Quantitative Measuring Model and Variable Speed-limit Technology of Complicated Traffic Environment of Freeway

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ABSTRACT: Variable speed-limit for complicated traffic environment of freeway lacks quantitative rules and decision -making technology. This paper establishes comprehensive quantitative measuring & evaluating model, depending on the values of 7-factor indices (including: visibility, wind force, rainfall/snowfall, pavement icing/snow thickness, traffic level of service), employing the relation model of traffic 'flowrate-density-velocity' and the calculating model of vehicle's stopping-sight-distance & critical-skidding-equilibrium, incorporated with authentic technical standards, based on single-factor fuzzy measuring & evaluation, executes multi-factor comprehensive measuring & evaluation on the reasonable limiting-speeds subject to given complicated traffic environment, so as to present the quantitative rules and tactics of the variable speed-limit of freeway.

KEYWORD: Complicated Traffic Environment of Freeway; Quantitative Single/Multi-factor Measuring & Evaluating; Quantitative Rules for Variable Speed-limit; Flowrate-density-velocity Relation Model of Traffic Flow; Stopping Sight Distance; Sliding/Skidding.

1 INDUCTION

Complicated traffic environment elements (including: Fog, Haze, Sandstorm, Rain, Snow, Icing, Congestion, etc) endangering traffic safety of freeway, entail temporary speed-limit. Over/under-estimated limiting speeds cause unnecessary efficiency loss or under- lying safety hazard. Thus, quantitative measuring & evaluating model and variable speed-limit techno-logy for complicated traffic environment of freeway are in urgent needs to executes multi-factor compre- hensive measuring & evaluation on the reasonable limiting-speeds subject to given complicated traffic environment.

2 LITERATURE REVIEW

The existing relevant literatures on the speed-limit of freeway are categorized as follows: (1) Comprehensive safety evaluation for traffic environment, represented bytechnical standards [3,4], evaluates multiple environmental factors (and their quantitative indicators) by a certain gauge, mostly outputting qualitative safety-grades or comparisons which are basically disassociated from quantitative limiting-speed, lacks quantitativeness; (2) Quantitative analyses on the limiting-speed under different environmental circumstances, represented by literatures [5,6], mostly limited to single factor (such as Rainfall or Fog), lacks the comprehensiveness of multiple factors (especially the congestion factor); (3) Comprehensive-quantitative studies guided by statistical data-mining, represented by HDM-III[7], HSM[8], acquire the driving-speed statistic subject to multi-factor impacts, in the nature of the Approxima- tion/Fitting of the Statistically Central values of safe speeds (without accidents) of dangerous speeds (accident-triggering), not being the Critical Thresholds between the two types of speeds (Note: Limiting speeds equal just critical thresholds), thus restricted eventually.

The reasonable limiting speed need to be analyzed in both comprehensive and quantitative ways, releying on model-driven methodology more than data-driven one. Moreover, expert experience need to be restrained with prudence, avoiding subjective bias.
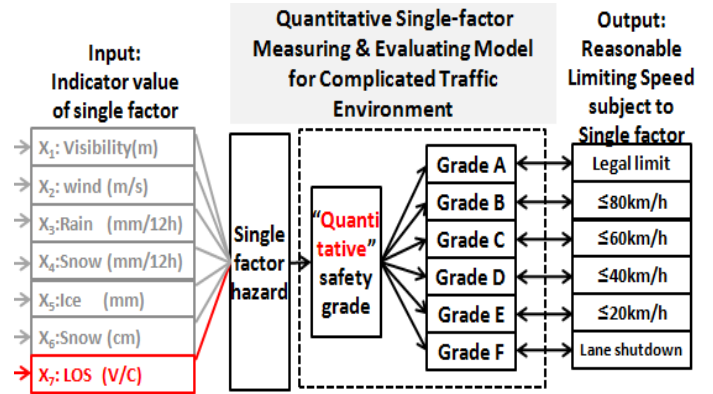
3 QUANTITATIVE SINGLE-FACTOR MEASURING & EVALUATING MODEL OF COMPLICATED TRAFFIC ENVIRONMENT AND SPEED-LIMIT TACTICS

The key to quantitative single-factor measuring & evaluation (model) is how to establish the

quantitative mapping rules of limiting speeds subject to the indicators' values of environmental factors. For sake of the feasibility of later comprehensive multi-factor evaluation by a certain gauge on multi-indicator with different dimensionalities, 6 safety-grades need to be introduced (into the model) equivalently bound with 6 graded limiting speeds respectively, as Fig.3-1-a, so as to enable both the quantitative analysis and the comprehensive evaluation.

In view of the observability, 7 factors are employed (Visibility, Wind velocity, Rainfall, Snowfall, Pavement Ice, Pavement Snow, Ratio of Volume to Capacity), with the quantitative indicators $\{x_i | i = 1, ... , 7\}$, where the V/C ratio implies 4 types of traffic-flow density[1] corresponding to 4 classes of Level of Service (LOS) of freeway. According to the grade differential of 10 or 20 km/h of design speed for freeway[1], limiting speeds is set

to 6 grades: Lane-shutdown, ≤20 km/h, ≤40 km/h, ≤60 km/h, ≤80km/h, Legal-limit (e.g. design speed or 85% percentile of practical speed [14]).

3-1-a "Quantitative Indicator x_i–Safety grades–Limiting Speeds" Modeling Design
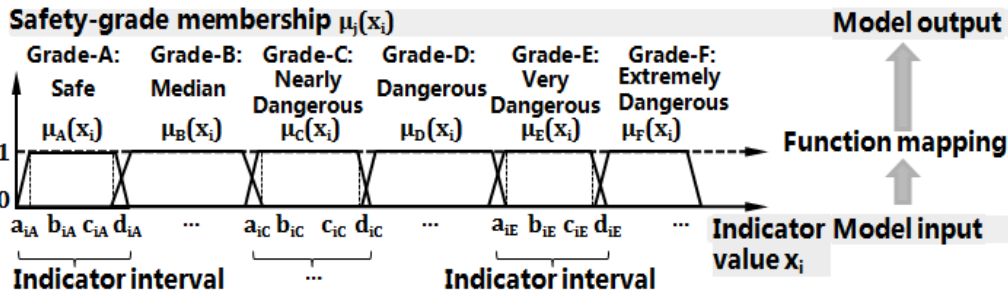
3-1-b Fuzzy Evaluation Membership Function $\mu_j(x_i)$ of Single-factor x_i (i=1,2, … ,7)

Fig.3-1 Quantitative Single-factor Measuring & Evaluating Model of Complicated Traffic Environment

"Fuzzy Evaluation"is selected as the method of single-factor measuring & evaluation, with the trapezoid-shaped membership function$\mu_j(x_i)$, where quantitative indicator x_i as the independent variables, $\mu_j(x_i)$ the membership degree of x_i belonging to jth safety-grade as the dependent variables, Grade $j \in \{$ A (Safe), B (Median), C (Nearly Dangerous), D (Dangerous), E(Very Dangerous), F(Extremely Dangerous)$\}$, $\mu_{ij} = (\mu_{iA}, \mu_{iB}, \mu_{iC}, \mu_{iD}, \mu_{iE}, \mu_{iF})$ for short as Fig.3-1-b and Formula 3-1. The key is how to calibrate the boundary thresholds of $a_{ij}, b_{ij}, c_{ij}, d_{ij}$ (i.e. to partition the indicator's intervals).

$$\mu_j(x_i) = \mu_{ij} = \begin{cases} 0 & , \quad x_i < a_{ij} \\ \frac{x_i - a_{ij}}{b_{ij} - a_{ij}} & , \quad a_{ij} \leq x_i < b_{ij} \\ 1 & , \quad b_{ij} \leq x_i < c_{ij} \\ \frac{d_{ij} - x_i}{d_{ij} - c_{ij}} & , \quad c_{ij} \leq x_i < d_{ij} \\ 0 & , \quad d_{ij} \leq x_i \end{cases} \quad (3-1)$$

$j \in \{A, B, C, D, E, F\}$

3.1 *Visibility Factor*

Vehicle's stopping sight distance (SSD) shall not exceed visible distance, therefore, the logical relation between limiting-speed (safety grade) and SSD and visible distance could be set as Fig.3-2.
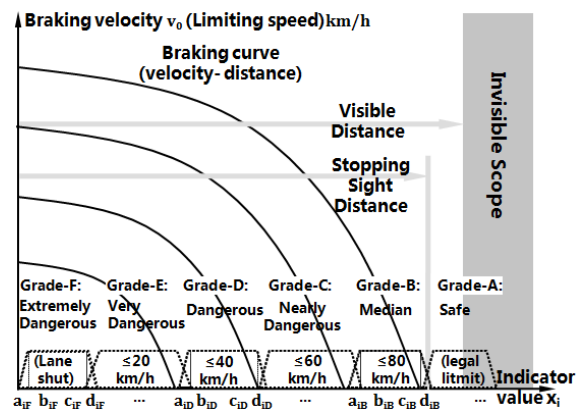

Fig.3-2 Relation of limiting-speed to visible distance

The 81st clause of the law[9] stipulates 3 graded limiting-speeds of 20/40/60 kmph subject to different visibility conditions. In view of the design speed of 80/100/120km/h, it's necessary to supplement 2 grades of speed-limit "≤80km/h" and "Lane-shutdown" , with the former to guarantee traffic safety and the latter to enhance traffic efficiency. The calculating model of SSD [1~2] (as Formula 3-2) could quantitatively indicate the mapping relation of 6 grades of limiting-speed

(safety grade) to 6 intervals of visibility (visible distance) respectively, as Tab.3-1 and Fig.3-3.

$$d_{ss} = \frac{v_0}{3.6}t_r + \frac{\left(\frac{v_0}{3.6}\right)^2}{2g(f+i)} + d_{safe} \qquad (3-2)$$

Where: d_{ss}(m) the stopping sight distance, v_0(km/h) the Braking (initiative)velocity, t_r(s) the Driver response time(assigned the norm value of 2.5s[1~2,22] corresponding to free/steady flow condition), d_{safe} equals 5~10(m), g=9.8m/s^2, f the longitudinal resistance coefficient between pavement(i.e. road surface) and tire to be assigned the downhill wet-pavement value of 0.25 according to technical standard [1,2] (Because of the inevitable correlation of visibility to wet weather elements including rain or snow), i the longitudinal gradient (i>0 if uphill, i<0 if downhill) to be assigned the most dangerous value of -3%.

Tab.3-1 Mapping relation of Limiting-speed to visibility

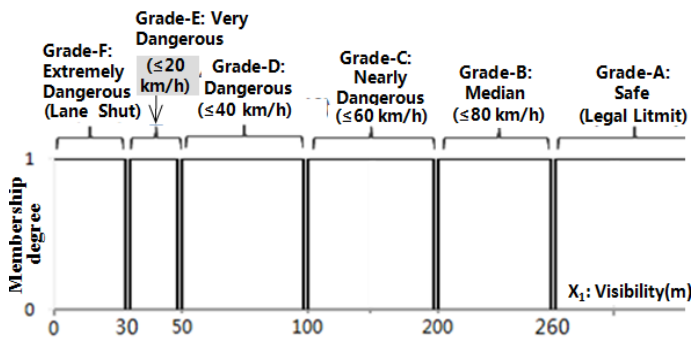| Braking speed km/h	Stopping sight distance m	Safe visible distance m	Indicator interval m
5	3.92 +5~10	10	0-30
10	8.73 +5~10	20	
20	21.05 +5~10	30	30-50
40	56.41 +5~10	50	50-100
60	106.09 +5~10	100	100-200
80	170.08 +5~10	200	200-260
90	207.44 +5~10	220	
100	248.39 +5~10	260	260 以上

Fig.3-3 Fuzzy membership function μ_{1j} of visibility x_1

3.2 Windforce (Wind speed) Factor

According to the traffic management measures against wind condition[11] and the definition of wind grades[15], the fuzzy membership function mapping relation of limiting-speed (safety grade) to windforce (wind speed) could be obtained as Tab.3-2 and Fig.3-4.

Tab.3-2 Mapping relation of Limiting-speed to wind speed

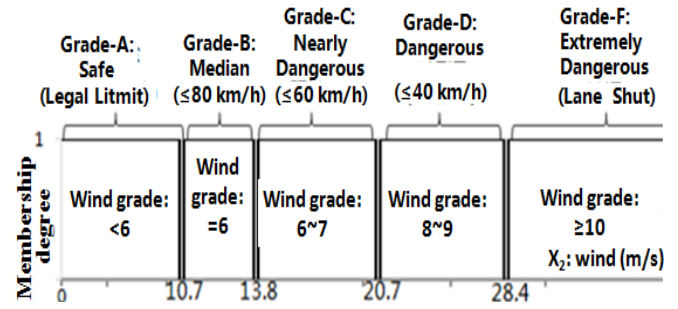| x_i (m/s)	[0, 10.7)	[10.7, 13.8)	[13.8, 20.7)	[20.7, 28.4)	≥28.4
Safety-grade	A	B	C	D	F

Fig.3-4 Fuzzy membership function μ_{2j} of wind force(wind speed) x_2

3.3 Precipitation-related Factors

3.3.1 Rainfall Factor

Railfall gives rise to water film on road surface, decreasing the resistance coefficient between pavement and tire, breaking vehicle's equilibrium between lateral resistance and centrifugal force, causing skid of vehicle. The calculating model of critical skidding-equilibrium of vehicle [1](as Formula 3-3), could answer the skid-avoiding limiting speeds.

$$v^2 \leq 127R(\varphi + \varepsilon) \qquad (3-3)$$

Where:R(m) the radius of vehicle turning path being smaller than road curvature in lane-changing or similar conditions(assigned to the value of 60m on basis of the minimal turing radius 6~20m of car/truck, and the minimal curve radius of 30~38m of highway intersection approach[13]); ε the super-elevation=0 representing the most dangerous horizontal pavement; as for φ the lateral resistance coefficient between pavement and tire, literatures [12,14] reveal the correlation between rainfall, water film thickness (WFT) and φ, as " The rainfall of 0.25mm/h could trigger WFT of 0.025~0.05mm in cases … cut 20%~30% off φ compared with the dry condition", with approximated/fitting equation is as Tab.3-3.

Tab.3-3 Approximated/Fit correlation between rainfall, WFT and φ

Rainfall (mm/12h)	Rainfall (mm/h)	WFT (mm)	φ
1.52	0.12	0.0254	0.8
3.04	0.25	0.0508	0.7
7.62	0.64	0.1270	0.475
15.24	1.27	0.2540	0.425
22.86	1.90	0.3810	0.382
30.48	2.54	0.5080	0.342
38.10	3.18	0.6350	0.321
45.72	3.81	0.7620	0.315
53.34	4.44	0.8890	0.301
Fitting equation: $\varphi=-0.14*\ln(WFT)+0.254$			

Embedding φ into Formula 3-3, leads to the limiting-speeds s.t. different rainfall, as Tab.3-4:

Tab.3-4 Mapping relation of Limiting-speed to rainfall

Rainfall (mm/12h)	10±0.1	70~100	160~185
φ	0.5±0.01	0.2±0.01	0.1±0.01
Limiting speed v(km/h)	61.72	39.04	27.60

In view of probable rainfall-observing time-lag deviation between practically observed indicator values during rain and final results after rain, it's necessary to combine the observed rainfall and forecasting one[16], expand the 3 intervals in Tab.3-4 to 4 intervals matching 4 grades of limiting-speeds, as Tab.3-5 and Fig.3-5.

Tab.3-5 Mapping relation of Limiting-speed to rainfall

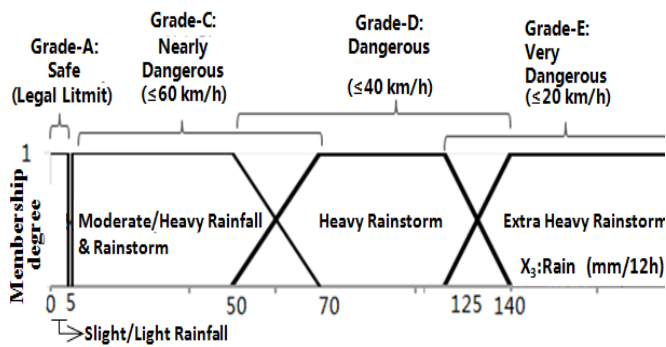| x_i (mm/12h)	[0, 5)	[5, 70)	[50, 140)	≥125
Safety grade	A	C	D	E

Fig.3-5 Fuzzy membership function μ_{3j} of rainfall x_3

3.3.2 Snowfall Factor

Refering to the modeling logic of rainfall factor, based on the definition of snowfall grades[16], the indicator values of snowfall could be categorized into 4 intervals (i.e. "Slight/Light snowfall", "Moderate/Heavy snowfall", "Blizzard", "Heavy/Extra Heavy Blizzard") matching 4 grades of limiting-speed (safety grade), as Tab.3-6 and Fig.3-6.

Tab.3-6 Mapping relation of Limiting-speed to snowfall

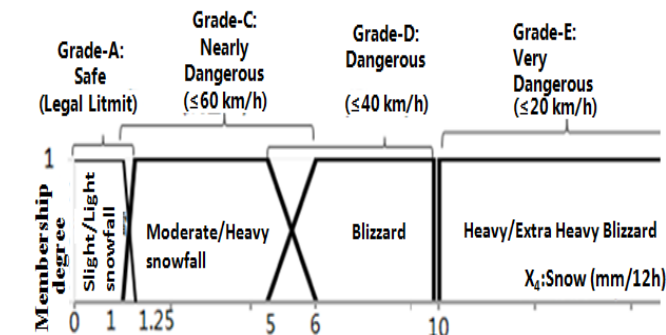| x_i (mm/12h)	[0, 1.25)	[1, 6)	[5, 10)	≥10
Safety grade	A	C	D	E

Fig.3-6 Fuzzy membership function μ_{4j} of snowfall x_4

3.3.3 Pavement Ice Thickness Factor

Based on the correlation of pavement resistance coefficient to pavement icing structure[17] and the test result[18] " The pavement texture depth of 0.2~1(mm) relate to pavement resistance coefficient of 0.6~0.2" and Formula 3-3, ice thickness could be categorized into 3 intervals matching 3 grades of limiting-speeds, with the modeling of fuzzy membership functions as Tab.3-7 and Fig.3-7.

Tab.3-7 Mapping relation of Limiting-speed to ice thickness

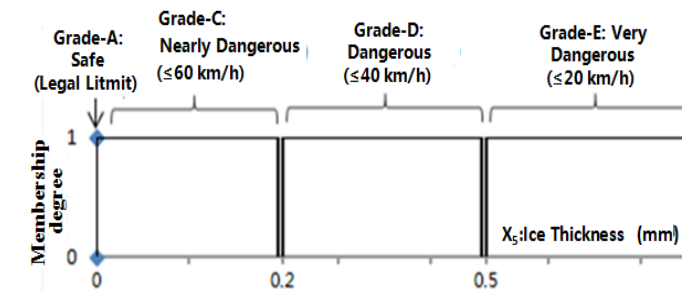| x_i (mm)	φ	limiting-speed	Safety-grade
0.0 <x_i<0.2	0.30~0.35	48~52 (km/h)	C
0.2≤x_i<0.5	0.15~0.25	34~44 (km/h)	D
x_i≥0.5	0.05~0.10	20~26 (km/h)	E

Fig.3-7 Fuzzy membership function μ_{5j} ice thickness x_5

3.3.4 Pavement Snow Thickness Factor

Based on the correlation between pavement snow depth and vehicle spacing(stopping sight distance) distribution[17,19], snow thickness could be categorized into 3 intervals matching 3 grades of limiting-speeds, with the modeling of fuzzy membership functions as Tab.3-8 and Fig.3-8.

Tab.3-8 Mapping relation of Limiting-speed to snow thickness

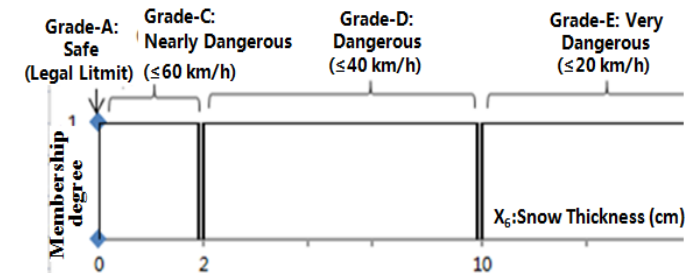| x_i (cm)	Safe spacing	Safe braking speed s.t. stopping sight distance	Safety grade
0 < x_i <2	>80m	60 (km/h)	C
2≤ x_i<10	80m	40~50 (km/h)	D
x_i≥10	20m	18~20 (km/h)	E

Fig.3-8 Fuzzy membership function μ_{6j} of snow thickness x_6

3.4 LOS (Ratio of V to C) Factor

Technical standard[1] defines 4 grades of freeway's level-of-Service(LOS). The minimal vehicle-spacing (corresponding to the maximal density) of

LOS-I equivalently being the maximal vehicle stopping-sight-distance of LOS-II, constrain the maximal speed of LOS-II etc, hence, the logical relation between limiting-speed (safety grade), stopping sight distance and V/C ratio could be set as Fig.3-9. The calculating model of vehicle's stopping-sight- distance[1~2](as Formula 3-2) could quantitatively indicate mapping relation of 6 grades of limiting- speed (safety grade) i.e. "0/20/40/60/80 kmph / legal-limit" to 6 intervals of V/C ratio(and time occupancy: o) respectively, with the fuzzy membership function as Tab.3-10 and Fig.3-10 (Design speed of freeway = 100km/h).
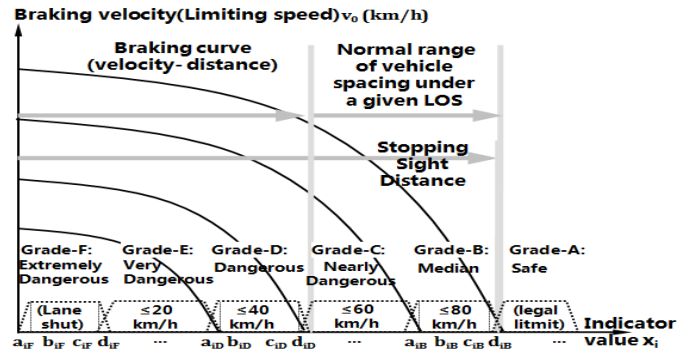

Fig.3-9 Relation of Limiting-speed to range of spacing

Tab.3-10 Mapping relation of Limiting-speed to V/C ratio(time occupancy)

V/C Ratio x_i (o)	[0, 0.86)	[0.86, 0.9)	[0.9, 1)	$x_i \geq 1$(o≤0.66)	$x_i \geq 1$(0.66<o≤0.9)	$x_i \geq 1$(0.9<o≤1.0)
Density (pcu/km/lane)	≤25	≤25	≤45	≤55	>55	>55
Safety grade	A	B	C	D	E	F

Notes: f the longitudinal resistance coefficient between pavement and tire to be assigned the downhill dry-pavement value of 0.9 according to technical standard [1,2] (In view of NO inevitable correlation existing between LOS to wet weather elements), i the longitudinal gradient to be assigned the most dangerous value of -3%, t_r(s) the Driver response time assigned the agile value of 1.0s[20] corresponding to non-steady/forced flow condition), dessity calibration is based on vehicle size as the upper limit value of light passenger car and the lower limit value of heavy cargo truck[10].
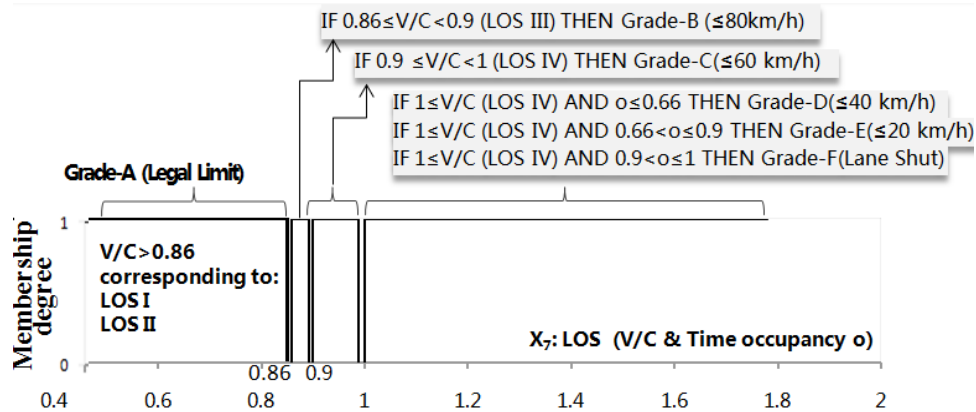

Fig.3-10 Fuzzy membership function μ_{7j} of LOS (V/C ratio) x_7

4 QUANTITATIVE MULTI-FACTOR MEASURING & EVALUATING MODEL OF COMPLICATED TRAFFIC ENVIRONMENT AND SPEED-LIMIT TACTICS

4.1 *Tactic for Measuring & Evaluation*

The quantitative single-factor evaluation of ith factor outputs a 6-dimension membership-degree vector $\mu_{ij} = (\mu_{iA} , \mu_{iB} , \mu_{iC} , \mu_{iD} , \mu_{iE} , \mu_{iF})$, called "Single-factor safety grade", 7 factors output seven 6 vectors comprising multi-factor membership-degree matrix $[\mu_{ij}] = \begin{bmatrix} \mu_{1j} \\ \mu_{2j} \\ ... \\ \mu_{7j} \end{bmatrix} = \begin{bmatrix} \mu_{1A} & \mu_{1B} & \cdots & \mu_{1F} \\ \mu_{2A} & \mu_{2B} & \cdots & \mu_{2F} \\ ... & ... & ... & ... \\ \mu_{7A} & \mu_{7B} & \cdots & \mu_{7F} \end{bmatrix}$.

The core of comprehensive quantitative multi-factor evaluation, is to assign 7 weights to 7 factors respectively, multiplying $[\mu_{ij}]$ by 7 weights, so as to incorporate 7 "Single-factor safety grade" into a "Multi-factor safety grade" $\mu_j = (\mu_A, \mu_B, \mu_C, \mu_D, \mu_E, \mu_F)$, as Fig.4-1and Formula 4-1. In condition of free-flow without rain/snow/wind, fog will push visibility factor's safety grade closer to "grade-F: Dxtremely Dangerous" than any other factor's.

Employing "Wooden Cask Effect Theory", visibility factor turns into the "Shortest Board" among 7 factors.The weight-assigning strategy of this paper is that the weight of shortest board factor(s) SHALL be 1 and the others be 0, i.e. multi-factor safe-grade equals the shortest board(s)'s.
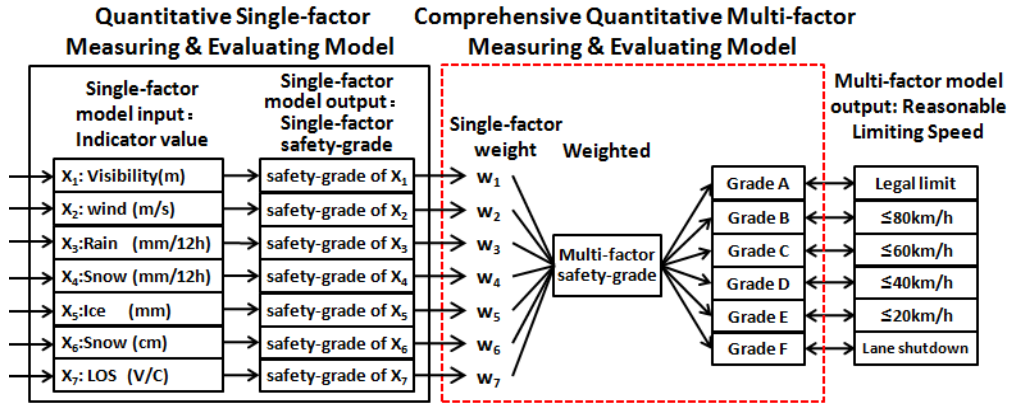
Fig.4-1 Comprehensive quantitative multi-factor measuring & evaluating model

$$\mu_j=(w_1, w_2, \ldots, w_7)*\begin{bmatrix}\mu_{1A} & \mu_{1B} & \cdots & \mu_{1F}\\ \mu_{2A} & \mu_{2B} & \cdots & \mu_{2F}\\ \ldots & \ldots & \ldots & \ldots\\ \mu_{7A} & \mu_{7B} & \cdots & \mu_{7F}\end{bmatrix}$$

$$=(\mu_A, \mu_B, \mu_C, \mu_D, \mu_E, \mu_F) \qquad (4\text{-}1)$$

Thus, the key to weight-assigning is how to identify the shortest board factor(s)'s safety-grade. Since the membership degrees of rainfall and snowfall might be either decimals (representing fuzzy safety-grade) or integer (0 or 1, representing deterministic safety-grade), whereas the membership degrees of all other factors are just integers, therefore the method of weight-assigning is classified into 2 categories, contingent on whether shortest board(s)'s safety-grade is deterministic or not, comprise the comprehensive quantitative multi-factor measuring & evaluating model.

4.2 *Method for Measuring & Evaluation*

4.2.1 *Situation of shortest-board being a member of deterministic grade (Membership degree=0 or 1)*

For example,

$$\begin{bmatrix}\mu_{1A} & \mu_{1B} & \cdots & \mu_{1F}\\ \mu_{2A} & \mu_{2B} & \cdots & \mu_{2F}\\ \ldots & \ldots & \ldots & \ldots\\ \mu_{7A} & \mu_{7B} & \cdots & \mu_{7F}\end{bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0.9 & 0.1 & 0 & 0\\ 0 & 0 & 0.2 & 0.8 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix},$$

shortest-board factor of visibility x_2 could be identified directly with its single-factor safety grade=D(Dangerous). Assigning the weight of 1 to visibility factor, Grade-D-matching limiting-speed of "≤40km/h" could be deduced.

4.2.2 *Situation of shortest-board being a member of fuzzy grade (0<Membership degree <1)*

When and only when rainfall x_3 and snowfall x_4 act as or <u>probably</u> act as shortest-boards simultaneously, moreover both of x_3 and x_4 belong to a fuzzy safety-grade, i.e. $0<\mu_{3j}<1$ and

$0<\mu_{4j}<1$ (j=C or D), for example $\begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.9 & 0.1 & 0 & 0\\ 0 & 0 & 0.2 & 0.8 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix},$ the shortest-board factor and its sinle-factor safety-grade could NOT be identified directly ($x_3\rightarrow$C / $x_4\rightarrow$D?). "Entropy Weighted Method" could be applied to: (1)Calculates the entropies of rainfall x_3 and snowfall x_4 respectively using formula of $e_i= -\sum_{j=A}^{F}\mu_{ij}*\ln(\mu_{ij})$, e_3=0.32 and e_4=0.50; (2) Entropy weithts w_i= 1-e_i(i=3 ,4) normalized as w_3^{**} = 0.58 and w_4^{**} =0.42; (3) $(w_3^{**}, w_4^{**})*\begin{bmatrix}\mu_{3A} & \mu_{3B} & \cdots & \mu_{3F}\\ \mu_{4A} & \mu_{4B} & \cdots & \mu_{4F}\end{bmatrix}$=[0.606,0.394], to obtain dual-fator membership degree of μ_C=0.606/ μ_D=0.394, which converts 2 fuzzy safety-grades into 1 deterministic one, so dimension-reducing

membership degree matrix = $\begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.606 & 0.394 & 0 & 0\\ 0 & 0 & 0.606 & 0.394 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix};$

(4) Identifing the shortest- board factor(s) for the second time, which are rainfall x_3, snowfall x_4, ice thickness x_5, LOS (V/C Ratio) x_7, assigning the weight(s) of 1 to the 4 factors (normalized $w_3^{**} = w_4^{**} = w_5^{**} = w_7^{**}$ =1/4=0.25), safety grade-C matching the limiting-speed of "≤60km/h" could finally be obtained.

5 CONCLUSION

The comprehensive quantitative measuring models for complicated traffic environment of freeway proposed by this paper, elaborate the **rationale** for variable speed-limit of freeway, theoretically and technologically support the R&D of relevant control system, with features as follows: (1) Comprehensiveness of the multi-factor model, embracing multiple factors of complicated traffic environment, also emphasizing the distinctive impact of shortest

-board factor(s), guarantees the reasonability and feasibility of the comprehensive outcome; (2) Quantitativeness of the single-factor/multi-factor models, produces the matching rules of reasonable limiting-speed subject to each and every factor, guarantees the maneuverability for the variable speed-limit of freeway.

6 ACKNOWLEDGEMENT

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