$$

subject to the constraint

$$\hat{\phi} = \int_0^\infty \left[\hat{f}(s) - \hat{h}_1(s) \right] ds \quad (8)$$

and the free headway distribution integral can be solved iteratively for the i^th^ approximation from the (i – 1)^st^ approximation, as given by **Eq. 9**

$$\hat{h}_1^{(i)}(t) = \hat{A}\hat{\lambda} e^{-\lambda t} \left\{ 1 - \frac{1}{\hat{\phi}^{(i-1)}} \int_t^\infty \left[\hat{f}(s) - \hat{h}_1^{(i-1)}(s) \right] ds \right\} \quad (9)$$

Hoogendoorn[3)] introduced an approach for estimating free speeds by generalising the original distribution-free method of Kaplan and Meier[4)] to include partially censored observations (observations that are constrained with a certain probability).

The modification involves deriving a conditional following probability function $\theta(t)$, given by $\theta(t) = g_1(t)/f(t)$, where $g_1(t)$ is the constrained headway distribution and $f(t)$ is the distribution of observed headways.

The conditional probability function is then applied to the Kaplan-Meier method to obtain FSD, $\hat{F}_\infty(v^0)$ from the modified survival function

$$\hat{S}_\infty(v^0) = \prod_{j=1}^{n_{v^0}} \left(\frac{n - j - 1}{n - j - \theta_j} \right) = 1 - \hat{F}_\infty(v^0) \quad (10)$$

where n_{v^0} is the number of samples of v_i that are smaller than or equal to v^0, and n is the total number of headway observations.

3. RESULTS AND DISCUSSION

This section first discusses the results from site 1, after which results from sites 2 and 3 are discussed in order to offer an insight to the variability of the various speeds investigated across different motorway sections.

The analysis was separated by lane, and by vehicle type: small vehicles (SV) and large vehicles (LV).

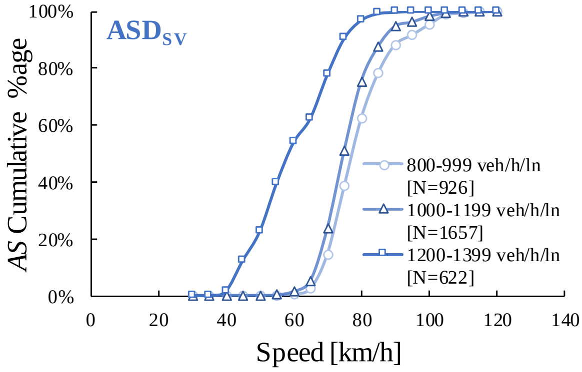

Fig.1 ASD of small vehicles on site 1, Lane 1 at various flow levels.

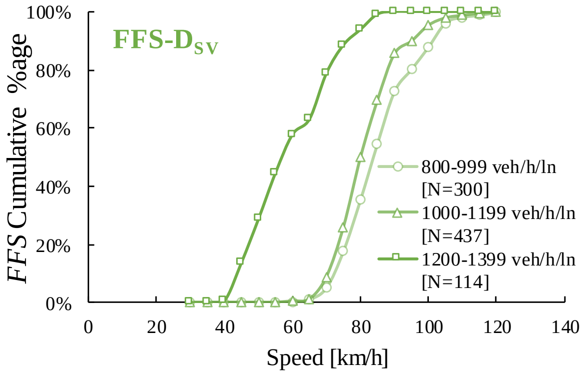

Fig.2 FFS-D of small vehicles on site 1, Lane 1 at various flow levels.

(1) Actual speed distribution (ASD)

Fig. 1 shows the variation of observed speed on lane 1, site 1 at varying flow levels. Speed reduction occurred with increasing flow rate, with a drastic reduction after 1,200 veh/h/ln. This can be attributed to the increased interaction between vehicles at higher flow levels, which leads vehicles to slow down and maintain a safe gap with the vehicles immediately ahead of them.

However, it is also possible that the impact of vehicle interactions could be further complicated by the behaviour of vehicles that just passed the upstream interchange, further lowering the observed speeds.

(2) Free-flow speed distribution (FFS-D)

The speeds of vehicles travelling with headways greater than 3 seconds were used to plot the graph in **Fig. 2**. The FFS-D follows the same trend as the ASD, with lower FFS at higher flow rates.

(3) Estimated free speed distribution (FSD)

The probability that the observed vehicle was free-flowing or not is estimated from observations of its speed and headway, which are in turn used to estimate the distribution of the free speeds of vehicles on the study section.

Fig. 3 shows the FSD on site 1 lane 1, and shows that the free speeds reduced with increased traffic flow. This was contrary to the authors' expectation of only slight variations in FSD with changes in traffic flow. It is possible that the location of the data collection point was not sufficiently far from the interchange to eliminate its impact on driving behaviour.

(4) Comparison of ASD, FFS-D, and FSD

Fig. 4 shows a comparison of the three speed distributions on site 1, lane 2. It can be seen that AS<FFS<FS both at low and higher flow rates. This result is logical because in a traffic stream, some vehicles will be travelling at their free speed, while others will be in a following condition. Therefore a distribution of all observed speeds (ASD) will be lower than that of only free vehicles based on a given headway threshold for following (FFS).

However, using headway alone to distinguish free flowing vehicles from following vehicles leads to vehicles with higher free speeds being excluded from the FSD estimation. The FSD obtained by using the Modified Kaplan-Meier estimation approach proposed by Hoogendoorn[3] captures these additional vehicles with higher free speeds, hence FSD>FFS-D.

(5) FSD by lane

FSD was also investigated on different lanes under similar traffic flow conditions. FSD at site 1 was compared for both lanes 1 and 2 at two flow levels.

Fig. 5 shows that small vehicles on lane 2 had higher free speeds than on lane 1 at both flow conditions, with the difference in free speed between 18 – 29km/h. A similar trend was observed for large vehicles at the same location, showing that free speed is lower on lane 1 by 15 – 22km/h. This is most likely because of the large proportion of large vehicles using lane 1 – in the analysed time periods, the large vehicle percentage on lane 1 averaged 62.37% compared to 36.79% on lane 2.

Although the analysis was separated for small vehicles and large vehicles, the headways used in the analysis were not separated by type of leading vehicle. This means that headways formed by small vehicles following large vehicles are also included in the analysis, and there is an inherent impact of large vehicle proportion in the computation of free speed distribution of small vehicles.

(6) FSD by flow rate

FSD variation by flow rate is examined separately for each lane and vehicle type.

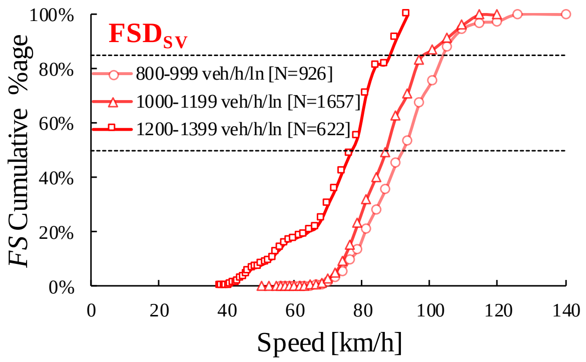

Fig.3 FSD of small vehicles on site 1, Lane 1 at various flow levels.

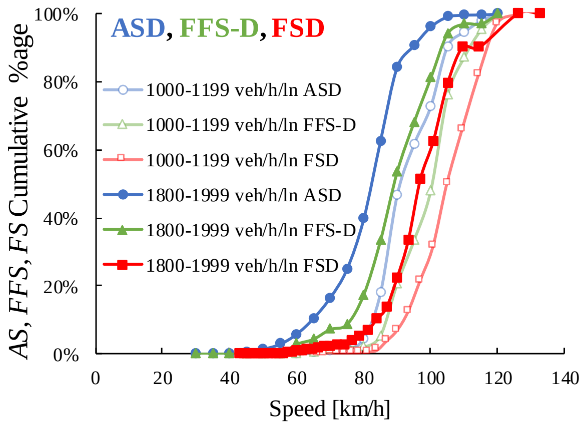

Fig.4 Comparison of ADS, FFS-D, and FSD of small vehicles on site 1, Lane 2

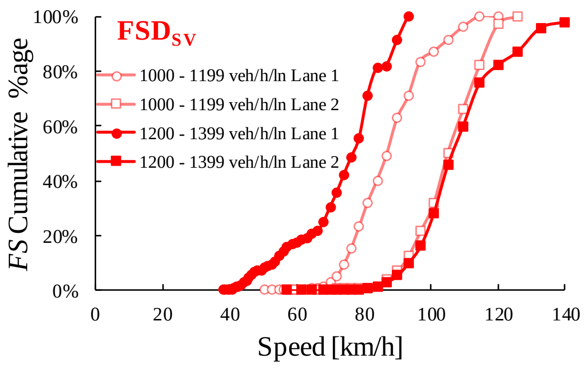

Fig.5 FSD of small vehicles on site 1 by lane

a) Lane 1

We previously observed in **Fig. 3** that FSD of small vehicles on lane 1 reduced with increased flow rate. A similar trend is observed for large vehicles as shown in **Fig. 6**, though the reduction is less drastic.

As shown in **Fig.6**, on lane 1, the decrease in FS when flow increases from 800 – 999 to 1000 – 1199, is not very large. For small vehicles, the 50th and 85th percentiles of the free speed reduce by 5.0 km/h and 6.0km/h respectively. The corresponding values for large vehicles are 1.0km/h and 0.8km/h respectively.

At these flow levels, it is possible that vehicles are still able to drive at their free speeds without any hindrances from other vehicles.

However, when flow rate on lane 1 increases to over 1200 veh/h/ln, the free speed reduces a further 10 km/h for small vehicles, and 7 km/h for large vehicles. It is logical to assume that a certain flow rate threshold under which vehicle interactions become significant has been crossed at this flow rate, leading to drivers choosing lower free speeds.

However, it is also possible that the vehicles that just passed the upstream interchange have not yet sufficiently accelerated to their ideal free speeds after just 900 metres.

b) Lane 2

Fig. 7 and **Fig. 8** show the FSD on site 1 lane 2 for small vehicles and large vehicles, respectively. From these figures, it can be seen that the highest flow rate, 1800 – 1999 veh/h/ln, corresponds to the lowest free speed distribution. However, unlike lane 1 (**Fig.3** and **Fig.6**), the free speeds are still relatively high until a higher flow rate of 1800 veh/h/ln is reached.

In addition, as the flow rate increases from the lowest level, FS fluctuates by 1.5 – 5 km/h for small vehicles and 1.75 – 4.25 km/h for large vehicles. The lower fluctuation in free speeds of large vehicles is possibly due to a large proportion of large vehicles in the traffic stream being platoon leaders, and therefore already travelling at their free speeds.

Results from study site 1 showed that free speeds in lane 1 were lower, and more sensitive to changes in traffic flow than in lane 2. This could be attributed to the impact of the interchange upstream of the study cross-section, the larger percentage of large vehicles in lane 1, and the assumption of relative uniformity of driving conditions in lane 2.

However, these observations could be localised to site 1. Therefore, in the next subsection we analyse data from a second site, on Chuo Expressway and ascertain if similar tendencies exist.

(7) Observations from site 2

In order to check if the speed trends observed at site 1 held true for other locations, the same analysis undertaken for site 1 was done on data from site 2 which has similar geometric characteristics. However, flows were lower on site 2, as was the proportion of large vehicles.

Fig. 9 shows FSD of small vehicles on site 2, lane 2 at two different flow levels. There is practically no difference between the distributions. It is possible that traffic flow does not influence free speed at lower flow levels.

At flow rates lower than 800 veh/h/ln, FS on lane 1 was lower than on lane 2 by about 15 km/h for small vehicles.

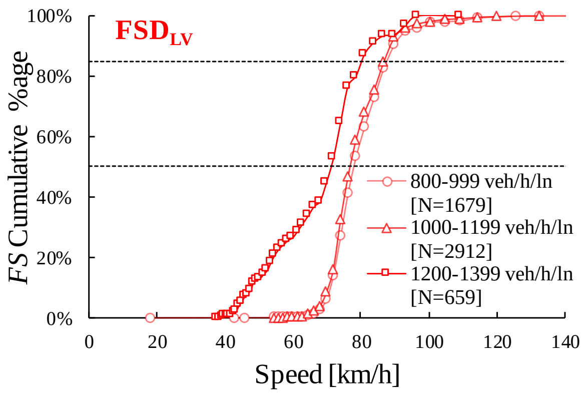

Fig.6 FSD of large vehicles at site 1 lane 1

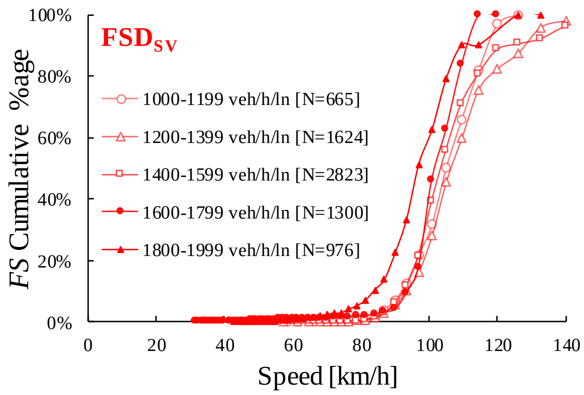

Fig.7 FSD of small vehicles at site 1 lane 2

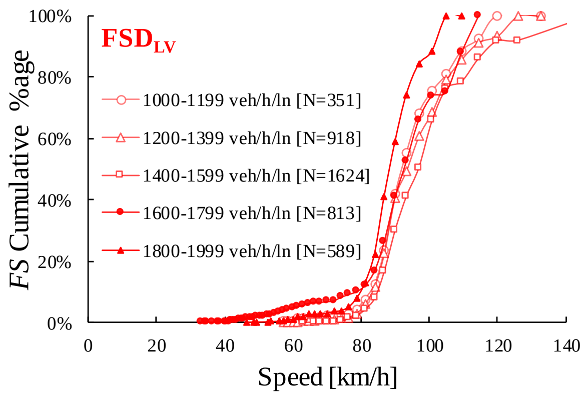

Fig.8 FSD of large vehicles at site 1 lane 2

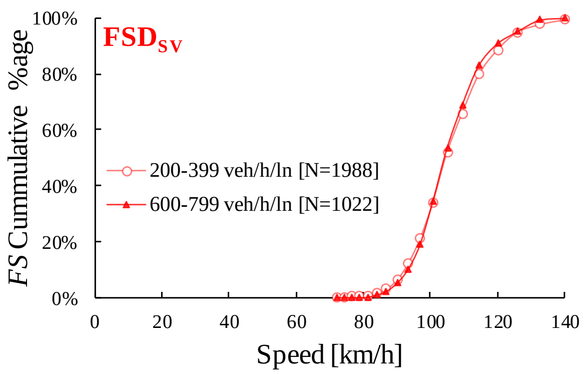

Fig.9 FSD of small vehicles at site 2 lane 2

Although the flow rates on site 2 were lower than those on site 1, it is clear that FS is different depending on the lane on which the vehicles travel, indicating that the drivers' evaluation of the QOS is also likely to vary by lane.

(8) FSD on site 3

On site 3 (Shin Meishin Expressway), the variation in FS with changes in traffic flow was small – just as at sites 1 and 2. **Fig. 10** shows FSD for small vehicles on lane 2 at this site. The difference in FS at the two flow levels is was between 2 – 5 km/h.

Due to the higher speed limit on site 3 compared to 1 and 2, the FS were higher on site 3. Except this, FSD showed slight reductions with increased flow rate and was higher on lane 2 than on lane 1 at all three sites.

Unlike sites 1 and 2, the location of site 3 was not in close proximity with an interchange. However, because the observed flows were much lower than those on site 1, we cannot conclude that the lack of drastic decrease in FS on site 3 was simply due to its location alone.

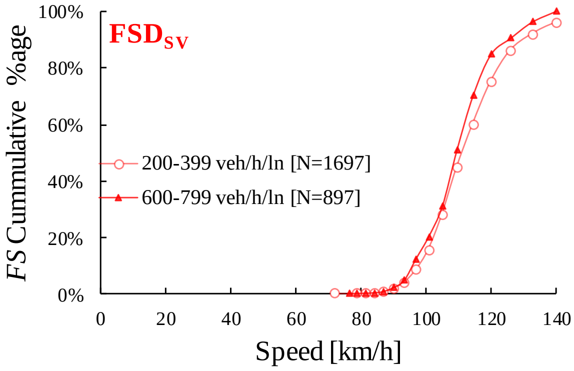

Fig.10 FSD of small vehicles at site 3 lane 2

4. CONCLUSIONS AND FUTURE WORK

Free speed was generally higher than the speed of free-flowing vehicles, which in turn was higher than the actual speed driven. The only time where the differences between these three types of speed was relatively small was under low flow conditions. This is logical because under low flow conditions, vehicle interactions are likely to be less frequent, allowing drivers to select their preferred free speed.

With the exception of lane 1 on site 1, FSD was found to only slightly vary based on traffic flow, but under specific circumstances. For example, the change in FSD due to changes in traffic flow rate was more pronounced on lane 1 than on lane 2, and for small vehicles rather than for large vehicles.

Although it was previously hypothesised that the interchanges located at 670 and 900 metres upstream of the site locations would not significantly influence the FSD, this assumption has to be carefully checked especially with respect to FSD in lane 1.

Site 3, which was not close to any interchanges, did not show drastic reductions in the FSDs at the examined flow rates. However, to confirm the impact of site location relative to FSD, larger flow observations on site 3 would be necessary.

Free speeds greatly varied by lane, indicating that the driver's perception of the QOS on the motorway is likely to be influenced by the lane in which they drive. This is an important observation because current performance measures consider the entire cross-section, yet it is clear that different traffic and driving conditions can exist along different lanes of the motorway.

Therefore, FSD could be used to include driver perception (FSD vs. ASD) in the evaluation of the QOS. This is not captured by existing performance measures such as traffic density, which is averaged over the entire motorway cross-section.

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