EXAMINATION OF FUZZY NOTION OF LEVELS OF SERVICE: CASE OF FREEWAY TRAFFIC FLOW

Partha CHAKROBORTY
Graduate Student
University of Delaware
Newark - U.S.A.

Shinya KIKUCHI
Associate Proffessor
University of Delaware
Newark - U.S.A.

INTRODUCTION

The level of service is a qualitative measure of the conditions of traffic flow from the user's perspective. It is an important decision criterion for highway planning and improvement. Determining and interpreting the level of service, however, is difficult because of the vagueness embedded in the definition of the level of service which is a combination of different qualitative attributes (factors) of flow; in the driver's perception of the driving environment; and in the process of comparison with a "desirable" condition.

In this paper we present a procedure which utilizes the concept of fuzzy set and fuzzy measure in order to deal with the vagueness and uncertainty when determining the level of service.

1. REVIEW OF THE CONCEPT OF LEVEL OF SERVICE AND THE PROBLEM

The level of service (LOS) is a composite measure of traffic flow from the driver's perspective. It is described in the Highway Capacity Manual (HCM) [1] as a "*qualitative measure describing operational conditions within a traffic stream, and their perception by motorists and/or passengers. A level-of-service definition generally describes these conditions in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety.*" In the HCM, six level of service categories (A through F) are defined, based on the quality of flow evaluated through the factors as mentioned above. These factors are measured based on qualitative comparison with a "desired" condition, such as "*extremely high* freedom to maneuver," "*excellent* driving comfort," etc. Furthermore, it should be noted that, the "desired" condition in itself is vague.

The HCM qualifies that these definitions are "general and conceptual in nature." However, at the same time it uses a single measure of effectiveness, traffic density, to describe the quality of flow on a basic freeway section. It also states that "each level of service represents a range of conditions for which boundaries are established." Thus, in reality, each LOS category is defined by an exact range of values of traffic density.

The concept and definition of the level of service in the HCM can be characterized by the following:

1. Definition of each LOS category is conceptual and vague,
2. LOS is a measure based on the motorist's perception of different attributes of the flow conditions,
3. Each attribute of the flow condition is evaluated, relative to the ideal condition, by linguistic measures, for example, very good, good, and so forth.

Nevertheless, the boundary between two LOS categories is clearly defined based on traffic density. These characteristics raise two problems:

1. Since each level of service is defined in vague terms, one should be able to express a degree that a given traffic condition belongs to a particular LOS category: for example, "very good LOS(A)," "very poor LOS(A)," or "between LOS(A) and LOS(B)." These ratings within a given LOS cannot be captured by the present procedure.
2. LOS is meant to represent motorist's perception of different factors affecting the driving conditions. Thus, the use of a single measure of effectiveness (traffic density) to represent the driver's perception of the different factors is questionable. Furthermore the weights, or the levels of contribution of the different factors to a LOS category are not accounted for.

In summary, the present HCM procedure allows the original vague notion of level of service to become a specific measure of flow with clear boundaries. In addition, the notion of driver perceived traffic conditions is no longer retained due to the use of a single objective measure of traffic flow, namely, the traffic density.

2. THE PROPOSED APPROACH

We propose an approach which preserves the original definition of LOS. It recognizes that the level of service is a qualitative measure and its definition is vague. It also recognizes that the attributes of traffic flow are qualitative and that these are subjectively evaluated by the drivers. The proposed method differs from the HCM procedure in that it attempts to incorporate driver's perception of traffic flow as much as possible.

The method is a multicriteria evaluation process with each criterion known only vaguely. The method utilizes fuzzy sets and fuzzy measures to represent the vague notions. The degree that a given flow condition belongs to a LOS category is derived using fuzzy integrals. The concept of fuzzy integrals using fuzzy measures was proposed by Sugeno [2]. Fuzzy integrals are suited to obtain an aggregate performance measure, when the performance of each criterion is determined subjectively, and the existence of dependency among the criteria is not ruled out.

The proposed procedure consists of the following steps:

Step 1. Identify the criteria which determine the level of service,

Step 2. For each criterion define the linguistic qualifications, which match with a particular LOS category,

Step 3. Develop fuzzy sets representing the linguistic qualifications with its membership function defined on a measurable indicator of traffic flow,

Step 4. Given a traffic flow condition, with its measurable characteristic, its membership grades in each of the fuzzy sets defined in Step 3 is the measure of its performance.

Step 5. Using the performance measures of the relevant linguistic qualifications of each criterion, an aggregate measure of performance is derived using fuzzy integral,

Step 6. Repeat Steps 4 and 5 for different level of service categories.

This approach allows a given flow condition to be described in terms of degrees of belonging in different level of service categories. An example of an outcome may be that a given flow condition is represented by LOS(A) with a confidence level of 0.8 and in LOS(B) with 0.3.

3. THE PROPOSED PROCEDURE

This section describes the proposed method step-by-step. It should be noted that this presentation is conceptual and it is meant to show the procedure only.

Step 1: Select Criteria Which Determine the Level of Service

This step identifies the attributes of the quality of flow. These include maneuverability, driver convenience, ability to select speed, and proximity to other vehicles.

Step 2: Establish Linguistic Qualifications for Each Criterion

This step establishes linguistic qualifications for each criterion. For example, the maneuverability criterion may be linguistically qualified into six categories: *very good* maneuverability; *good*; *restricted*; *very restricted*; *severely restricted*; and *no* maneuverability. These qualifications can be partially derived from the description of each LOS category in the Highway Capacity Manual [1].

Each level of service is a label (eg. "A," or "B") consisting of a string of different linguistic qualifications of different criteria. For example, LOS(A) is a label for traffic conditions in which maneuverability is *very good*, driving convenience is *very convenient*, freedom to select speed is *absolute freedom*, and proximity to other vehicles is *very far*. For each level of service the expected combination of linguistic qualifications is listed in Table 1.

Step 3: Develop Fuzzy Sets for Each Linguistic Qualification

A fuzzy set represents a vague notion and it is defined by a membership function. The membership grade indicates the degree that a given element is compatible with the notion. Each linguistic qualification is considered as a fuzzy set and its

Table 1: Expected Combination of Linguistic Qualifications for Different LOS Categories

LOS	Maneuver-ability (MAN)	Driving Convenience (CON)	Freedom to Sel. Spd. (SSP)	Proximity to Oth. Veh. (PRV)
LOS(A)	Very Good	Very convenient	Absolute freedom	Very far
LOS(B)	Good	Convenient	Free	Far
LOS(C)	Restricted	Less convenient	Constrained	More or less far
LOS(D)	Very Restricted	Inconvenient	More Constrained	Close
LOS(E)	Severely Restricted	Inconvenient	None	Very Close
LOS(F)	None	Inconvenient	None	Bumper-to -Bumper

membership function can be defined on values of a measurable characteristic of traffic flow. In this paper traffic density is used as the measurable characteristic of traffic flow according to the 1985 HCM.

Figures 1, 2, 3, and 4 show the membership functions of different linguistic qualifications for maneuverability, driving convenience, freedom to select speed, and proximity to other vehicles (as listed in Table 1), respectively. The following notation is used to represent the membership functions of the linguistic qualifications;

I. $h_{MAN(i)}(d)$: *maneuverability* for LOS(i), where $i \in \{A, B, C, D, E, F\}$
II. $h_{CON(i)}(d)$: *driving convenience* for LOS(i)
III. $h_{SSP(i)}(d)$: *freedom to select speed* for LOS(i)
IV. $h_{PRV(i)}(d)$: *proximity to other vehicles* for LOS(i)

where, d is the density of traffic flow.

Step 4: Determine Performance Measures

Given the density of traffic flow, its degree of membership in a particular fuzzy set is interpreted as the performance of the traffic flow in the corresponding linguistic qualification. For example, Figure 1 shows that when density is 14 vehicles per mile (14 vpm), the performance in *very good maneuverability* is 0.2, i.e., $h_{MAN(A)}(14) = 0.2$. In a similar manner, the performance of a given traffic condition is derived for all the linguistic qualifications.

Step 5: Determine an Aggregate Measure of Performance

Once the performance measures are determined for all the criteria, an aggregate measure of performance in the LOS category is developed using Sugeno's fuzzy

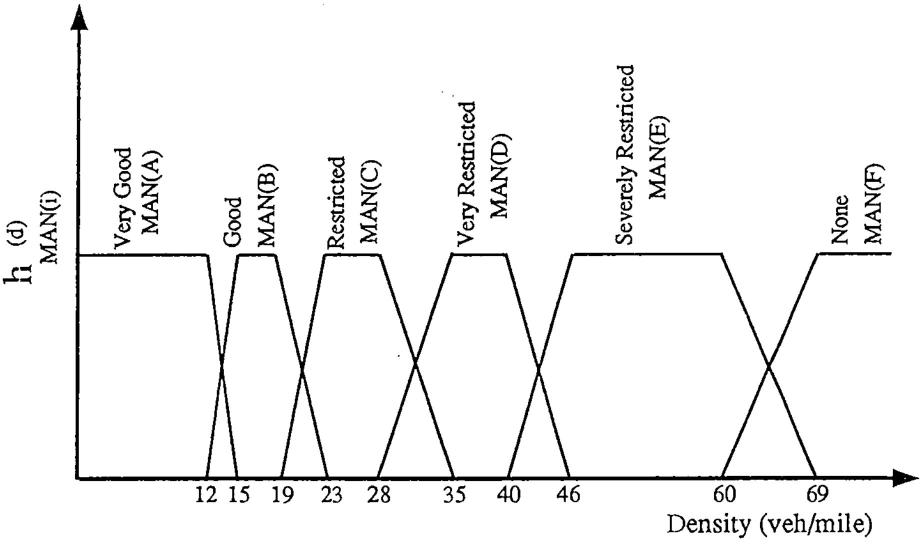

Figure 1. Definitions of the Categories of Maneuverability

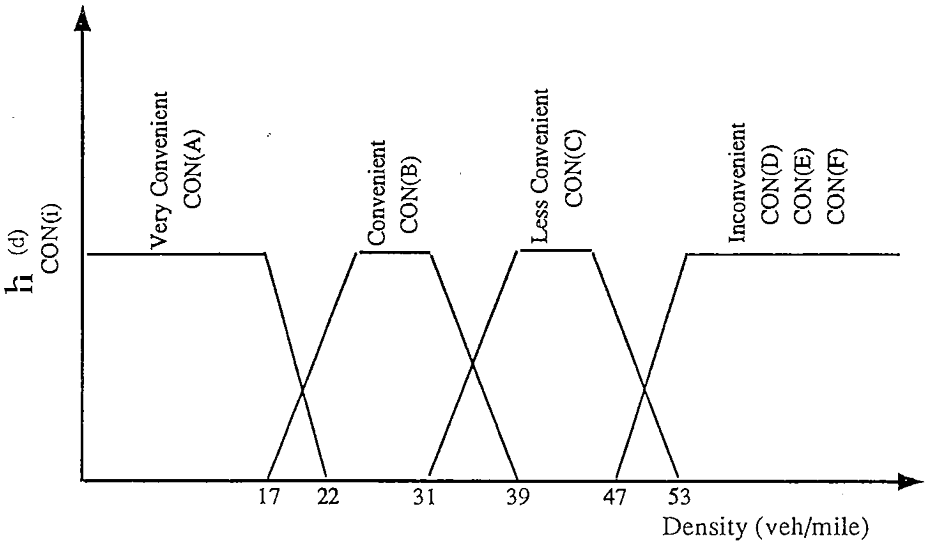

Figure 2. Definitions of the Categories of Driving Convenience

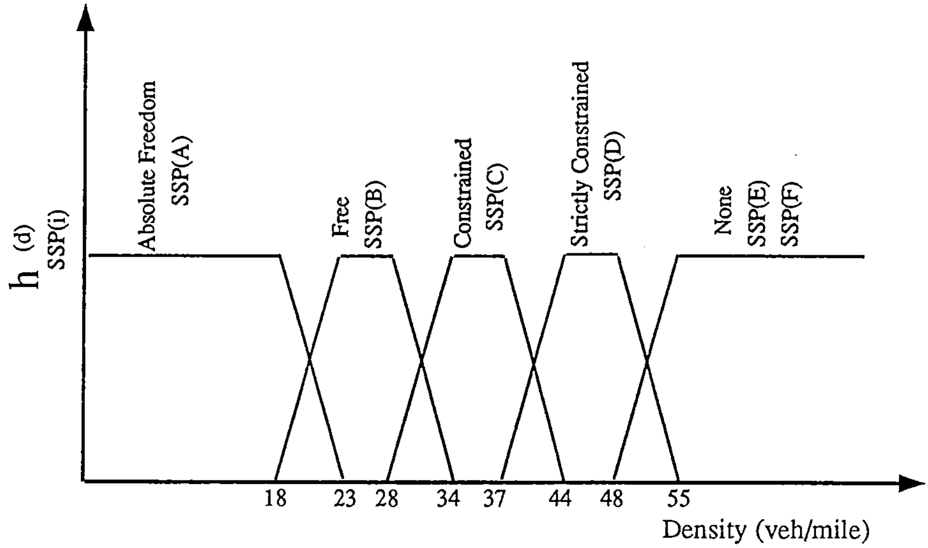

Figure 3. Definitions of the linguistic qualifications of freedom to select speed.

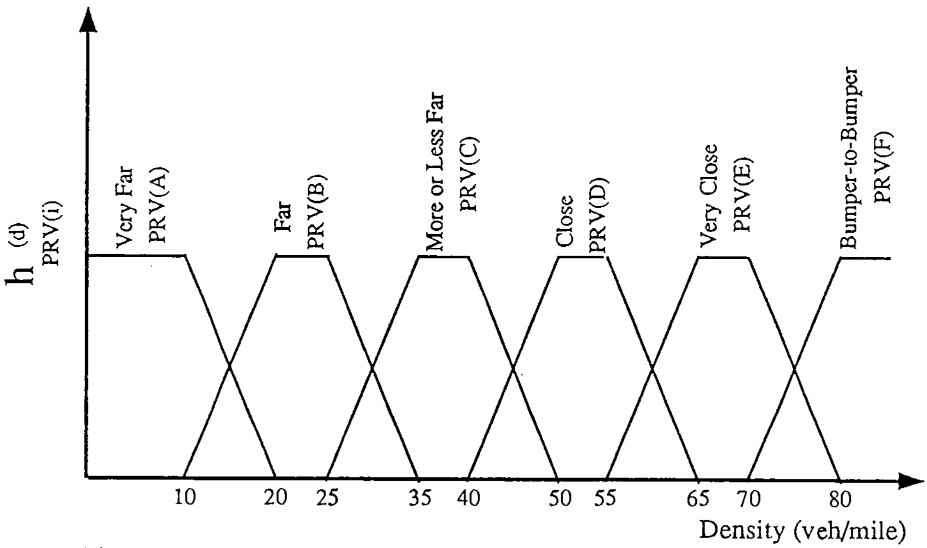

Figure 4. Definitions of the linguistic qualifications of proximity to other vehicles.

integral. As mentioned before, the fuzzy integral is a method for multi-criteria evaluation. It is used to evaluate the overall performance of a system (in this case the degree of belonging to a particular LOS) which has many attributes (in this case the linguistic qualifications of the criteria), each of which is weighed by a fuzzy measure. The use of fuzzy measures as the weights becomes essential when the utility derived from the attributes need not be mutually exclusive. In other words, the weights need not necessarily add up to unity; this is often referred to as the absence for perfect additivity.

If a system has n attributes and the performance of each attribute and the weight of each attribute is known, the overall evaluation of the system, according to fuzzy integral is

$$\max_j \min[h_j, g_j]$$

where, h_j is the performance measure for the attribute j such that,

$$h_1 \geq h_2 \geq \ \dots \ \geq h_n$$

and g_j is the cumulative weights of the attributes up to j. It is derived using,

$$g_j \ = \ g_{j-1} + w_j + \lambda g_{j-1} w_j$$

where, w_j is the weight of attribute j. λ is referred to as Sugeno's λ-measure. It functions as a modulator of the imperfect additivity of the weights. It lies in the range $(-1, \ \infty]$. The value may be derived from the boundary conditions of a fuzzy measure, which are

$$g_0 \ = \ 0$$
$$g_n \ = \ 1.$$

For a detailed explanation of Sugeno's fuzzy integral the readers are advised to refer to Dubois and Prade [3].

In the next section the process of evaluating the level of service has been further elaborated with the help of an example. For the purpose of exemplification, the weights were selected. These are,

$w(MAN) = 0.8$; $w(CON) = 0.6$; $w(SSP) = 0.5$; and $w(PRV) = 0.5$.

Note that $w(MAN)$ represents the weight of the criteria maneuverability. That is any of the linguistic qualifications of maneuverability carry the weight $w(MAN)$.

4. EXAMPLES

In this section a hypothetical example is presented in order to aid in the understanding of the process outlined above. Let us assume that traffic density on a given freeway section is 20 vpm. We shall now derive the confidence with which one can say, "it is LOS(A)."

The performance indices derived for $d = 20$ vpm (from Figures 1, 2, 3, and 4) and their weights are as follows:

$$h_{MAN(A)}(20) = 0 = h_4; \quad w_4 = w(MAN) = 0.8$$
$$h_{CON(A)}(20) = 0.4 = h_2; \quad w_2 = w(CON) = 0.6$$
$$h_{SSP(A)}(20) = 0.6 = h_1; \quad w_1 = w(SSP) = 0.5$$

$$h_{PRV(A)}(20) = 0.0 = h_3; \quad w_3 = w(PRV) = 0.5$$

We know,

$$g_0 = 0; \quad g_4 = 1$$
$$g_j = g_{j-1} + w_j + \lambda g_{j-1} w_j$$

From the above we can write,

$$\begin{aligned} g_1 &= 0.5 \\ g_2 &= 0.5 + 0.6 + \lambda 0.5 \times 0.6 \\ &= 1.1 + 0.3\lambda \\ g_3 &= (1.1 + 0.3\lambda) + 0.5 + \lambda(1.1 + 0.3\lambda)0.5 \\ &= 1.6 + 0.85\lambda + 0.15\lambda^2 \\ g_4 &= (1.6 + 0.85\lambda + 0.15\lambda^2) + 0.8 + \lambda(1.6 + 0.85\lambda + 0.15\lambda^2)0.8 \\ &= 2.4 + 2.13\lambda + 0.83\lambda^2 + 0.12\lambda^3 \end{aligned}$$

However, $g_4 = 1$. Therefore,

$$2.13\lambda + 0.83\lambda^2 + 0.12\lambda^3 = -1.4$$

Hence, $\lambda = -0.98$. Therefore,

$$g_1 = 0.5$$
$$g_2 = 0.806$$
$$g_3 = 0.911$$
$$g_4 = 1.0$$

Based on these values and the performance measures, Figure 5 is plotted. The aggregated performance measure is 0.55. Thus, it can be said that the current condition represents the notion of LOS(A) to a degree of 0.55 or, that the degree of confidence with which the given condition can be labeled LOS(A) is 0.55.

The next step is to see with what confidence one can say that "the same given condition is LOS(B)." The performance indices derived (from Figures 1, 2, 3, and 4) and their weights are as follows:

$$h_{MAN(B)}(20) = 0.75 = h_2; \quad w_2 = w(MAN) = 0.8$$
$$h_{CON(B)}(20) = 0.16 = h_4; \quad w_4 = w(CON) = 0.6$$
$$h_{SSP(B)}(20) = 0.4 = h_3; \quad w_3 = w(SSP) = 0.5$$
$$h_{PRV(B)}(20) = 1.0 = h_1; \quad w_1 = w(PRV) = 0.5$$

Obviously λ is the same, since it captures the dependence between the concepts of maneuverability, convenience, etc. However, the values of g_1, g_2, and g_3 are different (note $g_4 = 1.0$). These are,

$$g_1 = 0.5$$
$$g_2 = 0.902$$
$$g_3 = 0.911$$
$$g_4 = 1.0$$

Based on these values and the performance measures, Figure 6 is plotted. The aggregated performance measure is 0.82. Thus, it can be said that the current

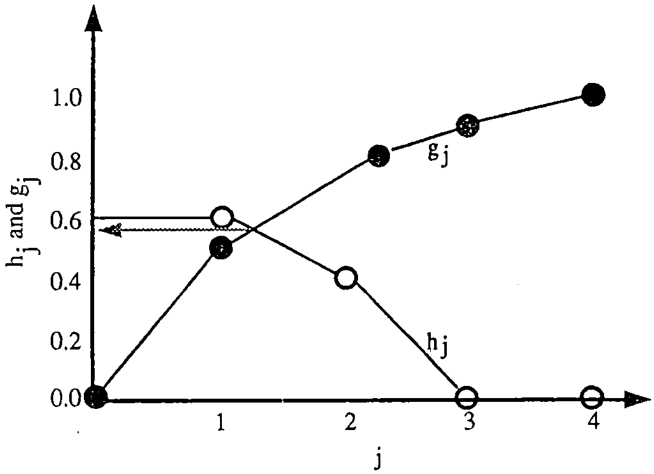

Figure 5: Determination of the aggregate measure of performance for LOS(A).

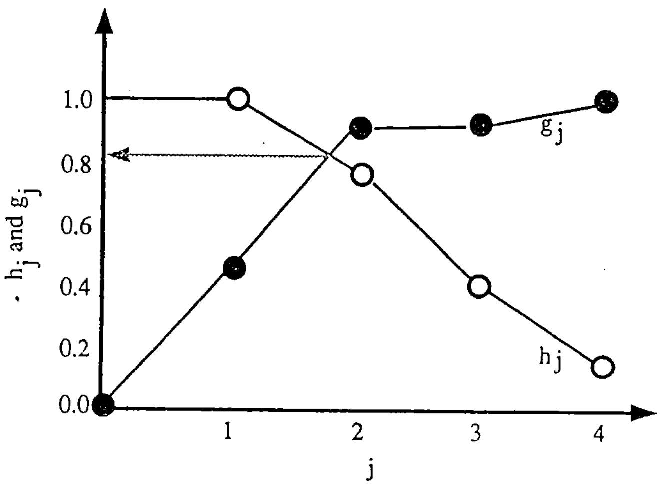

Figure 6: Determination of the aggregate measure of performance for LOS(B).

condition represents the notion of LOS(B) to a degree of 0.82 (as well as LOS(A) to a degree of 0.55) or, that the degree of confidence with which the given condition can be labeled LOS(B) is 0.82. This process should be continued for the other LOS categories.

5. CONCLUSION

This paper presents an approach which utilizes the theory of fuzzy sets and fuzzy measures to estimate the level of service of traffic flow. The approach models the vague notion of level of service. Two merits of this approach are, (1) it views the level of service as a driver perceived notion and incorporates driver's evaluation of the flow, and (2) it assigns degrees of confidence to the statement "the given condition is LOS(i)."

Though the approach holds promise as an alternative to the current LOS evaluation process, the procedure presented here is meant to be illustrative. In order to make it usable one must calibrate the membership functions of the fuzzy sets and identify the weights for the different criteria.

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