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Development of Freeway Corridor Capacity Measure to Improve Transportation Resilience

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EXCUTIVE SUMMARY

Conventional methods to assess the quality of service on freeways are based on the comparison of a specific peak hour traffic demand to the capacity of the facility, which is usually measured at a single uniform bottleneck section. However, estimating the quality of service of one bottleneck section may not be sufficient to assess the performance of an entire freeway facility. A driver travelling along a freeway corridor may actually encounter multiple flow breakdowns at independent bottleneck sections, which affect the overall quality of service. This paper introduces a comprehensive approach that considers an entire freeway corridor as a system consisting of successive independent bottlenecks with different characteristics and can be used to estimate the optimum sustainable volume. The methodology is based on the Sustained Flow Index (SFI), which is defined as the product of traffic volume and the probability of survival at this volume. Optimum volumes of two real-world corridors are estimated based on the new derivations. The empirical results reveal that the optimum volume and the capacity of an entire corridor is less than those of its most restrictive bottleneck.

Keywords: Freeway Corridor, Sustained Flow Index (SFI), Optimum Volume

1- INTRODUCTION

Capacity is one of the most fundamental and important parameters for the operational assessment of freeways. It serves as the foundation for estimation of many other performance measures such as Level of Service (LOS) or travel time. Capacity is defined as the maximum sustainable hourly flow rate that can pass a uniform segment of a freeway under prevailing geometric, traffic, and control conditions (*1*). In conventional procedures for quality of service assessment, capacity is regarded as a single, unvarying, maximum volume that can be conveyed over a uniform segment of the facility. However, research has shown that the transition from non-congested to congested flow (i.e. flow breakdown) may occur at volumes greater or lower than the conventional capacity values. This variability in traffic volume that leads to breakdown is not only due to the change in prevailing and external conditions, but may also be due to the momentary change in the behavior of individual drivers (*2*). Hence, the breakdown volume can be considered as a random variable that defines the momentary capacity of a facility. To apply the stochastic concept of capacity in real-world cases, a capacity distribution function is usually estimated for the section under investigation and the volume that corresponds to an acceptable probability of breakdown is considered as the capacity. The HCM suggests selection of a volume corresponding to the 15% probability of breakdown as a reasonable capacity estimate for freeways (*1*).

Due to the random nature of breakdown occurrence, it is not desirable to operate a freeway at full capacity. On the other hand, underutilization of a freeway should be avoided. Representing the tradeoff between sustaining fluid traffic conditions and maximizing the traffic throughput, the Sustained Flow Index (SFI) was recently introduced as a joint performance measure (*3*). The SFI is defined as the product of the traffic volume and the probability of survival (i.e. complement of the breakdown probability). The volume which at which the SFI is maximized provides the best balance between the probability of survival and the traffic throughput and is referred to as an "optimum volume".

In both deterministic and stochastic assessment approaches, freeway performance is defined for a single, uniform section of the facility. When assessing the performance of an entire freeway corridor, however, different bottlenecks throughout the corridor must be considered on an individual section-by-section analysis basis. Effectively, this means that in the absence of a method to comprehensively treat an entire corridor as a system, corridors have to be divided into multiple sections whose performance is assessed separately. For a comprehensive assessment of quality of service experienced by drivers travelling along a corridor, facing flow breakdown at multiple bottleneck sections, this study introduces a novel approach to estimate the optimum volume of freeway corridors based on the SFI concept. Here, a corridor is defined as a stretch of a freeway between two points, e.g. major freeway-to-freeway interchanges, consisting of several successive sections which might act as independent bottlenecks. Beyond the quality of service analysis for freeway facilities, the single estimate of the corridor optimum volume becomes particularly important in circumstances such as emergency evacuation where it may be critical to assess a corridor on the whole so that its overall throughput can be maximized and its breakdown probability minimized.

The following section provides a review of the related literature. This is followed by a more detailed description of the stochastic methodology that was used in this research as well as a description of the new procedure that extends the SFI concept to freeway corridor analysis. The proposed methodology is then applied to estimate optimum volumes of two real-world freeway corridors located in Germany and U.S. The paper concludes with a summary of the findings and recommendations for future application of this work.

2- LITERATURE REVIEW

The traffic performance of a roadway is usually addressed through its capacity. Roadway capacity is traditionally understood as "the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions" (*1*). This definition suggests that capacity is the maximum volume that can be traversed by a specific basic, weaving, or merge section of the roadway.

Several researchers have shown that freeway capacity may vary even under similar external and prevailing conditions (*4-8*). Consistent estimations of the capacity distribution function can be obtained with methods based on statistical models for censored data (*9*). Brilon et al. (*10, 11*) applied the Product Limit Method (PLM) to estimate the capacity distribution function of German Autobahns and found that capacity is best characterized by Weibull distribution. Liu et al. (*12*) adopted the PLM to examine the interaction between General Purpose (GP) and High Occupancy Vehicle (HOV) lanes and realized that GP lanes have greater capacity. Goto et al. (*13*) applied the PLM to analyze capacity distribution functions of individual lanes.

Based on the concept of stochastic capacities, Brilon (*14*) defined traffic efficiency as a measure that can be maximized to derive a traffic volume at which the optimum performance of a freeway facility is achieved. More recently, Shojaat et al. (*3*) introduced the SFI as a joint performance measure for freeways that reflects the tradeoff between maximizing the traffic throughput and minimizing the risk of a traffic breakdown. The volume that maximizes the SFI, referred to as the optimum volume, was analytically derived as a function of the parameters of the capacity distribution function. In a further empirical study (*15*), it was found that the optimum volume estimated in 5-minute intervals corresponds well to the 15 percent probability of breakdown in 15-minute intervals suggested by the HCM for selecting a representative value from the capacity distribution function (*1*). Further comparison between the optimum volumes and the conventional capacity values indicated that the optimum volume is a reasonable estimator of freeway design capacity. This was also supported by other researchers (*16-18*).

Wu and Geistefeldt (*19*) suggested a new link-related methodology to assess the reliability of freeway networks. Assuming temporal and spatial independence between the flow breakdowns, the survival function for a freeway link consisting of several bottlenecks was estimated based on empirical data collected from German freeways. The suggested methodology provides a better assessment of the reliability of freeways when multiple bottlenecks with different characteristics are considered for analysis.

While extensive research has been conducted to determine the capacity of single bottleneck sections, there is still a lack of analytical concepts to estimate the capacity and assess the optimum performance of freeway corridors. Therefore, this research aims to extend the SFI methodology and combine it with a network reliability model to estimate the optimum volume for freeway corridors. The proposed methodology is applied to empirical data of two freeway corridors in the U.S. and Germany, each consisting of several successive bottlenecks.

3- METHODOLOGY

3-1- Stochastic Capacity Estimation based on Models for Censored Data

To estimate capacity distribution functions for single bottlenecks, methods based on statistical models for censored data (*9*, *10, 11*) are applied in this study. Traffic breakdowns are determined by defining a threshold speed that divides the non-congested and congested states in the speed-flow diagram. If the speed in time interval (i) is above the threshold speed but drops below the threshold speed in the next time interval (i+1) and remains below for at least 15-minutes, the flow rate in time interval (i) is an uncensored value representing the momentary capacity. If the speed in time interval (i) is above the threshold speed and remains above in the next time interval (i+1), this interval contains a censored observation, which means that the flow rate is less than the momentary capacity of the section. Intervals that do not fall into any of the above categories, which happens either when the speed in time interval (i) is already below the threshold speed or when the speed drop is followed by a quick recovery, are not be considered for analysis.

For samples consisting of censored and uncensored observations, both parametric and non-parametric methods can be applied to estimate the capacity distribution function. The PLM is used to calculate a non-parametric capacity distribution function (*20*):

$$F_c(q) = 1 - S_c(q) = 1 - \prod_{i:q_i<q} \left(\frac{k_i - d_i}{k_i}\right) \tag{1}$$

where

$F_c(q)$ = capacity distribution function

$S_c(q)$ = capacity survival function

q = traffic volume (veh/h)

q_i = traffic volume in interval i (veh/h)

k_i = number of intervals with traffic volume $q_i \leq q$

d_i = number of breakdowns at volume q_i

Assuming a function type of the capacity distribution, its parameters can be calibrated with the Maximum Likelihood Estimation (MLE) method. For this, the set of parameters that deliver the maximum likelihood (or equivalently log-likelihood) value are chosen as the calibrated ones. The log-likelihood function to be applied for capacity analysis is (*10, 11*):

$$\ln(L) = \sum_{i=1}^{n} \{\delta_i \cdot \ln[f_c(q_i)] + (1 - \delta_i) \cdot \ln[1 - F_c(q_i)]\} \tag{2}$$

where

$f_c(q_i)$ = density function of capacity

$F_c(q_i)$ = capacity distribution function

n = number of intervals

δ_i = 1, if the interval i is uncensored

δ_i = 0, if the interval i is censored

According to the suggestion of the HCM (*1*) and other research findings (*10, 11*), this study assumes freeway capacity to be Weibull distributed. The Weibull capacity distribution function is:

$$F_c(q) = 1 - e^{-(\frac{q}{\beta})^{\alpha}} \quad (3)$$

where
$F_c(q)$ = capacity distribution function
q = traffic volume (veh/h)
α = shape parameter
β = scale parameter (veh/h)

3-2- Sustained Flow Index (SFI)

The SFI is defined as the product of the traffic volume and the probability of survival, i.e. the complementary value of the probability of breakdown, at this volume (*3*):

$$SFI = q_i \cdot S_c(q_i) = q_i \cdot (1 - F_c(q_i)) \quad (4)$$

where
SFI = sustained flow index (veh/h)
$S_c(q_i)$ = probability of survival at volume q_i
$F_c(q_i)$ = probability of breakdown at volume q_i
q_i = traffic volume in interval i (veh/h)

By replacing the capacity distribution function in the SFI formula with the Weibull distribution from Equation (3) and maximizing the SFI with respect to the volume, the optimum volume can be calculated as:

$$q_{opt} = \beta(\frac{1}{\alpha})^{\frac{1}{\alpha}} \quad (5)$$

where
q_{opt} = optimum volume (veh/h)
α = shape parameter
β = scale parameter (veh/h)

As shown by Shojaat et al. (*15*), the probability of survival at the optimum volume only depends on the shape parameter of the Weibull distribution:

$$S_c(q_{opt}) = e^{-\frac{1}{\alpha}} \quad (6)$$

3-3- Corridor Analysis based on the SFI concept

As derived above, the SFI delivers the optimum volume of a single bottleneck section. To extend the SFI for the analysis of corridors consisting of several bottlenecks, reliability (or survival probability) of the corridor needs to be calculated first. Thus, assuming a constant demand volume q along the corridor, the probability of survival of the entire corridor $S_n(q)$ can be estimated, and the SFI can be applied to estimate capacity of the corridor.

According to the multiplication rule, the probability of occurrence of n statistically independent events is equal to the product of their individual probabilities. The probability of survival of a freeway corridor consisting of n independent bottleneck sections is equal to the product of their individual survival probabilities. For Weibull distributed capacities and constant demand volumes within the corridor, this relationship is:

$$S_n(q) = \prod_{j=1}^{n} e^{-(\frac{q}{\beta})^{\alpha}} = e^{-\sum_{j=1}^{n}\left(\frac{q}{\beta_j}\right)^{\alpha_j}} \tag{7}$$

where
$S_n(q)$ = survival function of the corridor consisting of n bottlenecks
q = traffic volume throughout the corridor (veh/h)
α_j = shape parameter at section j
β_j = scale parameter at section j (veh/h)

Once the survival probability of the entire corridor is calculated, it is multiplied by the traffic volume to estimate the corridor SFI. To find the optimum volume of the corridor, a derivative is taken from the SFI with respect to the volume and the whole equation is set to zero. Thus, given the calibrated shape and scale parameters of bottleneck sections within the corridor, the optimum volume of the corridor can be found numerically from Equation (10).

$$SFI = q \cdot e^{-\sum_{j=1}^{n}\left(\frac{q}{\beta_j}\right)^{\alpha_j}} \tag{8}$$

$$\frac{\partial(SFI)}{\partial(q)} = 1 - \left[\sum_{j=1}^{n}\left(\alpha_j \cdot \left(\frac{q}{\beta_j}\right)^{\alpha_j}\right)\right] = 0 \tag{9}$$

$$\left[\sum_{j=1}^{n}\left(\alpha_j \cdot \left(\frac{q_{c,opt}}{\beta_j}\right)^{\alpha_j}\right)\right] = 1 \tag{10}$$

where
$q_{c,opt}$ = optimum volume of the corridor

In the above example, a single optimum volume is calculated for the whole corridor. However, the demand volume is usually not constant throughout the corridor. To count for the demand variation within the corridor, the optimum volume can be adjusted based on the directional average annual daily traffic (AADT) of each section. As an artificial parameter, the base demand is introduced to represent the directional AADT throughout the corridor. The volume adjustment factor (K_j), which is the ratio between traffic demand of each section and the base demand of the corridor, is calculated as:

$$K_j = \frac{AADT_j}{AADT_{base}} \quad (11)$$

where

K_j = volume adjustment factor at section j (-)

$AADT_j$ = directional average annual daily traffic at section j (veh/day)

$AADT_{base}$ = base directional average annual daily traffic of the corridor (veh/day)

Since the base demand in Equation (11) is not known, a reasonable starting value close to the average directional AADT of the sections within the corridor should be assumed as the first step to achieve faster convergence of the iterative process. Given the directional AADT of different sections and the base directional AADT, the volume adjustment factors (K_j) are calculated. The corridor optimum volume ($q_{c,opt}$) in Equation (10) is then multiplied by the volume adjustment factors to estimate the optimum volumes for each section. Given these optimum volumes, the probability of survival at each section and, subsequently, the reliability of the whole corridor (as the product of the survival probabilities of the sections) can be estimated. Next, the base directional AADT is iteratively changed until the corridor reliability under the set of new optimum volumes is the same as the reliability of the corridor under constant demand. The obtained set of optimum volumes for the sections of the corridor estimated with this method aims to optimize the operation of the entire corridor and hence differs from the optimum volumes estimated for individual bottlenecks.

Applying the volume adjustment factor needs careful consideration since, at any section, it is assumed to be a constant ratio over the time. In reality, however, the volume adjustment factor may change from one day (or week) to another for any given section. Also, in some cases the demand volume distribution may be significantly different on successive sections. In such cases, detailed numerical calculations are needed to estimate the volume adjustment factor.

4- CASE STUDIES

To investigate the methodology numerically, two urban freeway corridors with different prevailing conditions were selected for analysis: 1) a corridor along Autobahn 57 Northbound (A 57 NB) near Krefeld, Germany, and 2) a corridor along Interstate 5 Northbound (I-5 NB) near San Diego, U.S. Figure 1 shows both corridors under study.

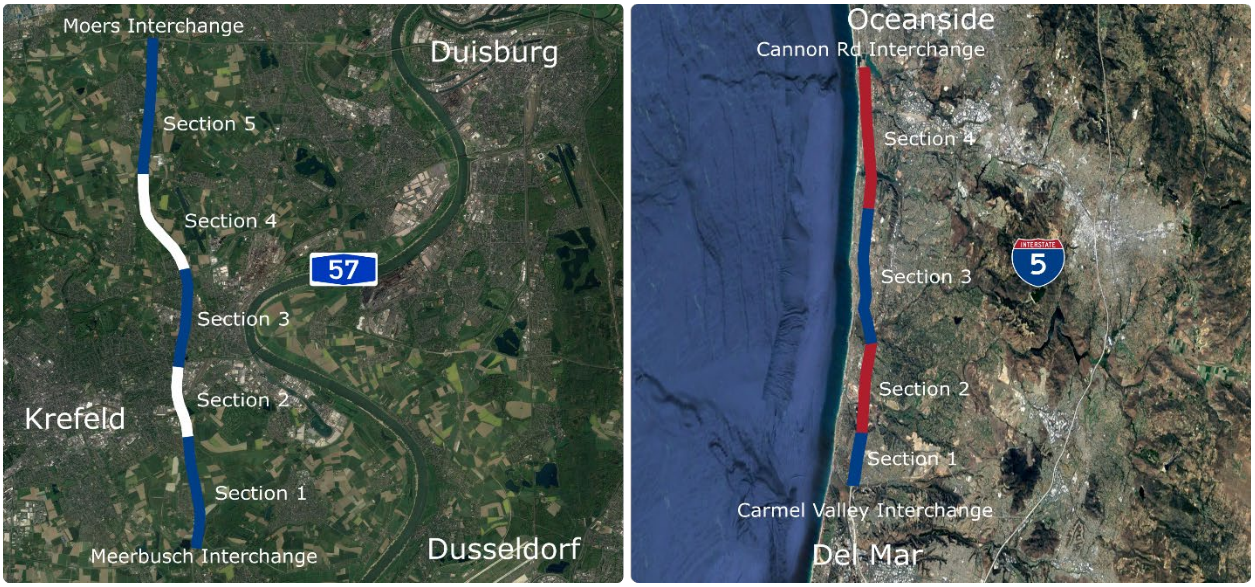

Figure 1 Corridors under study (Left: A57 NB, Germany Right: I-5 NB, U.S. ©Google Earth, 2019).

The A 57 NB corridor has two lanes and a length of 14 kilometers (8.7 miles). It is located in the Federal State of North Rhine Westphalia (NRW), Germany, and runs between city of Cologne and the Dutch border. The corridor consists of five bottleneck sections that operate almost independent of each other, despite the rather short distance between them. Variable speed limits are implemented throughout the corridor. The average share of heavy vehicles is about 13 percent.

The I-5 NB corridor is 14 miles long and has four- and five-lane sections. It is located in the state of California, U.S., and stretches between coastal cities of Del Mar and Oceanside. The corridor consists of four bottleneck sections that operate relatively independent of each other. Speed limit is 55 mph throughout the corridor. The share of heavy vehicles is near 4 percent. Tables 1 and 2 show the general characteristics of the bottleneck sections along both corridors.

Table 1 Characteristics of the A 57 NB corridor, Germany.

No.	Section	Detector ID	km	Lanes	Speed Limit	% Trucks
1	Meerbusch Interchange – Krefeld-Oppum	57.150	69.0	2	Variable	13.8%
2	Krefeld-Oppum – Krefeld-Zentrum	57.125	66.3	2	Variable	13.1%
3	Krefeld-Zentrum – Krefeld-Gartenstadt	57.105	63.5	2	Variable	13.3%
4	Krefeld-Gartenstadt – Moers-Kapellen	57.085	60.7	2	Variable	13.5%
5	Moers-Kapellen – Moers Interchange	57.040	55.1	2	Variable	13.3%

Table 2 Characteristics of the I-5 NB corridor, U.S.

No.	Section	Detector ID	Postmile	Lanes	Speed Limit (mph)	% Trucks
1	Carmel Valley – Del Mar Heights	1108507	34.0	5	70	3.0%
2	Del Mar Heights – Lomas Santa Fe	1108512	37.3	4	70	4.6%
3	Lomas Santa Fe – Luecadia Blvd	1108651	42.6	4	70	4.1%
4	Luecadia Blvd – Cannon Rd	1108659	48.0	4	70	5.0%

Traffic data of the German corridor were provided by the Traffic Management Center NRW. For the U.S. corridor, the data were collected from the Caltrans Performance Measurement System (PeMS) website. To avoid the effects of unfamiliar drivers on the estimated capacities, only workdays were considered for analysis of both corridors. Also, to prevent the negative effects of accidents or incidents, traffic breakdowns at volumes less than 1,200 vphpl were disregarded. For the German corridor, the impacts of accidents and work zones on traffic operation were removed based on additional accident and work zone data.

5- EMPIRICAL RESULTS

To calculate the SFI's and the optimum volumes, both non-parametric and parametric capacity distribution functions were estimated for each section by applying the PLM and the MLE technique assuming Weibull-distributed capacities, respectively. To obtain reliable estimates of the capacity distribution functions, large sample sizes with sufficient numbers of traffic breakdowns are required. Therefore, speed and volume data for a period of one year were collected in 5-minute intervals for all sections. With this long observation period, considerable numbers of breakdowns were observed, and well-fitted capacity distribution functions could be estimated for all sections of the corridors. The parameters of the estimated distribution functions and the resulting optimum volumes for the individual sections of the German and the U.S. corridor are given in Tables 3 and 4, respectively.

Table 3 Estimated parameters of A 57 NB corridor, Germany.

Section No.	No. of breakdowns	Weibull Shape α (-)	Weibull Scale β (veh/h)	Optimum Volume q_{opt} (veh/h)	Survival Probability $S_c(q_{opt})$
1	201	21.4	4,492	3,893	0.954
2	343	19.7	4,621	3,972	0.951
3	225	19.3	4,827	4,141	0.950
4	170	15.0	4,885	4,078	0.936
5	84	14.0	5,213	4,317	0.931

Table 4 Estimated parameters of I-5 NB corridor, U.S.

Section No.	No. of breakdowns	Weibull Shape α (-)	Weibull Scale β (veh/h)	Optimum Volume q_{opt} (veh/h)	Survival Probability $S_c(q_{opt})$
1	331	21.6	9,504	8,245	0.955
2	392	22.0	8,408	7,305	0.955
3	548	20.8	8,228	7,112	0.953
4	320	21.4	8,463	7,334	0.954

The calibrated Weibull shape and scale parameters (α_j, β_j) for the different sections of the corridors were inserted in Equation (10) and the optimum volumes of the corridors ($q_{c, opt}$) were calculated numerically.

Figures 2 and 3 show the estimated capacity distribution functions for all the bottleneck sections as well as the corridor capacity distribution functions and the corridor SFI functions. As can be seen in Figure 2, the optimum volume of the German corridor amounts to 3,691 veh/h, representing the maximum sustainable flow rate that should be maintained along this corridor to provide reliable trips. The optimum volume is reached at a probability of breakdown of 5.4%, which is equivalent to a probability of survival of 94.6%. Hence, the maximum SFI, as the product of the optimum volume and the probability of survival of the corridor, is 3,492 veh/h. As shown in Figure 3, the U.S. corridor reaches a higher optimum volume of 6,866 veh/h, which is due to its greater number of lanes. The probability of breakdown that corresponds with the optimum volume of this corridor is 4.6%, and the maximum SFI amounts to 6,548 veh/h.

In some real-world cases when a freeway corridor consists of multiple bottlenecks, capacity of the most restrictive bottleneck section is considered as being representative for the entire corridor. However, it is important to note that, as shown in the figures below, the capacity distribution function of the most restrictive bottleneck has a stochastic dominance over that of the corridor. This is due to the fact that reliability of a system comprised of different elements in series order is always less than their individual reliabilities (*21*). As a result, the optimum volumes of the most restrictive bottlenecks, shown in Tables 3 and 4, are greater than optimum volumes of the corridors (i.e. 3,691 veh/h < 3,893 veh/h and 6,866 veh/h < 7,112 veh/h). This finding suggests that the quality of service estimated for single sections may overestimate the performance of the entire corridor. Even if the traffic volume along the corridor remains near capacity of the most restrictive bottleneck, there is still a chance of breakdown in other less restrictive bottleneck sections due to the stochastic nature of freeway capacity.

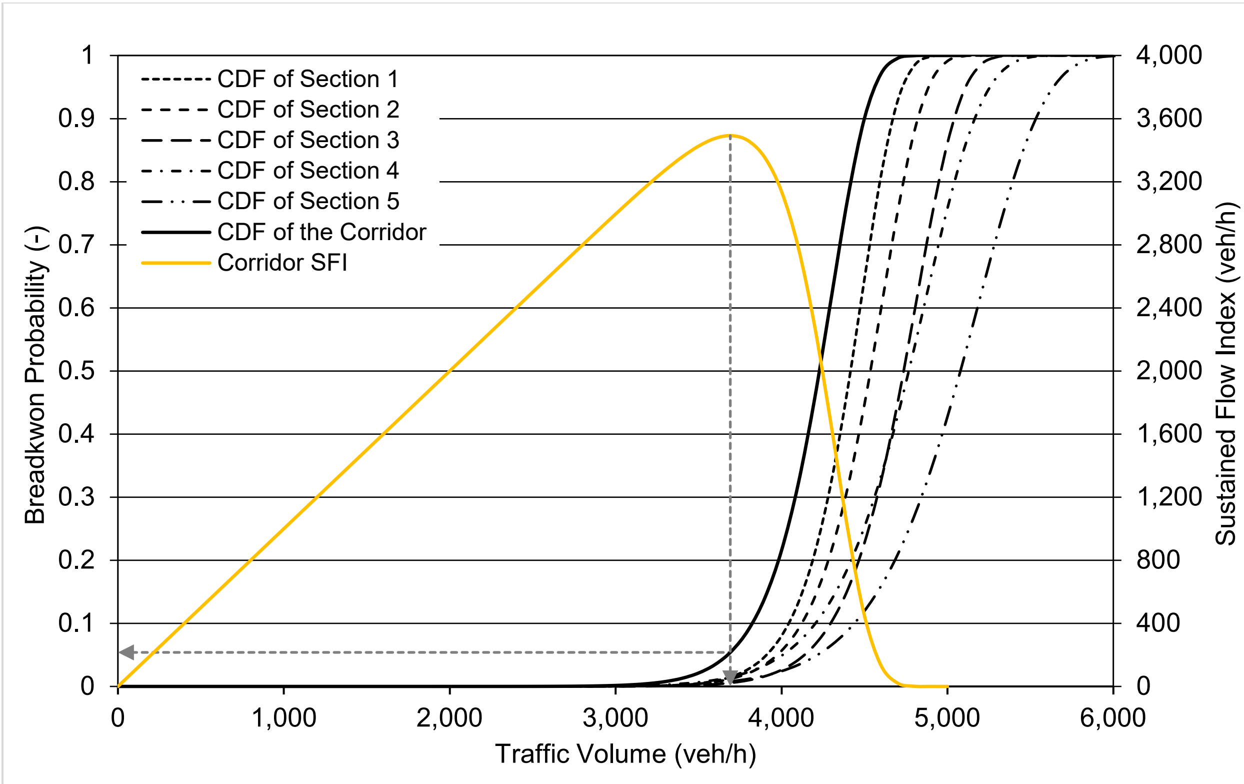

Figure 2 Estimated capacity distribution functions (CDF) and SFI of A 57 NB corridor, Germany.

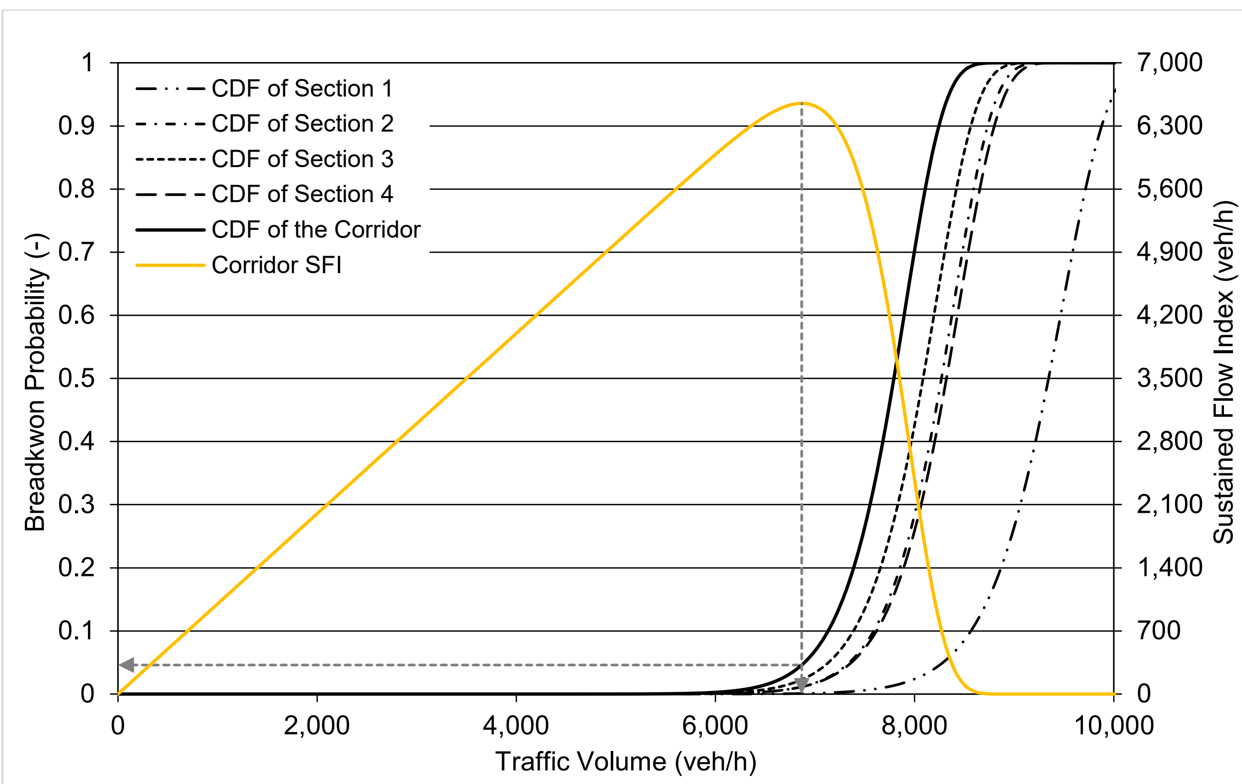

Figure 3 Estimated capacity distribution functions (CDF) and SFI of I-5 NB corridor, U.S.

In a second step, the assumption of constant demand along the corridor was relaxed and a set of adjusted volumes that optimize operation of the entire corridor were estimated. Given the directional AADT of the sections and assuming reasonable starting values for the base directional AADT, the volume adjustment factors (K_j) were calculated according to Equation (*11*). The volume adjustment factors were then multiplied by the corridor optimum volumes (3,691 veh/h and 6,866 veh/h) to calculate the adjusted optimum volumes ($q_{opt,adj}$). By replacing the adjusted optimum volumes in the Weibull formula given in Equation (*3*), the corresponding survival probabilities were estimated, and the reliability of each corridor was calculated as the product of the individual survival probabilities.

Tables 5 and 6 show the results of the first iteration in which base directional AADT volumes of 40,000 veh/day and 100,000 veh/day were assumed for the German and the U.S. corridor, respectively. Under the base AADT assumptions, the volume adjustment factors, adjusted optimum volumes, and survival probabilities were computed for each section. The corridor reliabilities, calculated as the products of the survival probabilities in the last columns, amount to 0.84 and 0.82.

Table 5 Initial set of parameters estimated for the German corridor under variable demand.

Section No.	Corridor Optimum Volume $q_{opt,c}$ (veh/h)	Directional AADT (veh/day)	Adjustment Factor (K_j)	Adjusted Optimum Volume $q_{opt,adj}$ (veh/h)	Survival Probability of the Adjusted Optimum Volume $S_{c,n}(q_{opt,adj})$
1		43,559	1.089	4,019	0.911
2		43,058	1.076	3,973	0.950
3	3,691	42,375	1.059	3,910	0.983
4		38,719	0.968	3,573	0.991
5		39,463	0.987	3,642	0.993

Table 6 Initial set of parameters estimated for the U.S. corridor under variable demand.

Section No.	Corridor Optimum Volume $q_{opt,c}$ (veh/h)	Directional AADT (veh/day)	Adjustment Factor (K_j)	Adjusted Optimum Volume $q_{opt,adj}$ (veh/h)	Survival Probability of the Adjusted Optimum Volume $S_{c,n}(q_{opt,adj})$
1		114,773	1.148	7,880	0.983
2	6,866	107,635	1.076	7,390	0.943
3		107,004	1.070	7,347	0.910
4		104,165	1.042	7,152	0.973

Since the corridor reliabilities estimated in the first iteration were different from the values obtained for a constant demand, the base demand was iteratively changed, and the resulting parameters were subsequently calculated until the reliability of the corridor matched the one under constant demand. It was found that at a base volume of 42,388 veh/day for the German corridor and 106,977 veh/day for the U.S. corridor, the reliability of the corridor under variable demand is equal to that under the constant demand (near 0.95 in both cases). It should be noted that the base demand values do not have any operational significance, but are used as artificial parameters for iteration to enable estimation of adjusted optimum volumes. Tables 7 and 8 show the final set of parameters estimated with this iterative approach. If all sections operate near their adjusted optimum volumes, then corridor operation will be close to optimal.

Table 7 Final set of parameters estimated for the German corridor under variable demand.

Section No.	Corridor Optimum Volume $q_{opt,c}$ (veh/h)	Directional AADT (veh/day)	Adjustment Factor (K_j)	Adjusted Optimum Volume $q_{opt,adj}$ (veh/h)	Survival Probability of the Adjusted Optimum Volume $S_{c,n}(q_{opt,adj})$
1	3,691	43,559	1.028	3,793	0.974
2		43,058	1.016	3,749	0.984
3		42,375	1.000	3,689	0.994
4		38,719	0.913	3,371	0.996
5		39,463	0.931	3,436	0.997

Table 8 Final set of parameters estimated for the U.S. corridor under variable demand.

Section No.	Corridor Optimum Volume $q_{opt,c}$ (veh/h)	Directional AADT (veh/day)	Adjustment Factor (K_j)	Adjusted Optimum Volume $q_{opt,adj}$ (veh/h)	Survival Probability of the Adjusted Optimum Volume $S_{c,n}(q_{opt,adj})$
1	6,866	114,773	1.073	7,366	0.996
2		107,635	1.006	6,908	0.987
3		107,004	1.000	6,868	0.977
4		104,165	0.974	6,685	0.994

It is important to notice that the independence assumption implies that if a breakdown occurs in any of the successive bottleneck sections, the whole corridor fails to operate properly. In other words, there will be n successive sections within the corridor, all of which can cause failure of the whole system. This suggests that in presence of correlation between some of the sections, the assumption of independence is conservative since in reality there are less than n independent sections which threaten fluid traffic operation of the corridor (i.e. a breakdown in one section is due to a breakdown in another section). In fact, according to the reliability theory, if the components in series order are perfectly dependent (i.e. fail exactly at the same time), the system reliability is the same as the reliability for a single component, whereas if they are perfectly independent, the system reliability will always be less than the reliability for a single component (*21*). As a result, in presence of a correlation between some of the components, the true probability of survival will be greater than the one predicted by the model and, thus, the actual corridor optimum volume will be greater than the estimated one. In this sense, slight dependency between traffic operation of the sections acts as a safety factor in estimation of the optimum volume. Nevertheless, to assure complete independence between the bottleneck sections and guarantee that queue backups from downstream do not affect the upstream sections, the distance between the sections should be selected long enough (i.e. considerably longer than the typical queue spillback of bottlenecks) in practice. In addition, for a more detailed analysis, times when traffic breakdowns occurred at different bottlenecks can be compared to make sure that a breakdown in one section did not trigger breakdowns in other sections. In such case, traffic operation of consecutive sections is deemed independent.

6- CONCLUSIONS

While various methods have been proposed to quantify and improve performance of single freeway bottlenecks, only few studies have focused specifically on freeway corridors. To address the need for more insight into freeway corridor capacity, this research approached the freeway segments as a system of sequential bottlenecks and applied the concept of the Sustained Flow Index (SFI) to assess the overall system performance. The basis of this method was to assume a constant demand throughout the corridor, then carry out derivations to estimate the optimum sustainable volume by accounting for the stochastic variability of capacity of each bottleneck and further expand the methodology to consider different demand volumes within the corridor.

To demonstrate the application of this approach, optimum sustainable volumes of two freeway corridors in both Germany and the U.S. were calculated. These two examples demonstrated both the robustness and wide applicability of the method as they featured different sets of geometric and traffic conditions. The empirical results suggested that the optimum volume of both corridors were less than optimum volume of each of their most restrictive bottleneck. This further suggests that the widely held belief that corridor capacity is controlled by its most restrictive bottleneck may be misleading. Another finding of note was that the probability of survival of both corridors remained significantly high (near 95 percent) under the optimum volume, suggesting that it provides a reasonable trade-off between the often-conflicting objectives of increasing throughput but maintaining flow reliability in freeway corridors.

Beyond its accuracy and ease-of-use, an additional benefit of this new analytical approach is its flexibility that allows analysts to estimate the traffic carrying capability for a range of specific local conditions. It can be applied to corridors that feature any number of bottlenecks and sections with different geometric, traffic, and control conditions. It also permits direct comparisons between corridors. This may be particularly useful for application in vehicle routing.

The optimum volume at which the maximum SFI is achieved represents desirable traffic operation of a freeway in terms of an optimal balance between traffic throughput and reliability. If consistently estimated in 5-minute intervals, the optimum volume is less than the average capacity. However, previous research (*15*) revealed that the optimum volume estimated in 5-minute intervals can be used as a reasonable estimate of the design capacity in 15-minute intervals consistent with the HCM (*1*). This is because the difference between the optimum volume and the capacity is compensated by the difference between capacities measured in 5-minute and 15-minute intervals. While this finding was obtained for single freeway bottlenecks, it is supposed that the same relationship applies for freeway corridors. Hence, the optimum volume of a freeway corridor in 5-minute intervals can be regarded as a reasonable estimate of the corridor capacity in 15-minute intervals. Validation of this assumption will be subject to further research.

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