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# Reliability and safety evaluation of selected road facilities: A review Paper

Huda Kareem Kadhim<sup>1</sup>, Abeer Khudhur Jameel<sup>2</sup>

<sup>1,2</sup>Highway and Transportation Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

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### ABSTRACT

Increasing traffic demand, rapid urbanization, and infrastructure limitations have intensified the need for integrated approaches to evaluate road performance. Traditional assessment methods often treat operational efficiency and safety independently, overlooking the influence of uncertainty in demand and capacity. This paper presents a comprehensive review of reliability concepts in transportation systems, with particular emphasis on capacity reliability and its relationship to road safety performance. The review synthesizes developments in connectivity reliability, travel-time reliability, and capacity reliability, highlighting methodological differences and practical applications. Capacity estimation approaches, demand forecasting models, the Level of Service of Safety (LOSS), and Crash Modification Factors (CMFs) are critically examined to establish a unified perspective for performance evaluation. The study identifies gaps in linking probabilistic capacity analysis with safety performance assessment and emphasizes the importance of integrating demand–capacity variability into safety evaluation frameworks. The paper provides a structured foundation for developing reliability-based decision-support tools aimed at enhancing both operational stability and road safety, particularly in urban networks facing fluctuating traffic conditions.


## 1. Introduction

Continuous advancements in the modern transportation systems, across design and vehicle technology, alongside rapid urbanization and increased vehicle ownership, have led to high traffic demand. This, in turn, has resulted in increased pressure on existing road infrastructure, creating congestion and unstable traffic operation, accompanied by higher conflict rates and more aggressive maneuvers. Consequently, road safety cannot be addressed independently of traffic operation and demand-capacity balance [1, 2].

Despite increased road capacity, including expansions and overpass construction, traffic performance remains at its lowest level. Though high costs have been spent on these programs, their goals of improving traffic flow to acceptable levels and avoiding road congestion and delays remain unfulfilled. Therefore, simply increasing capacity is not sufficient; linking them with solutions aimed at reducing transportation demand has been necessary. One of the indicators that links capacity and demand is reliability, particularly the capacity reliability. It is well-defined as the probability that the road network can support a particular traffic demand

Corresponding author E-mail address: [abeer\\_khudhur@uomustansiriya.edu.iq](mailto:abeer_khudhur@uomustansiriya.edu.iq)  
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volume at an established service level [3]. The reliability index is a crucial indicator used in the planning and design phases to select alternatives that improve capacity while simultaneously reducing transportation demand to achieve the highest level of reliability. On the other hand, road safety, a fundamental design criterion for roads, is not only about reducing accidents through infrastructure and regulation, but also about ensuring system reliability. A reliable road network helps reduce unpredictable conditions that can compromise safety [4]. Conventional road safety performance measures rely on crash frequency and severity, neglecting the traffic operation performance [5]. In addition, conventional traffic performance measures primarily quantify operational efficiency but neglect the safety measures [6]. Valid safety methodologies, such as the Highway Safety Manual HSM2010 [7], consider roadway geometry, traffic control, and traffic volume. However, fluctuating traffic demand has not been considered, despite its influence on driver behavior and temporal factors.

## 2. Reliability

### 2.1. Overview of Reliability

Reliability refers to the consistency of service performance, particularly in uncertain conditions. It measures the extent to which the current design meets objectives. It is also used to measure the extent to which the supplied design meets the demand [8, 9].

Higher reliability indicates reasonable road infrastructure with stable operational traffic. With increasing urban congestion and limited infrastructure capacity, transportation reliability has become a key performance measure for both road and transit systems [10-12]. Furthermore, according to Lomax & Margiotta [13], reliability is a core component of overall system performance, and it must be considered alongside efficiency and safety. Unreliable travel times increase user stress, reduce productivity, and decrease public confidence in transportation networks. Yu et al. [14] conducted research to investigate the feasibility of using reliability analysis methods in traffic safety analyses using data from a mountainous freeway in Colorado. The main aim was to diagnose the hazardous segment in terms of traffic flow and its use, and

real-time crash data. The reliability index was found using the probability of failure. The results showed that the segments with a low reliability index have the highest crash rate. They concluded that the reliability index could be used when crash data is not sufficient. Li et al. [15] developed a synthesized mechanism to integrate road safety system analyses with reliability analysis. Data on crashes at different time periods for ASEAN countries were used. The outcome has been used by policymakers in these countries in formulating strategic plans accordingly.

### 2.2 Reliability Analysis Objectives

Reliability analysis in transportation focuses on evaluating the consistency with which a facility or network performs over time. The main objectives of such an analysis include [16,17]:-

- Monitoring the reliability of a collection of facilities within a jurisdiction or region over time to prioritize them for operational or physical interventions,
- Identifying the fundamental causes of reliability issues in a specific facility to facilitate the development of an enhancement program, and
- Assessing the impact of a specific treatment or improvement on a facility post-implementation [16].

### 2.3 Applications of reliability in transportation systems:

Historically, studies on transport network reliability have primarily focused on travel time and connectivity reliability [18,19]. (Researchers have then focused on capacity reliability [20].

- **Connectivity Reliability**

Connectivity reliability refers to the probability that all network nodes remain connected. A key form is to assess whether a specific origin-destination pair remains linked. In this context, a network is considered functional if there exists at least one path between any pair of nodes. In 1982, Japan's Mine and Kawai introduced the notion of connectivity reliability, defined as the probability that a transport network can maintain a connection between any

pair of nodes. This concept primarily focuses on the connection between two nodes or two links [21]. However, it is inapplicable to small networks as it does not consider capacity limitations [10,22].

- **Travel-Time Reliability**

Travel-time reliability refers to the consistency of travel time across various traffic conditions. It is particularly valuable for assessing network performance under typical daily traffic fluctuations [23]. Asakura [24] developed this concept to account for road deterioration, defining reliability as the ratio of travel times under degraded versus normal conditions. The concept presented in this research was the basis for setting level-of-service standards. Chen and Recker [20,23] used the concept of travel time to examine the effect of different risk levels on route choice under supply and demand uncertainties. Alattar et al. [25] used travel time reliability index to assess the traffic performance at three arterial roads in Baghdad City. They found that the recorded travel time exceeds the free-flow travel time by 30% indicating substantial unreliability. Taher & Alkaissi [26] assessed the travel time reliability of Safi Al-Din Street, Palestine Street, and Army Channel Expressway using GPS data. By measuring the buffer time, an unreliable situation was recorded. The existence of signalized intersections with poor operation performance are the main contributing factors. Additionally, recommendations are provided for infrastructure and signal-control adjustments to improve consistency in travel times.

- **Capacity Reliability**

Capacity reliability refers to the capability of the supplied road infrastructure to accommodate travel demand under prevailing operational conditions and acceptable service standards without causing congestion and forming queues. It provides transportation engineers and planners with a structured, quantitative approach for evaluating system capacity and identifying areas for improvement [19,22]. Reliable capacity enhances operational efficiency and reduces the likelihood of unexpected delays caused by traffic-flow breakdowns [27]. Therefore, as a

direct reflection of road network capacity, capacity reliability has recently received greater attention from network planners and traffic management departments worldwide [19,28].

In terms of applications, Sumalee and Kurauchi [29] used capacity reliability to assess post-disaster traffic regulation. Chootinan et al. [30] proposed an alternative reliability index focused on daily route-choice reliability, which Chen et al. [31] later incorporated into a new reserve-capacity model for signal-controlled networks. This work was further extended by Chen et al. to a bi-objective model that integrates both capacity and travel-time reliability under demand uncertainty. Chen et al. [22] subsequently proposed a methodology that combines reliability analysis, equilibrium modeling, sensitivity analysis, and Monte Carlo simulations for degradable networks. A bi-level programming model of network capacity reliability was proposed by Fang & Pan [32] to consider elastic demand and travel time reliability in route choice models. They found that behavior of route choice has significant effect on the capacity reliability. Ji & Ma and Hosseini & Pishvaei and Wei et al. [33,34,28] then, incorporated capacity reliability index in route-choice models at larger scale network based on capacity and demand at certain time.

The most widely used method to determine the reliability index is the Probability Density Function (PDF). It is usually used to estimate the probability distribution over a link by measuring the deviation from standard values or a threshold; the mean value is usually used as a threshold. The probability of failure (non-compliance) can then be diagnosed [35,36,33]. Soltani-Sobh et al. [11] used the PDF assuming normal distribution of demand and capacity along the link. When the ratio of the estimated capacity probability density function (Capacity PDF) to the demand density function (Demand PDF) is less than 1 (Capacity PDF < Demand PDF), the situation is identified as a failure situation (non-compliance) [37]. It was found that the demand-capacity uncertainties method is more effective among travel time and connectivity reliability indices.

However, Darong et al. [19] stated that capacity reliability is more complex than travel

time reliability because travel time varies independently of traffic volume. They did not consider how low reliability can alter road users' route choice and how uncertain factors affect link capacity. Unlike travel time reliability, which addresses temporal uncertainty from the traveler's perspective, capacity reliability focuses on the physical and operational consistency of the infrastructure. This distinction helps prioritize interventions at critical bottlenecks to strengthen system performance.

### 3. Capacity estimation

Capacity is the maximum rate of vehicle traffic at a given point on a given road during a designated timeframe [16]. Increasing highway capacity to reduce traffic congestion is among the most significant challenges faced by traffic engineers. Traffic congestion in large metropolitan areas has adverse economic and environmental impacts; therefore, the capacity of urban streets and freeways it is a critical factor that is considered in transportation infrastructure improvement strategies [38]. The Highway Capacity Manual (HCM) defines two types of capacity [16]:

- Geometric Capacity, which is defined by the Highway Capacity Manual (HCM) as a constant value; for example, 2400 veh/h /lane for speed 110 km/h for freeways. It mainly depends on the physical characteristics of the road, such as lane width, road geometry, and vehicle type. earlier editions of the HCM defined design capacity as the flow rate when free-flow speed decreases by 15%.
- Operational Capacity, which is estimated to consider the effect of other factors, such as the proportion of heavy vehicles, obstruction and interference among vehicle traffic, road lane width, and vehicle parking on both sides of the road. All of these factors reduce capacity and are collectively referred to as operational capacity.

The concept of capacity in traffic engineering has been widely studied and debated, with different definitions and interpretations proposed in the literature. Some

common definitions include practical capacity [39], ultimate capacity, and stochastic capacity [40].

There are various methods for estimating road capacity, including HCM, model fitting, stochastic distribution, and breakdown-related methods [41]. These can be broadly categorized into empirical, statistical, and simulation methods. Empirical methods are considered easier ,but they are undesired in terms of accuracy. Statistical methods are more accurate only in cases derived from high-quality data. Simulation methods are the most precise, but also the most complex in computational terms and data-intensive. Many of the developed models lack validation with multiday observation data. Consequently, estimating different traffic capacities at various stages of planning, design, and control is crucial for improving urban traffic management quality [42].

The Highway Capacity Software (HCS) is a valid and widely used tool to estimate capacity when input data are accurate. Studies confirm its reliability and validity as a practical tool for traffic capacity analysis [43 ,44]. It is based on the procedures described in the Highway Capacity Manual (HCM) and permits a comprehensive analysis of signalized and unsignalized intersections, two-lane and multilane highways, roundabouts, and freeways.

Many investigations have demonstrated the ability of HCS to accurately assess traffic facility performance for different operational types and circumstances [7,45]. Brilon et al. [46] proposed a capacity estimation method based on a normal distribution defined by the mean and standard deviation of the time headway distribution. They introduced a methodology for estimating capacity distribution functions using statistical methods for lifetime data analysis. Moses et al. [47] compared various capacities in Florida to provide recommended capacity values for transportation operations and also examined the relationship between capacity, bottleneck type, number of lanes, and free-flow speed. Modi et al. [48] evaluated the advantages and disadvantages of capacity estimation methods based on mathematical functions and the breakdown probability distribution method and

developed a simple averaging method of the highest flow rates to determine capacity. Li and Laurence [49] compared and contrasted four popular capacity estimation techniques using a rich dataset, including the maximum method, Van Aerde model, break-down method, and product limit method, and found that the best method for capacity estimation depends on the available data, the application, and the goals of the modeler. Yang et al. [50] introduced an analytical approach to model queue length at a metered on-ramp. They also created a mesoscopic simulation model to estimate queue length across different demand-to-capacity scenarios. Recently, Wang et al. [51] proposed a Weibull distribution-based neural network to estimate stochastic capacity, and Cheng et al. [52] proposed two categories of stochastic capacity estimation approaches based on lognormal and skew-normal distributions.

#### 4. Demand Estimation

Travel demand is defined by Garber and Hoel [53] as the expected number of persons or vehicles per unit time travelling on a given transportation facility system under a set of given conditions. Traffic demand is different from traffic volume; as traffic volume is the number of observed vehicles at a certain time and certain site, while traffic demand is the number of vehicles desiring or attempting to travel along a roadway [54].

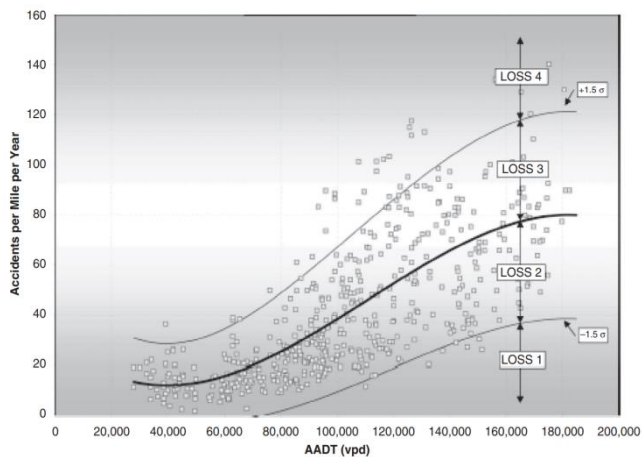
Travel demand modeling aims to forecast the origin, destination, mode, and route choice of trips. This process helps to comprehend the effects of current and future developments on the trip's characteristics [53]. Therefore, extensive research has been conducted on demand forecasting methods and models [55,56]. The four-step models, activity-based models, temporal categorization, such as the kernel density method (KDE), and statistical models, such as the upper percentile of observed volume in a given year are examples of the most common methods of travel demand forecasting [57]. These models provide essential information for decision-makers in route planning and travel management [58]. The selection of the most suitable method depends on the planning objectives and data availability.

The four-stage travel demand forecasting model is one of the widely used methods. It aims to estimate the number of trips between origins and destinations within a region. The model begins by estimating the total number of trips generated and attracted to each zone. These trips are then allocated from origin zones to destination zones using trip distribution models, creating an origin-destination trip matrix (O-D Matrix). Finally, each trip matrix is assigned to the route network of a particular mode using the trip assignment models.

TransCAD is a software application, GIS-transport modeling platform, designed for comprehensive travel-demand modeling, compatible with Windows, and essential for engineers and professionals in planning and traffic management [59]. TransCAD has been used in transport-planning studies for various purposes, including estimating origin-destination (O-D) flows, network coding and performance evaluation, and GIS-based accessibility/route assessment. It is often used to combine field traffic counts with zone-based socio-economic data and basic assignment procedures [60,61,62]. It has been employed at smaller spatial scales, reflecting a practical approach, especially when comprehensive household travel surveys are not feasible [63]. In addition, it has been used to estimate the O-D matrix for a certain trip mode or for specify trip purpose, for example for truck freight demand estimation, to investigate the impact of freight flows on traffic congestion and logistics planning [64]. Qasim et al. [65] combined TransCAD with GPS/GIS data to assess traffic performance in Dhi Qar City by attaching traffic volumes and link attributes to the built road network to identify performance issues such as long travel times and low vehicle speed. Aboodi & Qasim [66] used TransCAD to evaluate the operational performance of a road network in Al-Kut City. They employed TransCAD to analyze capacity utilization, travel time, and connectivity. Overall, the reviewed studies used TransCAD as a planning tool when detailed survey data are limited; therefore, researchers entered traffic volume data, GIS layers, zoning, and assignment to produce the required O-D matrices and network performance indicators.

## 5. Level of Service of Safety (LOSS)

The Level of Service of Safety (LOSS) is a safety performance measure; its concept was first introduced in 1972, and developed by Lu et al. [67] Kononov and Allery [68] have developed the concept of LOSS within the framework of the safety performance function (SPF) and employed it to quantify risk magnitude, describe the quality of safety level, and diagnose risky sites. It can also be used to frame a reference for decision makers. Kononove et al. [68] used a value of (1.5 times the standard deviation) to set the boundary limits of the LOSS, as shown in Figure (1).



**Figure (1)** LOSS Categories of Colorado six-lanes freeway (Kononove et al., 2015)

Lu et al. [67] showed that the LOSS method has been developed to address the issues of the random characteristics of crashes and insufficient crash data that result in biased safety assessments. The updated concept of LOSS by Kononov and Allery is adopted by the Highway Safety Manual HSM 2010 [69] to use as an indicator of the safety level at a road facility. The main applications of LOSS are to categorize the study area, identify the highest-risk site, determine contributing factors, and propose countermeasures to improve the safety level [70].

Determining LOSS is based on the statistical difference between the **observed crash frequency** and the **expected crash**

**frequency**, considering a **confidence interval**. The predicted crash frequency is derived from the safety performance function

(SPF) and crash modification factors. The Safety Performance function (SPF) is the expected crash frequency at a specific site based on Annual Average Daily Traffic (AADT) and base conditions of the assessed site, representing the engineering characteristics that were used in deriving the SPF model. The base conditions are different according to the facility type. When the engineering characteristics of the study area are different from the base conditions, crash modification factors (CMF) are used to adjust the SPFs to the predicted crash frequency. Four categories of LOSS can be identified [68,69].

- **LOSS I:** represents a high safety level when the actual crash frequency is 1.5 standard deviations ( $\sigma$ ) value below the expected mean at a **95% confidence interval** of the SPF
- **LOSS II:** represents a moderate safety level when the actual crash frequency is 1.5 standard deviations ( $\sigma$ ) above and the expected mean within the lower 95% confidence interval.  
**At LOSS I and LOSS II**, sites perform as predicted or better than predicted.
- **LOSS III:** represents low safety-level when the actual crash frequency is **higher** than the expected frequency and still **within** the upper 95% confidence interval. At this level, sites perform as predicted or slightly better than predicted; they may warrant attention.
- **LOSS IV:** represents too low a safety level (severe risk situation) when the actual crash frequency is **significantly higher** than expected **within** the upper 95% confidence interval. At LOSSIV, sites are experiencing **significant safety problems** and should be prioritized for treatments.

Fuquan et al. [71] developed a model of safety level of service (SLOS) for signalized intersections by combining the HCM level of service with a developed risk index. The developed risk index considered traffic conflicts, cycle time details, and geometric characteristics. However, the generalization and validity of the

model have not been approved, and further sensitivity analysis is required, as the authors recommended. In 2010, Lu et al. [72] developed the SLOS by incorporating the types of conflict points into the previous model. They applied the model to a signalized intersection in Jiangsu Province, China.

Makki et al. [73] combine the level of service with perception time and stopping sight distance to predict pedestrian risk. The considered factors were speed, type of vehicles (passenger car and heavy vehicle), and perception time. The results showed that incorporating perception time produced a more practical model than incorporating stopping distance. The validity test approved the practical applicability of the model.

Hamilton [74] applied the LOSS to proactively assess the safety of the intersection of State Highway 75 and Plank Road (County Road A) in Racine County, Wisconsin, US. The key factors that affect the safety of the corridor were identified, and countermeasures have been proposed based on the results of the assessment, including resurfacing the corridor with routine maintenance and corrections in the geometric design of the intersection.

Abdulla & Karim [75] applied the LOSS measure, along with four other measures, to assess safety and identify the highest-risk site among 40 intersections in Sulaymaniyah, Iraq. It has been found that the LOSS approach offers an intuitive safety performance assessment.

## 6. Crash Modification Factors (CMFs)

CMFs are essential tools in transportation safety engineering used to estimate the crash frequency change after implementing specific road safety measures. In general, the applicability of a CMF may vary by crash severity, crash type, and/or site condition [69].

A CMF is a multiplicative coefficient utilized to calculate the predicted number of collisions following the implementation of a specified countermeasure at a designated location. A CMF greater than 1.0 means that the suggested treatment will lead to an increase in crashes, whilst a value less than 1.0 indicates the effectiveness of the suggested treatment. For example, a CMF of 0.8 means that a 20%

decrease in crashes due to a certain treatment, while a CMF of 1.2 means that there will be an increase in crashes due to a certain treatment [76]. Various models have been developed to determine the CMF for various variables based on the facility type and the contributing factors. The Highway Safety Manual provides Part D to present methodologies for determining CMT for various facilities, crash types, crash severities, and area types.

## 7. Conclusion

Reliability refers to the consistency of service performance, and capacity reliability refers to the consistency of a designed system to accommodate the demand. Reliability analysis is important to monitor the performance of facilities within a jurisdiction over time, prioritize them for interventions, identify the fundamental causes, and assess the impact of a specific improvement on a facility post-implementation. Despite that travel time and connectivity reliability have been widely investigated, they ignore capacity limitations, therefore, this study will focus on capacity reliability as an index for assessing the current traffic situation of a selected facility.

Capacity Reliability was selected for the study because it best indicates the robustness of the network to varying traffic demand while maintaining stable service levels. This is critical in contexts like Iraq, where infrastructure is often limited and unstable. Capacity Reliability enables us to factor in unexpected breakdowns, selected fluctuating capacity, and to compare these to the expected capacity level, which our previous performance measures did not address. To estimate capacity reliability, road capacity and traffic demand are required. Therefore, the methods of estimating both were reviewed. According to simplicity, accuracy, availability, and validity, the Highway Capacity Software (HCS2010) and TranCAD software will be used to estimate road capacity and traffic demand, respectively.

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