Proposal of a criterion for defining the levels of service in a quantitative way: the "service index"

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Synopsis

In this study a criterion able to define the traffic levels of service, not only qualitatively but also quantitatively, is proposed. Since 1950 (year of the Highway Capacity Manual first published edition) the traffic conditions have been synthetized in six levels of service that, when only considering some of the traffic influencing factors, turn out fundamental for the representation of a much more complex phenomenon.
The necessity of a quantitative representation of LOS remains undoubted in many models, where a numerical index would be more applicable; on the other hand, a numerical continuity of the same index would be more representative of reality, that changes punctually and not in discrete way. The search of an index that represents the road traffic levels and that varies from 0 (worst condition) to 1 (best condition) can be lead in several levels of complexities, described in the paper and improved and tested in future research.
The objective of the study is therefore the search of a function that allows to quantify the levels of service and to give them a continuous representation. It is chosen to be named "service index" the index variable from 0 to 1 representative of this function.

Proposal of a criterion for defining the levels of service in a quantitative way: the "service index"

The levels of service represent a powerful tool for planning and testing of the road sections. As already mentioned, they discretely render the complex phenomenon of traffic in a qualitative way, in fact their definition is: "A qualitative measure describing operational conditions within a traffic stream”.
The definition of six levels of service (from A to F) gives a discrete classification of traffic conditions, taking into account only some parameters like the rate flow, the speed (average speed for two lane highways, and free flow speed for multilane highways and for freeways), the traffic density and the road capacity. The factors that constitute the input of the methodology are modified by corrective coefficients counting road geometry, traffic composition and kind of users.
Only considering some of the parameters that influence the traffic conditions and considering their discrete subdivision in six intervals, the LOS methodology shows being an effective and direct method to describe the complex phenomenon of traffic. Nevertheless, in some practical fields [2], a numerical representation of the levels of service could make more useful "the output number", quantifying road and traffic conditions, because directly usable in solving problems algorithms connected to the road networks studies.
On the other hand, a methodology for the levels of service determination, considering not only the input parameters used by the HCM tool, but a greater number of parameters for better representing the complex phenomenon of traffic, would be still more effective. In this case the obtained information would be available also for planning, designing and testing of road infrastructures, let alone for monitoring of the system and measuring of the customers, managers or society’s satisfaction.
Within this study, three degrees of complexity for the assigning of the "service index" (*Xi*) 0-1 variable and referring to every network link "*i*", are proposed. In the first two degrees of complexity it is attempted to attribute a quantitative value to the HCM qualitative levels of service, through two different procedures. The third degree of complexity stays apart from the HCM classification and considers the service index equal to the GLS (Global Level of Service). The GLS is a methodology elaborated in the last years [1], [3], [4], [5], [6] able to quantify the road service considering 54 input parameters. It supplies, like output, various quantitative indices variable from the 0 to 1 and expresses the road level of service from various points of view.

THE SERVICE INDEX DEDUCTED FROM THE HCM LEVELS OF SERVICE

In the first two degrees of complexity it is attempted to make quantitative the HCM levels of service through two different procedures. The first one considers a discontinuous subdivision of the 0-1 interval; the second one assumes a continuous variation of the index, depending on the traffic density and considering the jam density as its limit value (to which value 0 of the index corresponds). These attempts of the interval subdivision could be confirmed or modified by the calibration process, ones of the future objects of the research.

First degree of complexity: discontinuous subdivision

At first level of complexity, the service index can be recognized by subdividing the 0-1 interval in as many equal parts as are the levels of service (A to F), obtaining the following allocation:

Tab. 1: First discontinuous subdivision of Service Index

Level of Service	Index
A	1.00
B	0.80
C	0.60
D	0.40
E	0.20
F	0.00

This one could only be one adoptable subdivision for planning level and only for freeways. In fact, the methodology would consider the optimal situation on which basing a road plan, in the prevailing traffic conditions chosen for the road and would not consider situations with the level of service F. In these cases, in fact, the methodology would give the value 0 to road segments with level F, not considering the situations in which traffic flows that are uninterrupted become interrupted. Therefore it could be useful to subdivide the

0-1 interval in the following way, giving the value zero to the index only in the case of complete interruption of traffic flow:

Tab. 2: Second discontinuous subdivision of Service Index

Level of Service	Index
A	0.95
B	0.80
C	0.65
D	0.50
E	0.35
F	0.20

This subdivision would be assigned a non zero index to the F level of service and would leave an upper-margin to the level "A" (0.95-1.00) justifiable for the presence of positive factors not normally considered in the levels of service calculation (ie. ITS technologies). However this ulterior rigid subdivision would not allow an effective comparison between link with different characteristics, since it attributes the same numerical value to links with the same level of service, but pertaining to different road categories. Therefore a level of greater complexity could be effective.

Second degree of complexity: continuous service index for freeways or multilane highways.

The subdivision of the 1-0 interval service index described previously, being a discrete type, goes away from a punctual and continuous representation of reality. At a second level of complexity, therefore, it has been attempted to subdivide the 1-0 interval in a continuous way, through the parameter on which the subdivision of the levels of service is based: the traffic density.

Before developing the argument it is necessary to make a consideration regarding the road capacity in the critical cases, next to the congestion, since they do not correspond to "the prevailing" situations. In fact, the capacity to which the road studies refer (variable from 2,400 to 2,250 pc/h/lane for freeways and from 2,200 to 1,900 pc/h/lane for highway, depending to free flow speed), is an experimental concept, since it is obtained from surveys in the prevailing conditions of road and of its pertinent traffic; with good weather, diurnal visibility, good state of the paving and absence of incidents. On the contrary, in a complete representation of reality viewpoint, the infrequent and anomalous conditions also have to be object of study. Situations like road incidents, network overloads, anomalous atmospheric events and exceptional situations leave out of consideration the conventional capacity value of the afferent link. For this purpose a different limit value of the traffic flow must be considered, different from the capacity of the prevailing flow conditions. This consideration contributes to the conclusion that the assignment of our index must leave apart from the value of "the conventional" capacity.

Theoretically, if all motor vehicles were rigidly connected (as train coaches) and therefore could proceed with a minimal separation among them and with the same speed, the lane capacity would be higher than 1,900-2,200 pc/h/lane and would correspond to a value of density higher than 28 pc/km/lane (HCM density limit between levels of service E and F). The maximum density value that is able to consider anomalous situations, would be just the jam density, which is the congestion density. Therefore, in order to make an example of the jam density calculation we proceed as follows, considering:

- average length of a road vehicle = 4.5 m
- average length of a heavy vehicle = 12.0 m
- average separation between two following vehicles = 1.0 m
- average composition of flow = 10.0% of heavy vehicles

the average length of a vehicle will then be equal to:

4.5 x 0.9 + 12 x 0.1 = 4.05 + 1.2 = 5.25 m

jam density = 1,000/(5.25 +1) = 160 pc/km/lane.

This maximum value will depend on the traffic composition and on the real average separation between two following vehicles. However, since it is not binding for the study, we assume it to be the maximum possible density. Theoretically, given this value, the capacity would vary in function of the average flow speed. For example, with a speed of 100 km/h the maximum lane capacity C would be equal to ($d \times v = C$):

160 pc/km/lane x 100 km/h = 16,000 pc/h/lane.

In theoretical conditions, (without accounting the mutual conditioning between the customers, assuming the same travel speed and assuming a separation of 1 mt between following vehicles succeeded), the capacity of a road section would be much higher than the one normally assumed. In the reality, similar values would never be verifiable: it is well known that the safety distance between two following vehicles increases remarkably to the increasing of the travel speed. However, in traffic congestion situations, the capacity drastically decreases but the density considerably increases, tending just to the saturation density, the jam density previously calculated, to which nearly null travel speeds correspond.

In order to determine indexes useful to our study, the traffic density seems to be the quantity that better can represent the reality. On the other hand it represents the fundamental element of the HCM classification.
The levels of service introduced by the HCM assign density limits for every level of service as follows:

Tab. 3: Maximum density of L.O.S. for basic freeways segment

Level of Service	Max. Density (pc/km/ln)
A	7
B	11
C	16
D	22
E	28
F	>28

As previously seen, considering congestion states, the maximum value of traffic density to consider is equal to the jam density that has been calculated to 160 pc/km/lane. Consequently, the scale to consider will be the one represented in the following figure:

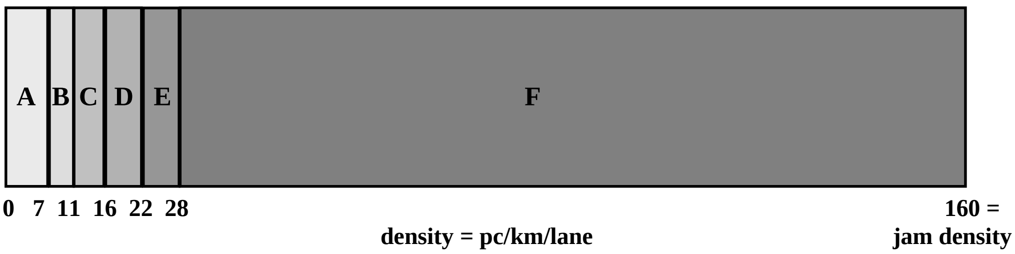

Figure 1: Correlation between traffic density and L.O.S. considering the jam density

Aiming at creating an index including between 0-1 interval and refering to density variabled from 0 to 160, a linear proportionality between the two intervals could be used obtaining the following results:

Tab. 4: First continuous subdivision of Service Index for basic freeways segment

L.O.S.	Density Interval (pc/km/ln)	Index Interval	Δ index
A	from 0 to 7	from 1.00000 to 0.95625	0.04375
B	from 7 to 11	from 0.95625 to 0.93120	0.02505
C	from 11 to 16	from 0.93120 to 0.89995	0.03125
D	from 16 to 22	from 0.89995 to 0.86245	0.03750
E	from 22 to 28	from 0.86245 to 0.82495	0.03750
F	from 28 to 160	from 0.82495 to 0.00000	0.82495

Aiming at following this methodology, the links with the level of service F, would have more than 82% of the index interval, reducing the variability of the other levels of service to less than 18% of the interval. For this reason, considering the traffic density like the discriminating factor for the service index determination and in order to have a more effective distribution of the intervals afferent to the six LOS, the speed-flow diagram has been considered. In this diagram the density is represented of the reciprocal of the angular factor of the straight lines outgoing from the origin, like the following figure shows:

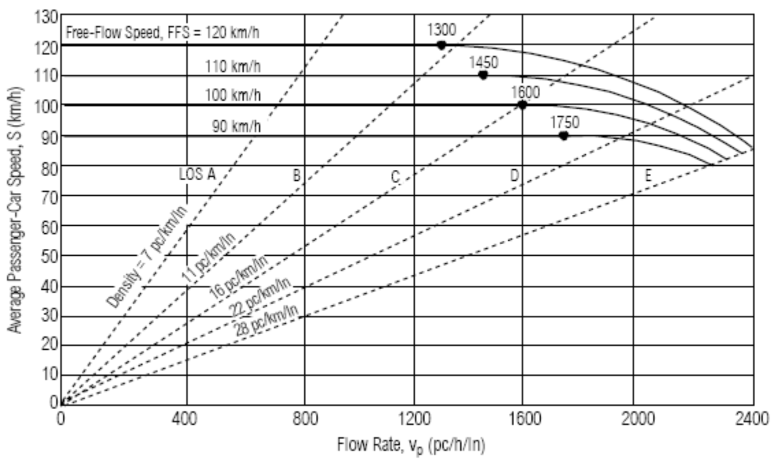

Figure 2: Speed-flow curves and L.O.S. for basic freeways segment

It could be noticed that the abscissa axis unit is expressed with one order rank higher compared to the ordinate axis unit. The straight line inclination afferent to d=11 pc/km/lane is approximately equal to 45°, while, in a uniform units diagram, it would be equal to approximately 5° (regarding the abscissa axis). The different scale of the two parameters (the flow Q and average speed V) allows to make the diagram more visible and, as is wanted for this study, to give wider intervals for every level of service. Therefore, in order to calculate the degree of several straight line inclination, the values of density will be divided by 10 before.
In order to place the density limit previously calculated (equal to 160), the slope of the limit straight line would have to be calculated. Under this slope, real situations would not still be possible and a value equal to zero would have to be given to the pertinent index.

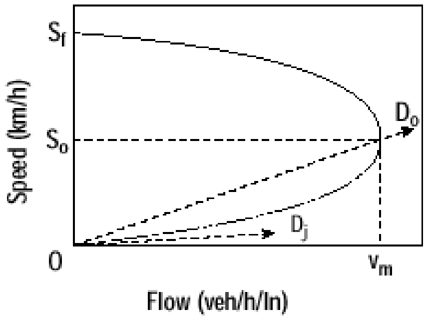

Figure 3: Speed-flow relation with traffic jam density straight line

The slope of the straight line pertinent to the calculated jam density is equal approximately to 3,57° in regard to the abscissa axis.
In the figure (for freeways LOS calculating) it can be noticed that the density represents the tangent of the angle below the straight lines outgoing from the origin in a diagram in which the ordinate values are expressed in terms of ten units and the abscissa values in terms of hundred units. Therefore, in order to obtain values comprised between 0 and 1 we consider the diagram like if it were uniform in ordinate and abscissa units (dividing the abscissa values by 10) and we calculate the degrees of straight line from the origin slopes, then we relate them to the interval 90-3,58°, equal to 86.42°, obtaining the competence intervals of every level of service in the total interval 0-1.

Tab. 5: 2nd continuous subdivision of Service Index for basic freeways segment (86.42° interval)

L.O.S.	Max density (pc/km/ln)	Degree Interval	Index Interval	Δindex
A	7	from 90.00 to 55.00	from 1.000 to 0.595	0.405
B	11	from 55.00 to 42.27	from 0.595 to 0.448	0.147
C	16	from 42.27 to 32.00	from 0.448 to 0.329	0.119
D	22	from 32.00 to 24.44	from 0.329 to 0.242	0.087
E	28	from 24.44 to 19.65	from 0.242 to 0.187	0.055
F	>28	from 19.65 to 3.58	from 0.187 to 0.000	0.187

Choosing to neglect last 3,57° (with traffic density higher to jam density and therefore not meaningful), we relate the degrees of straight line slopes to the entire interval 0-90° obtaining following results:

Tab. 6: 2nd continuous subdivision of Service Index for basic freeways segment (90.00° interval)

L.O.S.	Max density (pc/km/ln)	Degree Interval	Index Interval	Δindex
A	7	from 90.00 to 55.00	from 1.000 to 0.611	0.389
B	11	from 55.00 to 42.27	from 0.611 to 0.470	0.141
C	16	from 42.27 to 32.00	from 0.470 to 0.356	0.114
D	22	from 32.00 to 24.44	from 0.356 to 0.272	0.084
E	28	from 24.44 to 19.65	from 0.272 to 0.219	0.053
F	>28	from 19.65 to 0.00	from 0.219 to 0.000	0.219

For multilane highways (with non freeway characteristics) the density limit between E and F level of service changes in function of free flow speed of the link from 25 pc/km/lane related to VFL = 100km/h to 28 veic/km/corsia related to VFL = 70 km/h. In the following figure the HCM diagram is represented for this situation.

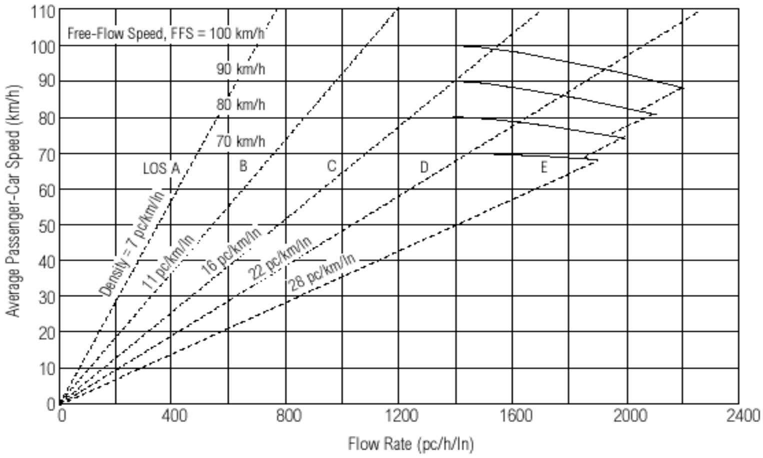

Figure 4: Speed-flow curves and L.O.S. for multilane highways segment

Consequently also the limit values of the service index vary in function of the different density limit. In the following table they have been calculated, considering all the interval 0-90.

Tab. 7: 2nd continuous subdivision of Service Index for multilane highways segment (90.00° interval)

L.O.S.		Max density (pc/km/ln)	Degree Interval	Index Interval	Δindex
A		7	from 90,00 to 55,00	from 1,000 to 0,611	0,389
B		11	from 55,00 to 42,27	from 0,611 to 0,470	0,141
C		16	from 42,27 to 32,00	from 0,470 to 0,356	0,114
D		22	from 32,00 to 24,44	from 0,356 to 0,272	0,084
E	FFS=100	25	from 24,44 to 21,80	from 0,272 to 0,243	0,029
F		>25	from 21,80 to 0,00	from 0,243 to 0,000	0,243
E	FFS= 90	26	from 24,44 to 21,03	from 0,272 to 0,234	0,038
F		>26	from 21,03 to 0,00	from 0.234 to 0,000	0,234
E	FFS= 80	27	from 24,44 to 20,32	from 0,272 to 0,226	0,046
F		>27	from 20,32 to 0,00	from 0,226 to 0,000	0,226
E	FFS= 70	28	from 24,44 to 19,65	from 0,272 to 0,219	0,053
F		>28	from 19,65 to 0,00	from 0,219 to 0,000	0,219

Considering the degrees interval devoid of the 3,75 degrees, the values exposed in next table are obtained:

Tab. 8: continuous subdivision of Service Index for multilane highways segment (86.42° interval)

L.O.S.		Max density (pc/km/ln)	Degree Interval	Index Interval	Δindex
A		7	from 90,00 to 55,00	from 1,000 to 0,595	0,405
B		11	from 55,00 to 42,27	from 0,595 to 0,448	0,147
C		16	from 42,27 to 32,00	from 0,448 to 0,329	0,119
D		22	from 32,00 to 24,44	from 0,329 to 0,242	0,087
E	FFS=100	25	from 24,44 to 21,80	from 0,242 to 0,211	0,031
F		>25	from 21,80 to 3,58	from 0,211 to 0,000	0,211
E	FFS= 90	26	from 24,44 to 21,03	from 0,242 to 0,202	0,040
F		>26	from 21,03 to 3,58	from 0.202 to 0,000	0,202
E	FFS= 80	27	from 24,44 to 20,32	from 0,242 to 0,194	0,048
F		>27	from 20,32 to 3,58	from 0,194 to 0,000	0,194
E	FFS= 70	28	from 24,44 to 19,65	from 0,242 to 0,187	0,055
F		>28	from 19,65 to 3,58	from 0,187 to 0,000	0,187

Following this methodology all the 0-1 interval is completely used and it is more representative of the reality.
In order to examine two lane highways, the specific HCM methodology for the levels of service determination refers to the percent time spent following (referring to the 3 seconds car-following criterion) and to the average travel speed. For this kind of highways, the reference capacity is 1700 pc/h/lane for every direction, while on large segments the total capacity for the two directions is 3200 pc/h/lane.
In order to take advantage of the flow/capacity ratio for the service index subdivision, a representation that would exclude non conventional cases and traffic congestions would be obtained, assigning 0 to the to the F level. However, knowing the average travel speed of a link (from the speeds diagram or from surveys carried out) and the level of afferent flow, it is always possible to obtain the density and therefore to return to the

previous methodology. For simplicity, waiting for further determinations, the same values about multilane highways could be assumed, until a specific study will establish the correct limits of density. In the next diagram, as an example, the result of a study carried out in United States is represented. It regards the correlation between traffic density, average travel speed and the afferent levels of service.

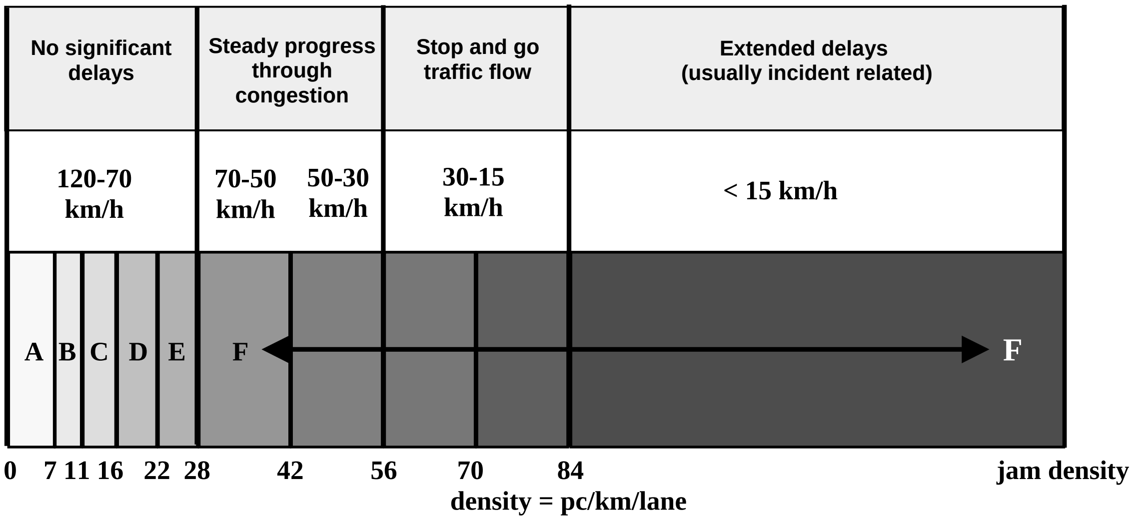

Figure 5: Correlation between traffic density, average travel speed and the afferent L.O.S.

In future applications we want to determine this graph correspondent to the Italian traffic, sure different from the one shown over for kind of vehicles, user attitudes and road characteristics.

Service Index for links in series – testing methodology

The methodology exposed until now is suited for searching the service index for a single link. How should one assign the service index afferent to an entire path?

Considering a path composed from links in series, the service index value will have to be included between 0-1 interval too, more exactly, between the limit values of the service indexes assigned to the path links. For this reason it is efficient to use a weighted mean, with weights given to every link, representing its minor or major influence in the whole path. The chosen weight is equal to the ratio between the single link length and its afferent path length:

$$\alpha_{ip} = \frac{l_i}{L_{percorso}} \qquad (1)$$

Where *i* is the link index and *p* is the path index. Therefore one link, if used in different paths, will assume different weights depending on these path lengths. Other discriminating factors could be used in order to carry out the weighted mean of the indexes, for example the average speed. However since this factor already is considered for the service index determination, it would mean considering it doubly in the methodology. Since the service index is representative of traffic conditions and road service (it represents a "photography" of the road service in a fixed moment) but since it is independent from the link length, the use of the weight α_{ip}, described previously, therefore seems simple and fit.

The single link length related to the whole path length can be used also in the calibration process described later on. The attempts described previously to subdivide the 1-0 interval, will serve just for a faster convergence of the calibration process. Therefore they have to be considered as the first step of an iterative process. Through the calibration, this process can carry out a valid subdivision of the 1-0 interval strengthened not only from a theoretical point of view but also from practical applications.

For the proposed calibration process, two links in series are considered with lengths equal to L1 and L2; supposed the afferent levels of service are well-known and from the same ones it is possible to go up to their service indexes (X1 = f (LOS1) and X2 = f (LOS2)). For determining the total service index it is the average weighed of X1 and X2 carried out using the lengths of the links. At the same time the total service level of the two links is determined with the HCM 2000methodology [7], making use of the combined average speed (ATSc) pertinent to the same two links and consequently its service index $X_{1+2} = f\,(LOS_{1+2})$ is obtainable.

$$\begin{cases} X_{1+2} = (X_1 \times L_1 + X_2 \times L_2)/L_{1+2} \\ X_{1+2} = f\,(LOS_{1+2}) = f\,(L_1, L_2, ATS_{c,\,1+2}) \end{cases} \qquad (2)$$

The obtained two service indexes have to converge towards the same value for which, repeating continously the procedure, it will be possible to recognize the values X1 and X2 (corrected) satisfying the fixed conditions. This operation, led for several link tipologies, would allow to assign a single value of service index to an whole path and, having general valence, it would allow the calibration of whichever methodology able to gain a quantitative value to an associated qualitative value of a service level.

THIRD DEGREE OF COMPLEXITY: THE GLOBAL LEVEL OF SERVICE (GLS).

The methodology described in the previous section is characterized by a higher level of precision and difficulty than the case of discontinuous intervals (first degree of complexity). In any case, previous two attempts, searching a service index that can represent all traffic levels, are born however from the forces to give a quantitative aspect to the HCM levels of service, even if they intrinsically have been born as a qualitative subdivision of the traffic conditions. In the second place the HCM levels of service consider only some of the parameters influencing the circulation (traffic density and therefore flow and average speed, influences from the traffic composition, from the kind of users, road geometry and peak hour factor, too) omitting many others factors that would give thoroughness to the traffic complex phenomenon representation. In fact, traffic is connected to numerous variables, some ones analytically measurable, others difficultly predictable and others tied to customer perception and therefore aleatory. Safety of a transfer, in the more general sense of the term, mutual impact of an infrastructure on neighbouring areas, exceptional traffic, confort of travel and special events, are all factors that influence the road service of a link and in a more generalized manner of the whole network.

In order to exceed these two limits (the forces to give a quantitative aspect to a qualitative classification and the consideration of only some of the road service influencing parameters), the third level of complexity and detail for the service index allocation consider all factors influencing the road service through the theory of the GLS (Global Level of Service), developed in last years in the Department of Highways and Transportation, in the Polytechnic University of Bari (Italy). This theory has been born, already in origin, like quantitative representation of the traffic levels and road service.

In the Global Level of Service theory 54 indicators are considered. They are parts of six macrogroups: Safety (S); Travel Time - (T); Services - (R); Environment- (A); Traffic Conditions - (Q); Comfort - (C). The safety group is in its turn subdivided in the following subgroups: Geometric characteristics of the alignment - (GL) of the section - (GS); Structural characteristics - (St); Functional characteristics - (F); External interferences - (E). These indicators are expressed in 54 indexes varying from 0 to 1 and they are meant through one weighted mean that leads to a total index, also variable from 1 to 0. In order to carry out this weighting comparison between the indicators it is possible to apply the "Analytic Hierarchy" methodology proposed from T.L. Saaty in first years'80, (Saaty, 1990 - Saaty, 1990 - Saaty, 1998), particularly suitable in order to carry out a congruent allocation of weights to largeness sets non congruent between them. Other revolutionary aspect of this theory is to carry out the analysis in relation to three different points of view: the road customer, the infrastructure manager and the society that are influenced in some way from it.

The GLS theory contributes therefore with a variable index between 0 and 1 that is able to be equal to the service index. Its general and total valence would make it able to support planning and projecting steps, service, maintenance and emergency of a road infrastructure and would seem to exceed the limits of the methodologies exposed previously.

FUTURE OBJECTS

In the future applications a systematization will be given to the application of the service index, in particular it is thought opportune:

- to collect flow data refered to several road tipologies;
- to apply and to perfect the procedure of calibration for the first two levels of complexities exposed previously for the service index determination obtaining a more valid and effective subdivision of the 1-0 interval;
- to compare turns out obtained from the three various degrees of complexity and from the classic theory of the HCM;
- to model the GLS theory in accordance with specific applications, verifying the choice of the more opportune pointers for the study to lead and make the calculation algorithms elaborated in the previous years for its application more precise.

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