A New Measure for Evaluating Level of Service for Traffic Operational Systems

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***Abstract* — This paper proposes a new measure to evaluate level of service for traffic operation based on the process capability indices (PCIs). A brief introduction to the concepts of PCIs and the characteristics of traffic flow is presented and followed by a discussion on the appropriateness of applying PCIs to measure the quality of traffic flow. Several case studies have conducted to investigate the effectiveness of the proposed new measure for traffic LOS and the results indicate that the speed and density are the most appropriate parameters for this purpose. The paper concludes with directions for future works.**

***Index Terms* — Level of Service, Process Capability Indices, Highway Capacity, Traffic Flow, Mean, Variance.**

I. Introduction

FOR most traffic operational systems, the concept of level of service (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]. However, the most of measures currently used or proposed for LOS do not fully take the effects of statistical characteristics of traffic process into account [2]-[5].

Process capability indices (PCIs), as a process performance measure, 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 [6]-[10]. 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 [11]-[15]. Over 170 papers on PCIs have been published from 1993 to 2000 and cover a broad range of topics from theoretical mathematical issues to various practical process control applications. Normally, PCIs can be estimated from sample data and then used to judge the capability of a process by those estimates.

Traffic flow is a very complex process involving vehicles, roads, people, control signals, traffic managements 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 hi-technology in computer, communication and control. Clearly, studies on effective methods to assess the LOS for traffic systems would be one of interesting and important topics for transportation systems, particularly for advanced traffic management systems (ATMS) in the proposed architecture for intelligent transportation systems (ITS).

In this paper, we investigate the potential use of PCIs for measuring the LOS for traffic systems. The paper is organized as follows. A brief introduction to the traffic LOS and PCIs is given in Section 2, followed by a discussion on the effectiveness of applying PCIs to evaluate the traffic operational quality through a new measure. Several case studies are conducted in Section 4. Finally, it concludes with a brief summary and discussion on the future works in Section 5.

II. LOS and PCIs

A. Level of Service

Currently, there are two different LOSs proposed for traffic operation: intersection LOS and lane LOS. The first is defined in terms of delay time and the second can be determined through several different procedures. Here we focus on the lane LOS only. Six LOS levels, designated from A to F, are defined for the lane LOS, with A representing the best operating condition and F the worst. Each level of service represents a range of operating conditions and the driver's perception of those conditions [1]. 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 [4]:

- For urban street systems, the percentage of the free flow speed for through vehicles determines the LOS.
- For rural 2 lane highways, the percentage of time following a slower vehicle and average travel speed

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determine the LOS.

- For multilane highways, the density of traffic determines the LOS.
- For freeways, the speed, density, and flow rate determine the LOS.

Obviously, concrete measures must be provided to determine the specific levels of service in each individual cases.

B. Definitions of PCIs

Four popular PCIs are considered here [6][8]. Let U and L be the given upper and lower specification limits, respectively. Assume that the corresponding variable is X and its expected mean and standard deviation are μ and σ. Our discussion is limited to the situations where μ is always in the specification region, i.e. $L \le \mu \le U$.

Process Capability Index C_p:

In this case, the index is defined as,

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

which is generally called as process capability index (PCI). It involves only with the process standard deviation σ. Eq. (1) is for double-sided specifications. The indices for single-sided specifications are given in Eqs. (2) and (3).

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

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

Behavior Process Capability Index C_{pk}:

In this case, the index is defined as,

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

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

Taguchi Index C_{pm}:

In this case, the index is defined as,

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

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.

Hybrid Index C_{pmk}:

In this case, the index is defined as,

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

It is actually a combination of other three indices, which are C_p, C_{pk} and C_{pm} [6].

Since process capability indices 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: 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 [16][17].

C. Estimators of PCIs

The estimation of indices is needed for actual applications of PCIs. Since the sample mean $\overline{X}$ and variance S^2 are unbiased estimators of a process expected mean μ and variance σ^2 [18], the natural and most commonly used estimators of C_p, C_{pk}, C_{pm} and C_{pmk} are determined as follows:

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

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

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

$$\hat{C}_{pk} = \frac{d - |\overline{X} - M|}{3S} = \frac{\min\{U-\mu, \mu - L\}}{3S} = \min\{\hat{C}_{pl}, \hat{C}_{pu}\}, \quad (10)$$

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

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

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

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 [8][19]:

1) The process evaluated is statistical controllable.
2) The sample data follow a normal distribution.

It should be pointed out 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 [16]. Otherwise, we have to use non-normal capability indices to evaluate the capability of the process [20].

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 [18][21][22], when the sample size approaches a couple of dozens, the distribution of the average measure $\overline{X}$ is a nearly normal distribution, even though the parent distribution is not a normal one. Comparatively, traffic flow data reach easily a very large size in actual applications. Traffic flow is a slow process, its change needs a period of time, does not happen instantaneously [23][24]. Thus, sample data from a relatively long time period are normally used, and usually each datum from traffic sample data is an average value. If its sample size is large enough, we can assume that traffic flow data follow or approximate a normal distribution. In addition, the process of traffic flow is obviously statistical controllable [2][19][25]. As a consequence, we can safely assume that PCIs can be used to evaluate the process capability of traffic flow systems.

Three primary variables in traffic flow are speed, volume, and density. As usual, a linear equation is used to approximate the relationship between the speed and density of traffic flow on an uninterrupted traffic lane [2][3], see Fig. 1(a). Based on this, the relationship between the speed and volume, and that between the volume and density can be derived, as shown in Fig.1 (b) and (c).

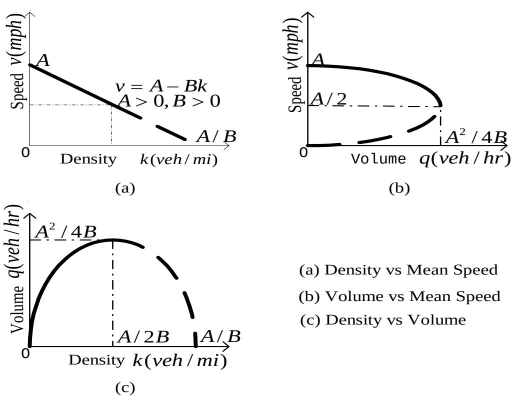


Fig.1: Relationships among Speed, Volume and Density

Based on those relationships, we can find the analytical equations among the speed, volume, and density as:

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

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

where v is the mean speed of vehicles (mph), q the average volume of one hour (veh/hr), k the average density of vehicles (veh/mi), and A, B are two empirically determined parameters.

From Fig.1, we find the jam density is equal to $A/2B$, the critical speed is $A/2$, and the maximum volume is $A^2/4B$. The solid lines in Fig.1 are called “free” traffic flow conditions while the dashed called “congested” or “forced” traffic flow conditions. Obviously, it is anticipated that the traffic system is operating under the traffic condition corresponding to the solid lines. Thus, specification limits of satisfactory traffic flows can be determined from the region indicated by the solid lines.

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 new measures can be constructed using those PCIs to evaluate the traffic operational quality. As the first step, we proposed a linear combination as the measure of the Level of Service Index (LOSI) for traffic operational systems. Denoted as I_{LOS}, the measure is given as,

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

where $0 \le \alpha_i \le 1$, $i = 1,2,3,4$ and $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$.

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

IV. CASE STUDIES

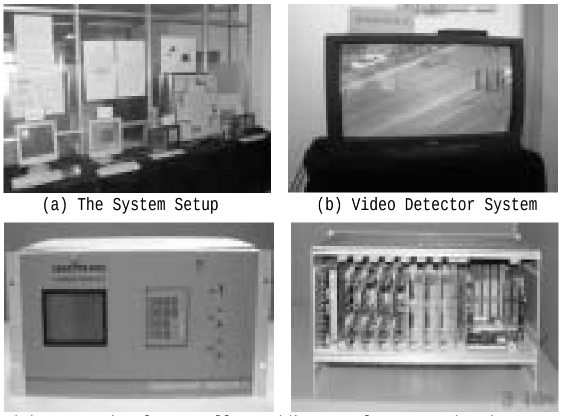
In the following case studies, we have chosen the coefficients in Eq. (15) to be [0.1, 0.25, 0.3, 0.35] so that a value over 60% (i.e., 0.6) by I_{LOS} indicating a satisfactory level of service and a value below 60% implying an unsatisfactory level of service for traffic operational systems.

A. Case One: Hardware-in-Loop Traffic Emulation

As the first case study, we use PCIs and LOSI to evaluate the traffic operational quality of the hardware-in-loop traffic emulation system at the CASIC Intelligent Transportation Systems Lab of the Key Laboratory of Complex Systems and Intelligence Science, Chinese Academy of Sciences. The traffic emulation system consists of a traffic simulation software, several CASIC intersection signal controllers, a video detector system that collects real traffic flow information from a 4-lane road in the front the CASIC ITS Lab and feeds the information to the controllers and the simulation software (see Fig. 2). Note that the traffic situation displayed in Fig. 2 (b) was the actual road traffic. Sample data were collected from a 60 second output period and used in our case study.

Sample speed data was used here. The lower and upper specification limits for speed are 20mph and 60mph, respectively. Fig. 3 shows the Shewhart plots for the sample speed distributions of Lanes 6, 4, 3 and 2, and based on the specified limits, ratios of outliers for those lanes are found to be 0%, 19.27%, 39.15% and 54.24% respectively. Table I summarizes sample mean (SM), sample standard deviation (SSD), ratio of outliers (RO) for speeds, different PCIs and LOSI for traffic variables (TV) on the different lanes (LN).

From Table I, it is very clear that the traffic operational quality I_{LOS} descends with the ratio of outliers increasing, and same can be observed for other PCIs. The traffic flow on Lane 6 is under a free flow condition with a LOSI at the level of 70%, indicating a satisfactory service, and the LOSIs for Lanes 2, 3 and 4 are less than 60%, implying unsatisfactory service since the flows on those lanes are in a congested condition.



(a) The System Setup (b) Video Detector System

(c) CASIC Singal Controller (d) Control & Communication Board

Fig.2: CASIC Hardware-in-Loop Traffic Emulation System

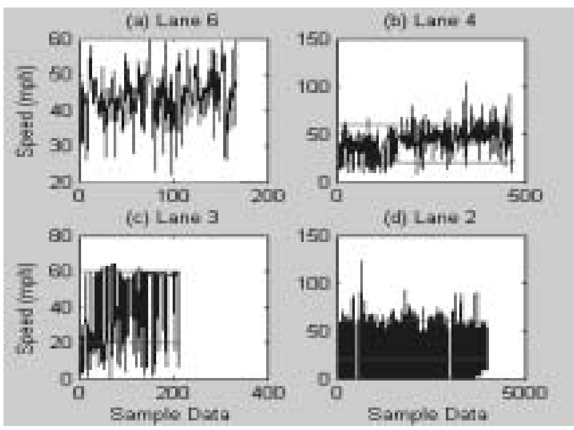


Fig. 3 : Shewhart Plots for Speed Distributions for Different Lanes

TABLE I: PCIS AND LOSI FOR DIFFERENT LANES

TV	LN	SM ($\bar{X}$)	SSD (S)	RO (%)	C_p	C_{pk}	C_{pm}	C_{pmk}	I_{LOS}
v	6	43.67	7.91	0	0.84	0.69	0.76	0.62	0.70
	4	43.17	14.85	19.27	0.45	0.38	0.44	0.37	0.40
	3	40.23	22.66	39.15	0.29	0.29	0.29	0.29	0.29
	2	25.52	24.00	54.24	0.28	0.08	0.24	0.07	0.14

B. *Case Two: Data from California I-880 Freeway*

The data collected from the Freeway Service Patrol Project of UC Berkeley Path Program are used in the second case study. The data set was acquired from 16 dector stations on a 5.9-mile stretch of I-880 around Hayward, California, see Fig. 4. Note that the left lane is a high occupancy vehicle lane. The traffic volume, speed and occupany data were generated from a 30 second output period. Particularly, the data sets collected from Lane 2 and Lane 3 are used here.

Based on the discussion in the end of Section 2, to valid the data collected for PCI computation, we need to process the data so that they approximate the normal distribution. To this end, a data smooth method is used to change the original volume, speed and occupancy data from a 30 second output period into traffic volume, speed and density with a 2 minute interval. As a result, the size of the sample data is reduced to 1315. Fig. 5 presents relationships among traffic volume, speed and density on Lane 2 from the modified data.

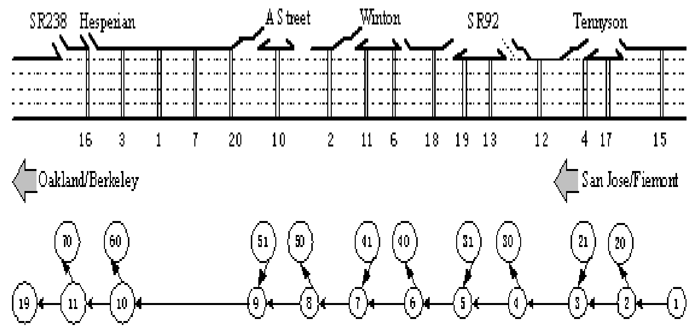
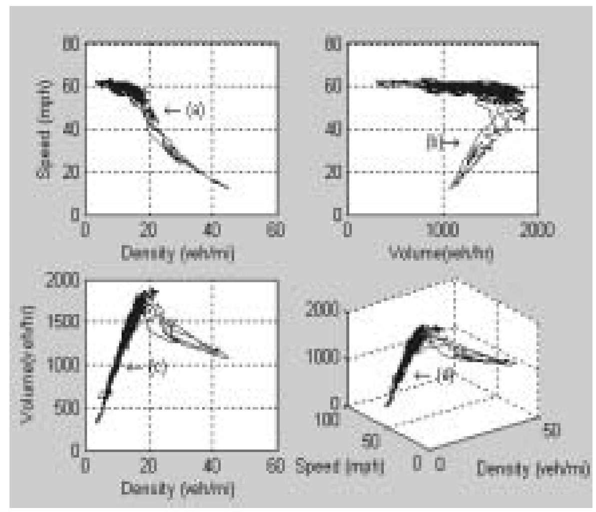


Fig. 4: I-880 North Freeway Network



(a) Density vs Speed; (b) Volume vs Speed; (c) Density vs Volume; (d) 3D Relationship among Speed, Density and Volume

Fig. 5: Relationship among Speed, Density and Volume on Lane 2

The curves in Fig. 5 indicate the traffic process contains both free and congested traffic flow conditions (no incidents involved). Based on those curves, different specification limits for different traffic flow parameters are used in this case study [4][5]. For speed, the upper is 80 mph and the lower is 50 mph; for density, the upper is 20 veh/mi, the lower is zero; for volume, the upper is 1900 veh/hr, lower is zero.

Based on those specification limits, Shewhart charts for speed and density can be plotted. In order to compare the PCIs values for different sampling periods, the sample data are divided into 4 sets, i.e., Data Sets 1 to 4, covering the data from 1 to 1315, 600 to 1315, 400 to 550, and 420 to 500, respectively, and Figs. 6 and 7 are the corresponding Shewhart plots 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 1315 indicate a free traffic condition. PCIs and LOSI under different data sets are summarized in Table II, where DS represents data set number.

From Table II, the LOSI and other PCIs also descend with the ratio of outliers increasing in this case study. In addition, it is 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 volume is not valid. For example, when DS=2 in Table II, the traffic flow is in a free condition, however, I_{LOS} calculated from the data set of volumes is close to the minimum. Obviously, this value is far off from the actual state of the traffic flow condition.

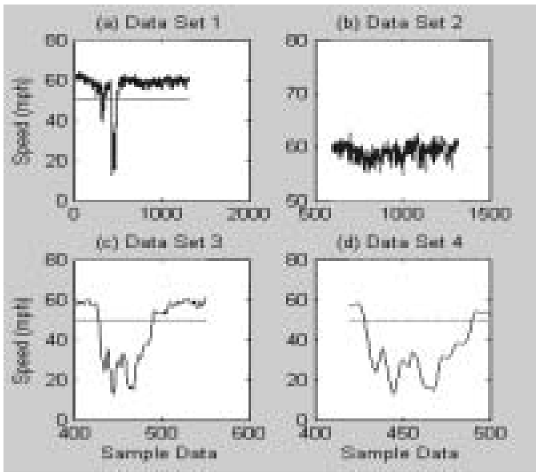


Fig. 6: Shewhart Plots for Speed Distribution on Lane 2

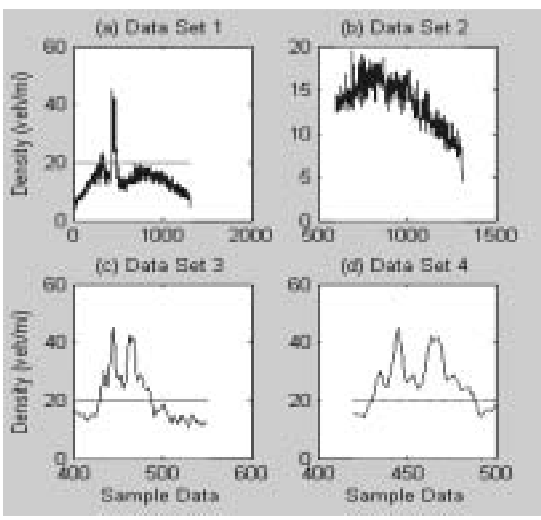


Fig. 7: Shewhart Plots for Density Distribution on Lane 2

Further investigation reveals that the reason why traffic volume is not a valid measure for evaluating the traffic operational capability: the state of traffic flow can not be uniquely determined from the traffic volumes, as one can see easily from both Fig. 1(b) and Fig. 5(b). Therefore, we will not consider the volume data in the further discussion here.

As before, the LOSI is equal to 1.30 or 0.72, over 60%, in DS=2 when the traffic flow is in a free condition, and still less than 60%, in DS=1, 3, and 4 when the traffic flow is congested

The same observation can be made from Table III, which presents PCIs and LOSI under different data sets for Lane 3. In this case the specification of upper and lower limits for speed, density, and volume are 80 to 50 mph, 30 to 0 veh/mi, and 2200 to 0 veh/hr, respectively.

TABLE II: PCIS AND LOSI UNDER DIFFERENT TRAFFIC FLOW CONDITIONS ON LANE 2

T V	D S	SM ($\bar{X}$)	SSD (S)	RO (%)	C_p	C_{pk}	C_{pm}	C_{pmk}	I_{LOS}
v	1	57.20	7.19	6.77	0.70	0.33	0.47	0.23	0.37
	2	59.13	1.45	0	3.46	2.10	0.83	0.50	1.30
	3	45.51	15.24	41.06	0.33	-0.10	0.20	-0.06	0.05
	4	34.88	13.62	76.54	0.37	-0.37	0.15	-0.15	-0.06
k	1	13.96	4.94	6.08	0.67	0.41	0.53	0.32	0.44
	2	13.45	2.73	0	1.22	0. 80	0.76	0.55	0.72
	3	20.51	8.70	37.73	0.38	-0.02	0.24	-0.01	0.10
	4	26.14	8.35	70.37	0.34	-0.25	0.18	-0.11	-0.06
q	1	1342.3	312.24	0	1.01	0.60	0.63	0.37	0.57
	2	1387.5	270.59	0	1.17	0.63	0.62	0.33	0.58
	3	1395.3	157.22	0	2.01	1.07	0.67	0.36	0.79
	4	1403.6	152.77	0	2.07	1.08	0.66	0.35	0.80

TABLE III: PCIS AND LOSI UNDER DIFFERENT TRAFFIC FLOW CONDITIONS ON LANE 3

T V	D S	SM ($\bar{X}$)	SSD (S)	RO (%)	C_p	C_{pk}	C_{pm}	C_{pmk}	I_{LOS}
v	1	55.10	7.39	8.14	0.68	0.23	0.40	0.14	0.30
	2	56.89	1.84	0.56	2.72	1.25	0.60	0.28	0.87
	3	42.98	15.45	48.34	0.32	-0.15	0.19	-0.09	0.02
	4	32.57	14.20	79.01	0.35	-0.41	0.14	-0.16	-0.08
k	1	19.29	6.53	4.41	0.77	0.55	0.64	0.46	0.57
	2	18.14	3.43	0	1.46	1.15	1.08	0.85	1.05
	3	28.42	12.03	33.77	0.42	0.04	0.28	0.03	0.15
	4	35.01	13.04	62.96	0.38	-0.13	0.21	-0.07	0.04

C. Case Three: A Simulated Traffic System with TSIS

Here we investigate PCIs and LOSI for traffic flow when incidents occur. To this end, traffic simulations with CORSIM software from the Traffic Software Integrated Systems (TSIS) are conducted. Fig. 8 is the traffic network simulated. An incident occurred on Lane 82 while the traffic flow conditions on Lanes 81 and 89 are free. The results of simulation and corresponding analysis are presented in Table IV. The sample size is 24. The specification of upper and lower limits for speed, density, and volume are 80 to 44 mph, 15 to 0 veh/mi, and 1200 to 0 veh/hr, respectively.

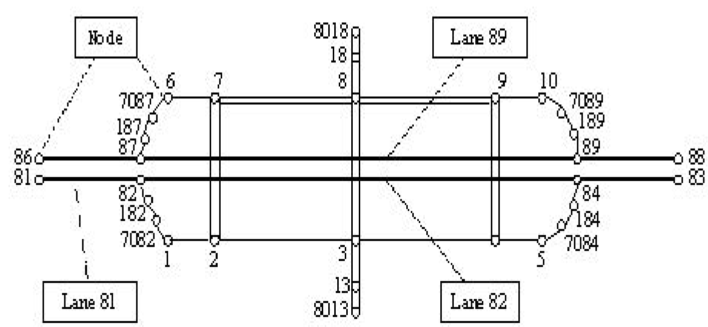


Fig. 8: A Simulated Traffic Network using CORSIM

From Table IV, the LOSI of Lane 82, where an incident occurs, is very small but the corresponding standard deviation is quite large, and contrary to this, LOSI of other Lanes are very large but the corresponding standard deviations are quite small. Again in this case, the LOSIs of all free traffic flows are much larger than 60%, reaching as high as 20.08, while the LOSI of the congested traffic flow is far less than 60%.

TABLE IV: PCIS AND LOSI FOR DIFFERENT LANES

TV	LN	SM ($\bar{X}$)	SSD (S)	RO (%)	C_p	C_{pk}	C_{pm}	C_{pmk}	I_{LOS}
v	82	38.22	15.08	70.83	0.40	-0.13	0. 20	-0.06	0.04
	81	63.40	0.11	0	53.69	49.51	3.74	3.45	20.08
	89	63.33	0.11	0	53.71	49.75	3.58	3.32	20.04
k	82	21.02	5.67	75.00	0.44	-0.35	0.17	-0.14	-0.04
	81	14.12	0.05	0	48.91	5.74	0.38	0.04	6.45
	89	12.32	0.10	0	24.57	8.78	0.52	0.19	4.87

D. Remarks and Observations

The following observations and remarks can be made based on the results of the three case studies described above:

1) LOSIs calculated based on traffic speeds and densities can correctly reflect the capability of traffic process, while LOSIs based on traffic volume are not valid for this purpose.

2) It is observed that the higher ratio of outliers is, the lower the LOSI is, and vice versa.

3) Compared with the empirical values observed in other conventional applications, it is not necessary for $C_{pk} > 1.33$ or $C_p > 1.67$ for satisfactory traffic flows.

Although, LOSI can be used to distinguish between the free and congested traffic conditions, however, one must remember that it offers no help to separate traffic congestions caused by normal traffic activities or traffic incidents.

V. CONCLUSIONS

In this paper a new measure, Traffic Level of Service Index (LOSI), has been proposed to evaluate the traffic operational capability based on process capability indices introduced in statistical process control.

Compared with the approaches used to classify six LOS in Section 2, it is obvious that LOSI contains more statistical information of traffic operational process due to the unique characteristics of PCIs. Initial experimental and simulation studies have indicated that LOSI is a reliable and an effective measure to describe the level of service for traffic operational systems under various situations. However, more case studies and extensive field investigations must be conducted before a practical measure for the level of service for traffic systems can be established. Issues regarding the effects of different PCIs on traffic flow and the selection of their corresponding weighing factors in the calculation of LOSI also require more studies.

For future works, applications of multivariate process capability indices in traffic flow and the use of LOSI for the 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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