A PCI-Based Evaluation Method for Level of Services for Traffic Operational Systems

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***Abstract*—This paper proposes a new measure to evaluate level of services (LOS) for traffic operations based on process capability indices (PCIs). First, a brief introduction to the concept of PCIs and the characteristics of traffic flows is presented and followed by a discussion on the appropriateness of applying PCIs to measure the quality of traffic flows. Then, several case studies are conducted to investigate the effectiveness of the proposed new measure for traffic LOS, and the results indicate that speed and density are the most appropriate parameters for this purpose. Finally, this paper concludes with remarks on future research directions.**

***Index Terms*—Highway capacity, level of services (LOS), process capability indices (PCIs), traffic flow.**

I. Introduction

FOR MOST traffic operation systems, the concept of level of services (LOS) has been used to determine the quality of traffic operation within a traffic stream and at a given location. This quality is generally described in terms of speed and travel time, ratio of volume and capacity, delay time, freedom to maneuver, traffic interruptions, as well as comfort and convenience [1], [2]. However, the majority of measures currently used or proposed for LOS do not fully take the effects of statistical characteristics of traffic processes into account [2]–[6].

Process capability indices (PCIs), as a measure of process performance, provide an effective way for describing assessments of ability to meet specification limits. They are dimensionless and associated with the process mean and variance with one-sided or two-sided specifications with or without a target value for the process mean [7]–[11]. Recently, more efforts have been focused on studies and applications of PCIs, and a remarkable progress has been made in this area between 1992 and 2000 [12]–[16]. Over 170 papers on PCIs have been published from 1993 to 2000 and cover a broad range of topics from theoretical and/or mathematical issues to various practical process control applications. Normally, PCIs can be estimated from sample data and then used to judge the state of capability of a process by those estimates.

Traffic flow is a very complex process involving vehicles, roads, people, control signals, traffic management, and many environmental factors. The recent urban development and the significant increase in the number of mobile vehicles on roads demand advanced research and evaluation of traffic operational systems using new methods and high technology in computer, communication, and control. Clearly, studies on effective methods to assess the LOS for traffic systems would be one of the interesting and important topics for transportation systems, particularly for advanced traffic management systems in the proposed architecture for intelligent transportation systems.

In this paper, we investigate the potential use of PCIs for measuring the LOS for traffic systems. This paper is organized as follows: A brief introduction to the traffic LOS and PCIs is given in Section II, followed by a discussion on the effectiveness of applying PCIs to evaluate the traffic operational quality through a new measure. A detailed application is conducted in Section IV. Finally, it concludes with a brief summary and discussion on future works in Section V.

II. LOS and PCIs

A. LOS

Currently, there are two different LOSs proposed for traffic operations, namely 1) the LOS of uninterrupted flow transportation facilities (freeways, multilane highways, and two-lane highways) and 2) the LOS of interrupted flow facilities (signalized intersections, arterials, pedestrian ways, bikeways, etc.). The first is defined in terms of density (in vehicles per mile), speed (in miles per hour), time delay (in percent), etc., and the second can be determined by throughput, delay (in seconds), etc. [2]. Here, we focus on the LOS of uninterrupted flow transportation facilities only.

The U.S. Transportation Research Board has defined six LOS levels, designated A through F, for the link LOS, with A representing the best operating conditions and F the worst [2]. Each LOS represents a range of operating conditions and the driver's perception of those conditions [1], [4], [17]. Each LOS represents a class of conditions defined by a range of one or more operational parameters. Although the concept of LOS attempts to address a wide variety of operating conditions, limitations on data collections and their availability make it impractical to consider the full range of operational parameters for every type of transportation facility. The parameters that best

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describe the quality of operations on the facility are selected to define LOS for that facility type and are called measure of effectives [4]. Note that safety is treated separately and is not included in the measures for service levels.

Generally, for a given feature under consideration, the corresponding LOS is established by the following guidelines according to the Highway Capacity Manual [2].

- For urban street systems, LOS is based on average through-vehicle travel speed for the segment, section, or entire urban street under consideration.
- For two-lane highways on which motorists expect to travel at relatively high speeds, the primary measures of LOS are the percentage of time-spent-following and average travel speed.
- For multilane highways and freeway, the density of traffic stream is the assigned primary performance measure for estimating LOS.

Obviously, concrete measures must be provided to determine the specific LOS in individual cases.

In the study concerning LOS, highway capacity is a very important measure. In general, the capacity of a facility is the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions [4], [17].

B. Definitions of PCIs

Four popular PCIs are considered here [7], [9]. Let U and L be the given upper and lower specification limits, respectively. Assume that the corresponding variable is X and that its expected mean and standard deviation are μ and σ. Our discussion is limited to situations where μ is always in the specification region, i.e., $L \le \mu \le U$. Meanwhile, $d = (U-L)/2$, $M = (U+L)/2$, and T is the expected target value of μ.

1) PCI C_p: In this case, the index is defined as

$$C_p = \frac{U-L}{6\sigma} = \frac{d}{3\sigma}, \quad X \in [L, U] \tag{1}$$

which is generally called PCI. It involves only with the process standard deviation σ. Equation (1) is for double-sided specifications. The indices for single-sided specifications are

$$C_{pl} = \frac{\mu - L}{3\sigma}, \quad X \ge L \tag{2}$$

$$C_{pu} = \frac{U - \mu}{3\sigma}, \quad X \le U. \tag{3}$$

2) Behavior PCI C_{pk}: In this case, the index is defined as

$$C_{pk} = \frac{d-|\mu-M|}{3\sigma} = \frac{\min\{U-\mu, \mu-L\}}{3\sigma} = \min\{C_{pu}, C_{pl}\}. \tag{4}$$

It reflects the impact of both process mean μ and standard deviation σ.

3) Taguchi Index C_{pm}: In this case, the index is defined as

$$C_{pm} = \frac{d}{3\sqrt{E\left[(X-T)^2\right]}} = \frac{d}{3\sqrt{\sigma^2 + (\mu - T)^2}}. \tag{5}$$

It takes into account not only the process mean and the standard deviation but also the departure of the process mean μ from its target T.

4) Hybrid Index c_{pmk}: In this case, the index is defined as

$$C_{pmk} = \frac{d-|\mu-M|}{3\sqrt{E\left[(X-T)^2\right]}} = \frac{d-|\mu-M|}{3\sqrt{\alpha^2 + (\mu - T)^2}}. \tag{6}$$

It is actually a combination of the other three indices C_p, C_{pk}, and C_{pm} [7].

Since PCIs C_p and C_{pk} are easy to understand and calculate, they are quite popular in real applications. The general guidelines for their uses are as follows: 1) $C_p > 1.67$ means the process is highly capable. 2) For C_{pk}, 1.33 is used as a benchmark in assessing the capability of the process, and it is commonly considered that C_{pk} between 1 and 1.33 indicates the process is barely capable [18].

C. Estimators of PCIs

The estimation of indices is needed for the actual applications of PCIs. Since the sample mean $\overline{X}$ and variance S^2 are unbiased estimators of process expected mean μ and variance σ^2 [19], [20], the natural and most commonly used estimators of C_p, C_{pk}, C_{pm}, and C_{pmk} are determined as

$$\hat{C}_p = \frac{U-L}{6S} = \frac{d}{3S}, \quad X \in [L, U] \tag{7}$$

$$\hat{C}_{pl} = \frac{\overline{X} - L}{3S}, \quad X \ge L \tag{8}$$

$$\hat{C}_{pu} = \frac{U - \overline{X}}{3S}, \quad X \le U \tag{9}$$

$$\begin{aligned}\hat{C}_{pk} &= \frac{d-|\overline{X}-M|}{3S} = \frac{\min\{U-\mu, \mu-L\}}{3S} \\ &= \min\{\hat{C}_{pl}, \hat{C}_{pu}\}\end{aligned} \tag{10}$$

$$\hat{C}_{pm} = \frac{d}{3\sqrt{S^2 + (\overline{X} - T)^2}} \tag{11}$$

$$\hat{C}_{pmk} = \frac{d-|\overline{X}-M|}{3\sqrt{S^2 + (\overline{X} - T)^2}} \tag{12}$$

where $\overline{X} = (1/n)\sum_{i=1}^{n} X_i$, and $S = \sqrt{(1/n) - 1}$ $\sum_{i=1}^{n}(X_i - \overline{X})^2$.

Note that not all processes can be evaluated by these indices for their capabilities. The following two preconditions should be satisfied in order to make these indices meaningful [9], [20].

1) Process evaluated is statistically controllable.
2) Sample data follow a normal distribution.

It should be pointed out that even if the sample data are not normally distributed, we can still use PCIs to evaluate the capability of the process after we fix it with a satisfactory normality approximation [17]. Otherwise, we have to use nonnormal capability indices to evaluate the capability of the process [21].

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III. Traffic Flow and PCIs

In this section, we discuss the possibility of using the PCIs described in the previous section in traffic flow to evaluate its operational capability with proper specification limits.

According to the central limit theorem [19], [22], [23], when the sample size approaches a couple of dozens, the distribution of the average measure $\overline{X}$ will be a nearly normal distribution, although the parent distribution is not a normal one.

Usually, the output of a traffic detector is the average of traffic data samples (collected every few seconds) in a few minutes. Therefore, every output of a traffic detector is the mean value of over 30 to 60 traffic samples. Comparatively, traffic flow is a slow process, and its change needs a period of times and normally does not happen instantaneously [24], [25]. Meanwhile, traffic data over a relatively long time period are normally used for analysis and decision making in actual applications. Thus, normally, every traffic datum is an average of no less than a couple of dozens collected samples so it is natural to assume that traffic flow data (mean values) follow or approximate a normal distribution. In addition, since parameters for traffic flow modeling can be detected directly or indirectly, the process of traffic flow is obviously statistical controllable [3], [20], [26]. As a consequence, a typical process of traffic flow could meet the two preconditions required for the use of four PCI indices presented at the end of the previous section. In conclusion, it is safe to assume that PCIs can be used to evaluate the process capability of traffic flow systems.

Speed, volume, and density are three primary variables in traffic flow. In many cases, a linear equation is used to approximate the relationship between speed and density of traffic flow on an uninterrupted traffic lane [3], [4], [27], [28]; see Fig. 1(a). Based on this approximation, the relationship between speed and volume and that between volume and density can be derived subsequently, as shown in Fig. 1(b) and (c). As a result, we can find the analytical equations among speed, volume, and density as

$$v = A - Bk \tag{13}$$

$$\begin{aligned} q &= kv \\ &= Ak - Bk^2 \\ &= -B\,(k - A/(2B))^2 + A^2/(4B) \end{aligned} \tag{14}$$

where v is the mean speed of vehicles (in miles per hour), q is the average volume of 1 h (in vehicles per hour), k is the average density of vehicles (in vehicles per mile), and A, B are two empirically determined parameters.

Usually, Fig. 1 is called the fundamental diagrams for traffic. The solid lines in Fig. 1 are called "uncongested" traffic flow conditions, while the dashed as "congested" or "forced" traffic flow conditions. The critical values from uncongested to congested conditions are called jam density, critical speed, and maximum volume, respectively. From Fig. 1, we find that the jam density is equal to $A/2B$, the critical speed $A/2$, and the maximum volume $A^2/4B$. Obviously, it is anticipated that a traffic system should be operated under the traffic condition corresponding to solid lines. Thus, satisfactory operating states

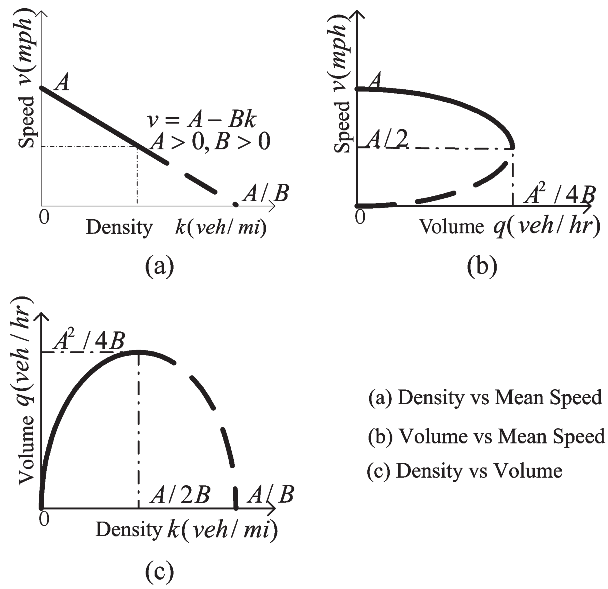

Fig. 1. Relationships among speed, volume, and density.

of traffic flows should be specified as the region indicated by the solid lines, and PCIs should be defined in this region to evaluate the corresponding levels of traffic services.

Fig. 1 also shows that one density value corresponds to one speed and one volume value, one speed value to one volume and one speed value, respectively, but one volume value is mapped into two speed values that are in different traffic flow conditions. Therefore, from volume data alone, we could not identify uniquely which traffic condition the current traffic flow is in. As a result, traffic volume parameter is not appropriate for direct use in PCI calculation for traffic flow evaluation; this would become even clearer in the following case study.

Since different PCIs have different meanings and play different roles in evaluating the capability of a statistical process, and C_p, C_{pk}, C_{pm}, and C_{pmk} cover all characteristics of a statistical process, we believe that new measures can be constructed using those PCIs to evaluate the traffic operational quality. As the first step, we have proposed a linear combination as the measure of the LOS index (LOSI) for traffic operational systems. Denoted as I_{LOS}, the measure is given as

$$I_{\mathrm{LOS}} = \alpha_1 C_p + \alpha_2 C_{pk} + \alpha_3 C_{pm} + \alpha_4 C_{pmk} \tag{15}$$

where $0 \le \alpha_i \le 1$, $i = 1, 2, 3, 4$, and $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$. Note that it is not necessary to have all four coefficients in LOSI formula, any but not all coefficients could be zero in actual applications.

It should be pointed out that the coefficients associated with each PCI in the LOSI equation can be determined by calibrating I_{LOS} to specified values empirically through sample data and other heuristic knowledge, as one can see from case studies provided in the next section.

IV. Testing and Evaluation

In the following applications, we have chosen the coefficients in (15) to be [0.1, 0.25, 0.3, 0.35] so that a value over 60% (i.e., 0.6) by I_{LOS} indicates a satisfactory LOS and a value

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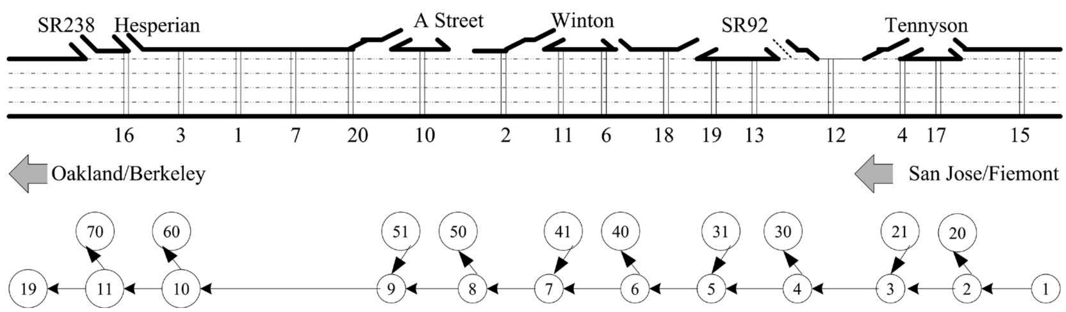

Fig. 2. I-880 North Freeway Network.

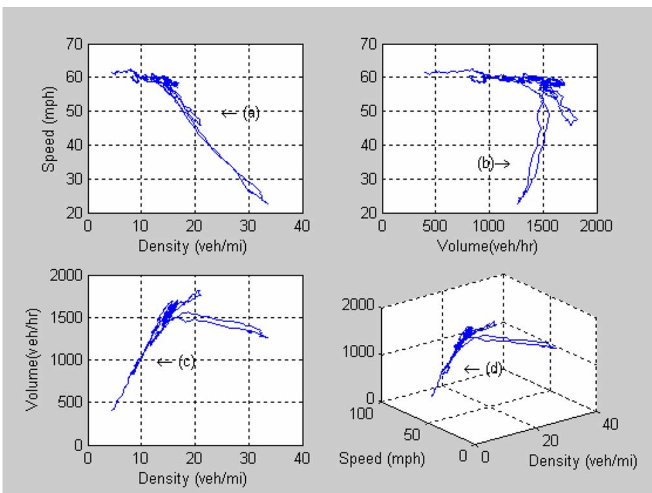

Fig. 3. Relationship among speed, density, and volume on Lane 2. (a) Density versus speed. (b) Volume versus speed. (c) Density versus volume. (d) Three-dimensional relationship among speed, density, and volume.

below 60% implies an unsatisfactory LOS for traffic operational systems. Here, Shewhart control charts are used to show the charts of traffic data under upper and lower limits. Measurements are plotted on the chart versus a time line and those that are outside the limits are considered to be out of control. The data beyond the specification limits are defined as outliers.

The data collected from the Freeway Service Patrol Project of UC Berkeley Path Program are used in this application. The data set was acquired from 16 detector stations on a 5.9-mi stretch of I-880 around Hayward, CA (see Fig. 2). Note that the left lane is a high-occupancy vehicle lane and Lane No. is arranged 1 to 4 from left to right. Traffic volume, speed, and occupancy data were generated from a 30-s output period. Particularly, the data sets collected from Lane 2 are used here.

Based on the discussion in the end of Section II, in order to validate the use of PCIs for the data collected, we need to preprocess them so that their distribution could be approximately a normal one. To this end, a data smooth method is used to change the original volume, speed, and occupancy data from a 30-s output period into traffic volume, speed, and density averages over a 12-min interval. As a result, the size of the sample data is reduced to 1295. Fig. 3 presents three-dimensional (3-D) relationships among traffic volume, speed, and density information on Lane 2 from the processed data. Obviously, they follow the corresponding patterns described in the traffic flow theory; see Fig. 1.

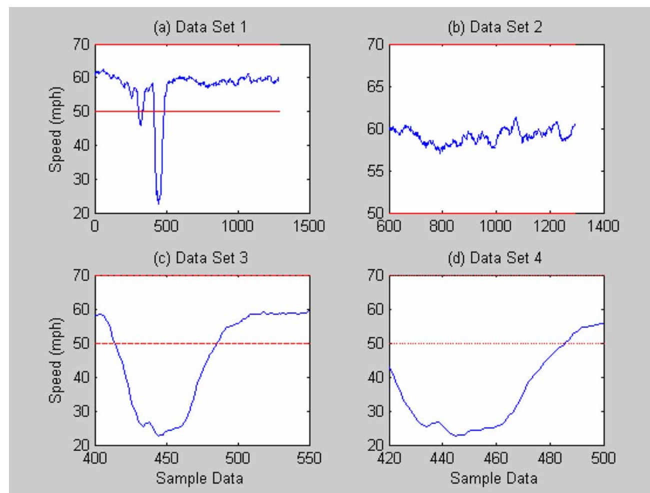

Fig. 4. Shewhart control chart for speed distribution on Lane 2.

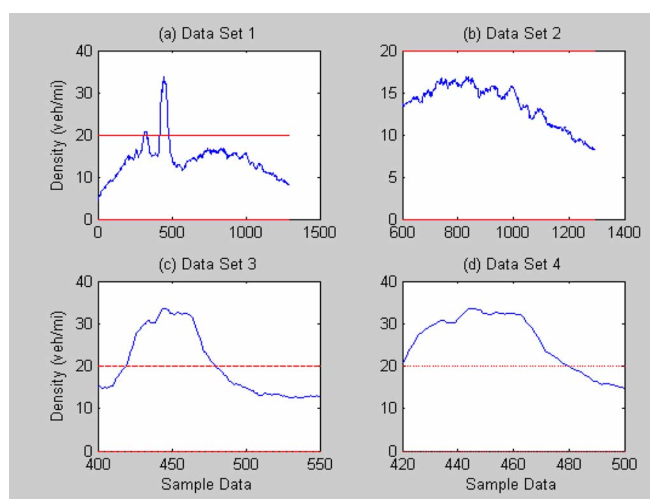

Fig. 5. Shewhart control chart for density distributions on Lane 2.

The curves in Fig. 3 indicate that the traffic process contains both uncongested and congested traffic flow conditions (however, no incidents involved). Based on those curves, different specification limits for different traffic flow parameters are used in this case study [2], [5], [6]. For speed, the upper limit is 70 mi/h, and the lower is 50 mi/h; for density, the upper is 20 vehicles/mi/ln, while the lower is zero; for volume, the upper is 1900 vehicles/h, and the lower is zero.

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TABLE I
PCIs AND LOSI UNDER DIFFERENT TRAFFIC FLOW CONDITIONS ON LANE 2

TV	DS	SM($\overline{X}$)	SSD(S)	RO(%)	C_p	C_{pk}	C_{pm}	C_{pmk}	I_{LOS}	LOS
v	1	57.138	6.725	7.64	0.7435	0.3538	0.4833	0.2300	0.3883	-
	2	59.0916	0.8447	0	3.9460	3.5875	2.6871	2.4430	2.9526	-
	3	45.5905	13.8329	47.68	0.2410	-0.1063	0.1669	-0.0736	0.0218	-
	4	35.6646	11.5672	81.48	0.2882	-0.4131	0.1237	-0.1773	-0.0994	-
k	1	14.0819	4.5049	5.95	0.7399	0.4379	0.5483	0.3245	0.4615	B
	2	13.5444	2.4435	0	1.3642	0. 8807	0.7743	0.4999	0.7638	B
	3	20.3579	7.6092	40.40	0.4381	-0.0157	0.2594	-0.0093	0.1144	C
	4	25.7838	6.4317	74.07	0.5183	-0.2998	0.1956	-0.1131	-0.0040	D
q	1	1353.9	282.1423	0	1.1224	0.6452	0.6427	0.3694	0.5956	-
	2	1397.2	245.2348	0	1.2913	0.6834	0.6209	0.3286	0.6013	-
	3	1380.3	96.9585	0	3.2660	1.7867	0.7179	0.3927	1.1261	-
	4	1399.4	92.3001	0	3.4308	1.8079	0.6902	0.3637	1.1294	-

TABLE II
LOS CRITERIA FOR BASIC FREEWAY

Estimated Free-Flow Speeds	70km/h					
LOS	A	B	C	D	E	F
Maximum Density (veh/mi/h)	<=10	<=16	<=24	<=32	<=43.6	>43.6

Based on those specification limits, Shewhart control charts for speed and density can be plotted. In order to compare PCIs values at different sampling periods, the sample data are divided into four sets, i.e., Data Sets 1 to 4, covering data from 1 to 1295, 600 to 1295, 400 to 550, and 420 to 500, respectively. (Note that those numbers are actually the serial numbers of sampling data according to their sampling times.) Figs. 4 and 5 shows the corresponding Shewhart control charts for the speed and density sample data of Lane 2. As one can see from those plots, outliers concentrate between 420 and 500 sample points, and the data from 600 to 1295 indicate a uncongested traffic condition. PCIs and LOSI under different data sets are summarized in Table I, where DS represents data set number. Table II is an LOS criteria for the basic freeway.

Table I indicates that in this case study, the values of LOSI and other PCIs decrease as the ratio of outliers (RO) to normal points increases. It is also found that I_{LOS} from traffic speed and density data can correctly reflect the real states of traffic flows, while I_{LOS} calculated from traffic volumes is not valid. For example, when $\mathrm{DS} = 2$ in Table I, the traffic flow is in a uncongested condition; however, I_{LOS} calculated from the volume data set is close to the minimum. Furthermore, the traffic condition for $\mathrm{DS} = 4$ is the worst, but its LOSI is the highest. Obviously, these two indications are far from the actual states of the traffic flow conditions.

As discussed earlier in the previous section, traffic volume is not a valid measure for evaluating the traffic operational capability since the state of traffic flow cannot be uniquely determined from traffic volumes, as one can see easily from either Figs. 1(b) or 3(b). Therefore, we will not consider volume data in the further discussion in this paper.

Numerical results in Table I show that LOSI is over 60% (larger than 2.9526 for speeds or 0.7638 for densities) when the traffic flow is in a uncongested condition (see $\mathrm{DS} = 2$) and less than 60% when the traffic flow is congested (see $\mathrm{DS} = 1, 3,$ and 4). This is due to our particular selection [0.1, 0.25, 0.3, 0.35] for PCI coefficients, but it demonstrates the feasibility of using PCIs for traffic LOS evaluation. Also note that it is not necessary to have $C_{pk} > 1.33$ or $C_p > 1.67$ for satisfactory traffic flows.

According to the LOS criteria for basic freeways on density, we find that the same LOS corresponds to a large range of LOSI, as one can see from Table II. Further investigation on the meaning, significance, and statistical characteristics of LOSI in traffic flow evaluation could be an interesting topic for future study.

V. CONCLUSION

In this paper, a new measure for traffic services, i.e., traffic LOSI, has been proposed to evaluate the traffic operational capability based on PCIs introduced in statistical process control.

Based on the case study described above, the following observations and remarks can be made.

1) LOSIs based on traffic speeds and densities can correctly reflect the capability of traffic process, while LOSIs based on traffic volumes are not valid for this purpose.
2) It is observed that the higher RO, the lower the LOSI, and vice versa.
3) Compared with the empirical values observed in other conventional applications, it is not necessary to have $C_{pk} > 1.33$ or $C_p > 1.67$ for satisfactory traffic flows.
4) The same LOS can correspond to a relatively large range of LOSI.

Compared with the conventional approaches used to classify six LOSs defined by the Highway Capacity Manual, it is obvious that LOSI could contain more statistical information on a traffic operational process due to the unique characteristics of PCIs. Initial case studies have indicated that LOSI is a reliable and an effective measure to describe the LOS for traffic operational systems under various situations. However, more case studies and extensive field investigations must be conducted before a practical measure for the LOS for traffic systems can be established. Issues regarding the effects of different

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PCIs on traffic flow and the selection of their corresponding weighing factors in the calculation of LOSI also require more studies.

Furthermore, while LOSI can be used to distinguish between uncongested and congested traffic conditions, it offers no help to separate traffic congestions caused by normal traffic activities or traffic incidents.

For future works, applications of multivariate PCIs in traffic flow and the use of LOSI for traffic incident detection are possible directions, along with combining rule-based service evaluation and agent-based real-time implementation for large transportation networks and complicated traffic situations.

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