Probabilistic Risk Analysis in Road Tunnel Safety

Renato Lamberti
Full Professor, Department of Transportation Engineering “L. Tocchetti”- Naples
rlambert@unina.it

Maria Luisa De Guglielmo
PhD Student, Department of Transportation Engineering “L. Tocchetti”- Naples
mdegugli@unina.it

Synopsis

This article suggests a methodology of the risk index assessment connected to the one-way and two-way road tunnel crossing, based on the use of Probabilistic Risk Analysis.

This study is included in the course of an extensive research programme started by the Department of Transportation Engineering “L. Tocchetti” – Naples University “Federico II”; the final goal of this research is the interpretation of the system man-vehicle-road tunnel environment (where service management for users gathers unusual prominence); the started programme also includes an experimental physical and virtual survey of the speed into road tunnel.

We have specialized a general methodology, with applications in different fields of Engineering, on the basis of a detailed and complete database of the car-crashes (reconstructed by Police minutes) occurred between 1997 and 2002 in all road tunnels in the province of Salerno.

Particularly in-depth analysis, carried out until now, has given the possibility to create an event tree for the accident probability determination in both types of the road tunnels (one-way and two-way) and as many fault trees as typical accidental sequences are reconstructed. Besides, we have determined the consequences size distribution (in terms of dead, injured and damages) of occurred accidental events, on a statistical basis.

So we have planned the means for the risk index determination connected to the undesired event in one-way road tunnel accident and in two-way road tunnel accident; after stating the means clearly there will be surely a detailed numerical application realizable only by a close and reasoned data finding, that isn’t organized in a proper way to the request of this procedure, concerning the road tunnels (at a national level too).

Probabilistic Risk Analysis in Road Tunnel Safety

The concept of “safety”, despite of its undeniable importance for many systems evaluation (transportation infrastructural systems have a leading position) is abstract and not directly quantifiable; to fix an index standing for the technical features of a system as regards to safety target, we resort to the “distance” measure of its real state from an abstract condition identified as optimal. This distance represents “risk”; that is the possibility of an undesired event occurrence, eventually causing a damage (whose size is not always assessable a priori). For events causing serious immediate and/or delayed damages to community (people, goods and environment) we call risk (or risk index R) the conventional product between the estimated frequency (F) of the accidental event occurrence and its consequences magnitude (M). In the beginning (1970s), the risk quantitative analysis was applied to the dangerous plants (chemical and nuclear), to which deterministic algorithms were applied (potential damage, potential loss). Instead, up-to the minute scientific evolution prefers Probabilistic Risk Analysis (P.R.A.).

Probabilistic risk analysis

P.R.A is a quantitative analysis applied to complex systems; it has the goal to formalize the functional relationship between a system fault and its component faults. It represents the result of other half-quantitative or qualitative modelling analyses: Failure Modes and Effects Analysis (F.M.E.A.); but these analyses have the goal to detect the fault causes, with the application of scientifically sophisticated methods. P.R.A. basic means are event tree (E.T.) and fault tree (F.T.); even if they are schematic representations of a process in a Boolean Logic, they take in the relationship with time evolution too. Event tree uses a forward logic; that is, it begins from a starting event (accident or generally anomalous and undesired behaviour of the system, called Top Event) and goes on spreading this event through the study full system, and examining all ways affecting the sub-system behaviour. So it is characterized by a top-down development: the event tree nodes represent the possible alternatives between the sub-system working or not working; if not operation is characterized by a sufficiently operative part, will be able to get back to the normal functions of operation, although the accident. The course through an event tree created from an accident, is called Accident Sequence (A.S.). The structure of an E.T. is like alternative tree put on the bases of the decision analyses methods.

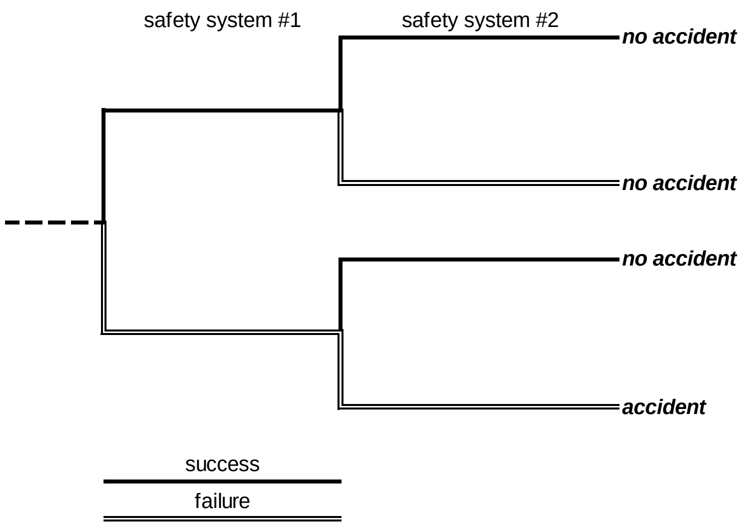


Figure 1: An event tree

So the event tree root is a top event (accidental result typical event of the analysed problem); the tree ramifications are derived or base events (reciprocally excluding). They are associated to an occurring probability conditioned to the top event occurrence concerned. The different top events are considered statistically independent, even if incompatible, in the algorithm. The independence of top event and especially the reciprocal exclusion of base events represent P.R.A. applicative limitation, that is unable to manage interdependent and/or connected events.

Fault tree works with a backward logic: in view of a clear system fault, we can gradually trace to the "fault components", taking part in breaking equilibrium, in a progressive way. Using the Boolean operations AND, OR, NOT ("gates" in the tree graphic representation), we can write the combination of "fault components" causing the malfunctioning of the system and we can assess the qualitative and quantitative features by equivalent Boolean equations. So F.T. is characterized by a bottom-up development. The fault tree study begun in 1960s at Bell Telephone laboratories and also developed like analysis (fault tree analysis, F.T.A.) for the process control: it was supported by theory of reliability and especially by Boolean algebra.

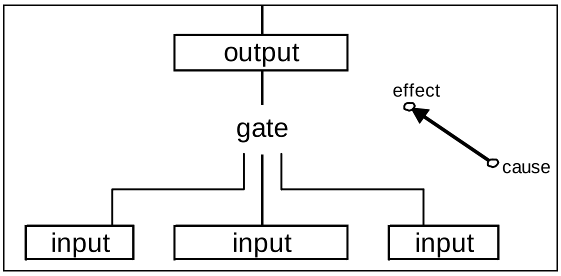


Figure 2 – The gate function in a fault tree

gate	operation	mathematics
AND	intersection	$\boxed{A \cap B}$
OR	union	$\boxed{A \cup B}$
NOT	complement	$\boxed{\overline{A}}$

Figure 3 – Symbology with two events A and B

A P.R.A. model starts from the logic analysis of a top event for the creations of events tree representing accidental sequences and then it goes on inserting as many fault trees as they are necessary to describe the above-stated sequences in detail (see Figure 4). So it's possible to assess the probability of initial top event occurring by union and intersection of simple primary or base event probabilities.

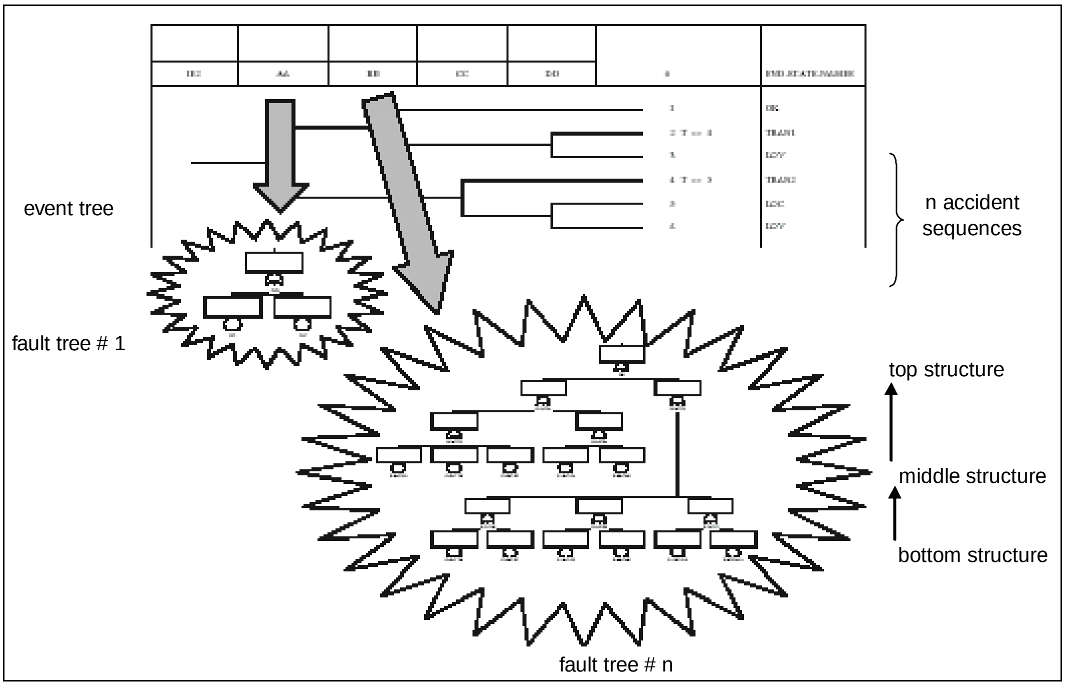


Figure 4 – P.R.A. concept: an event tree with n fault trees, if n are the accidental sequences

As we have explained before, this complete P.R.A. course, has found several applications over the years, providing with interesting results, but all available applications are partial in the road field: they are limited to the risk assessment deducible from the single use of an E.T. or a F.T.

APPLICATION METHODOLOGICAL PLANNING TO ROAD TUNNEL SAFETY

The first step of risk analysis, that is proposed in methodological form al the begin, is a qualitative approach, examining all aspects of study system (in terms of elementary components and possible fault ways), by using tabular techniques; the support of this phase is analysis of accident data bank registered in assimilable contexts; the result is the identification of one or more reference critical events (top event). This result will be the object of risk quantitative assessment, in the second phase. We have applied P.R.A. general procedure, described before, to risk size determination (R), connected to some road tunnels, beginning from accidents analysis occurred in the past and their functional, physical-geometrical features study.
After getting the distribution of accident seriousness (magnitude M) on a statistical basis, the risk assessment procedure has been addressed to the most complex frequency (F) or probability quantification of these events occurring.
Now available complete database, on which we have planned the method application, is summarized in the following table:

Tab 1: Database

Surveyor	Time	Tunnel type	Accidents	Tunnel accidents
Military Police	1997 / 2002	Two-way road tunnel	1745	7
Motorway Police	1998 / 2002	One-way road tunnel	2902	18
Total			4647	25

At the beginning, we have used the available database to organize application:

- analysed road tunnel type;
- occurred accident type;
- accident seriousness (or magnitude).

Tab 2: Accident type for tunnel type

Accident Type	One-way road tunnels	Two-way road tunnels
1	Bumper-to-bumper crash	Bumper-to-bumper crash
2	Skidding or Going Off the road	Skidding or Going Off the road
3	Side crash	Head-on crash

Tab 3: Accidents seriousness for tunnel type

	Accidents in	
Size	Two-way road tunnel	One-way road tunnel
damages	2	0
1 injured at least	5	15
1 dead at least	0	3
Total	7	18

The division between two tunnel types (one-way and two-way road tunnels) must be always considered during working-out, because occurring ways of every accident (collision, skidding or going off the road) are conceptually different, according to whether the stream of traffic moves to the same or opposite directions.

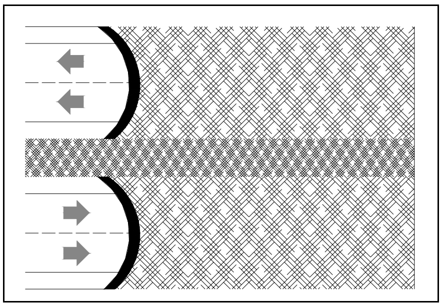


Figure 5 – One-way road tunnel

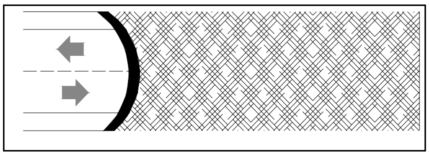


Figure 6 – Two-way road tunnel

P.R.A. procedure starting with the event tree organization, with top event ”tunnel accident”, that is showed below: it represents how the risk of making an accident for a driver can be picked out, depending on the following different event types:

1. bumper-to-bumper crash;
2. skidding or going off the road;
3. side crash or head-on crash;
4. no accident.

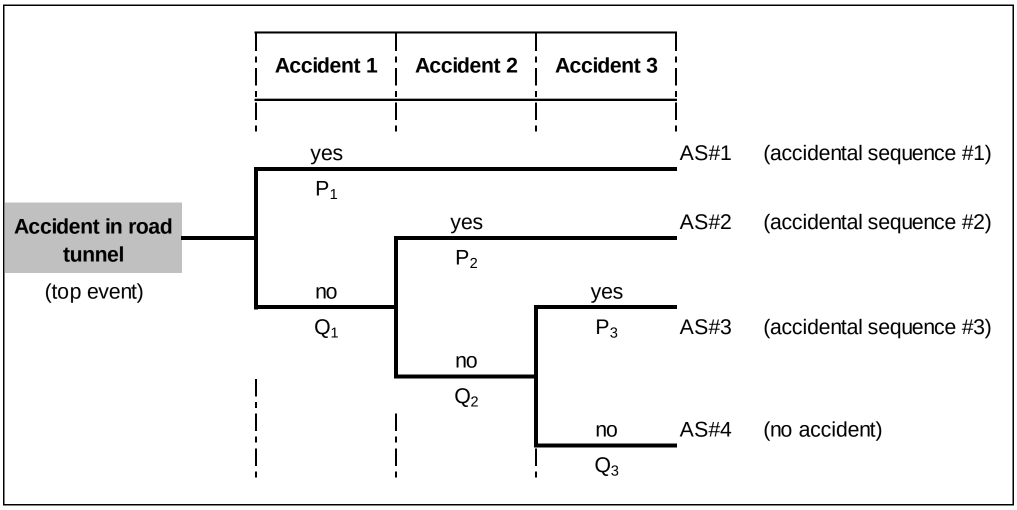


Figure 7 – Event tree for the case study

We mark the probability of occurring with P_i for every i-th accidental sequence and the probability of not occurring with $Q_i=1-P_i$.

Tab 4: Probability of accidental sequences

Accidental Sequence A.S.# i	Probability P(A.S.# i)
# 1	P_1
# 2	Q_1P_2
# 3	$Q_1Q_2P_3$

So the probability of an accidental event occurring in a tunnel will be:

$$P=\sum_{i=1}^{3}P(AS_i)=P_1+Q_1P_2+Q_1Q_2P_3=P_1+(1-P_1)P_2+(1-P_1)(1-P_2)P_3$$

P_1, P_2, P_3 (that are the occurring probabilities of the three above-mentioned accidental types) must be known to establish P.

As there is no reference data of these probabilities, also in national field (in this case the application process would stop at the only event tree), we go on creating as many fault trees (6) as they are necessary:

- 2 fault trees for bumper-to-bumper crash (for both one-way road tunnel and two-way road tunnel);
- 2 fault trees for skidding or going off the road (for both one-way road tunnel and two-way road tunnel);
- 1 fault tree for side crash (for one-way tunnel);
- 1 fault tree for head-on crash (for two-way tunnel).

Known P value, it's possible to calculate the connected risk index for every road tunnel type by magnitude value determination.
This magnitude is calculable in many ways: we propose an assessment, considering the different levels of severity found into the two parts of database, by the introduction of simple severity coefficients

Tab 5: severity coefficients

Size	Accidents in one-way road tunnel [n_i]	Accidents in two-way road tunnel [n_i]	severity coefficients [k_i]
damages	2	0	1
1 injured at least	5	15	2
1 dead at least	0	3	3
Total [N]	7	18	

So magnitude, calculated by the relation $M = \frac{\sum_{i=1}^{3} n_i k_i}{N}$, provides with the following values:

Tab 6: Magnitude for tunnel type

M	One-way road tunnel	Two-way road tunnel
	1,71	2,17

As a result, the risk index for every tunnel type (depending on P probability of the accident occurring in each of them, as we have explained before) is given by:

Tab 7: Risk index for tunnel type

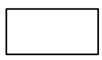
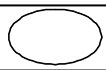
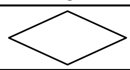
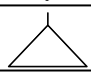
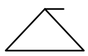
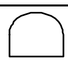
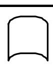
R	One-way road tunnel	Two-way road tunnel
	$1{,}71P_{one\text{-}way}$	$2{,}17P_{two\text{-}way}$

So the essential difficulty of this procedure is P calculation, that will be the object of the quantitative part of our future study. As we have told in advance, to that end, a course develops by the complex use of a certain F.T. number.

Fault Tree Construction

It should be noted that the used symbols play an important role inside a F.T. (it's obvious, being a graph).
We have adopted the following symbols in the case study, in line with international signs:

Tab 8: Symbol in fault trees

	top event / other event
	base event
	udeveloped terminal event
	transfer out *
	transfer in **
	AND gate
	OR gate

* tree attached at location of corresponding *transfer in*
** tree continues from corresponding *transfer out*

3 of 6 fault trees are showed below: these fault trees concerning two-way road tunnels; the other trees concerning one-way road tunnel develop with simple devices beginning from the first trees.

We have considered for every F.T. that:

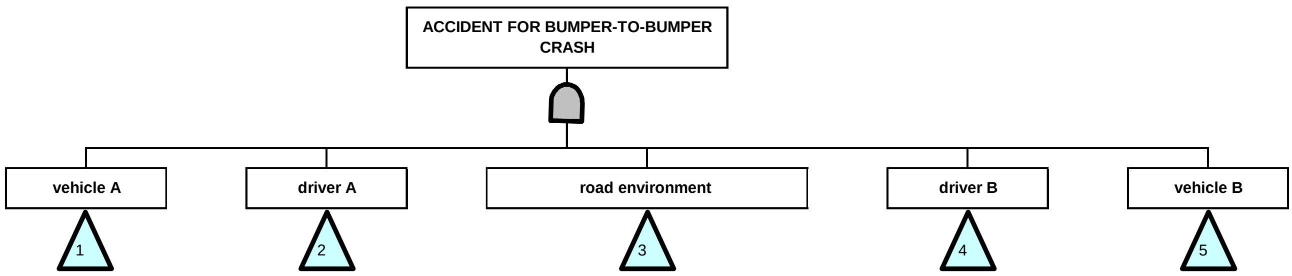
- every road accident is seldom a not-working consequence of only one of the three factors affecting road safety: man - vehicle - road environment; many times not-working depends on faults in the reciprocal interactions;
- an important fourth factor is added to the above-mentioned three factors in the tunnel direction: it's the right working of systems (lighting, ventilation, fire- fighting).

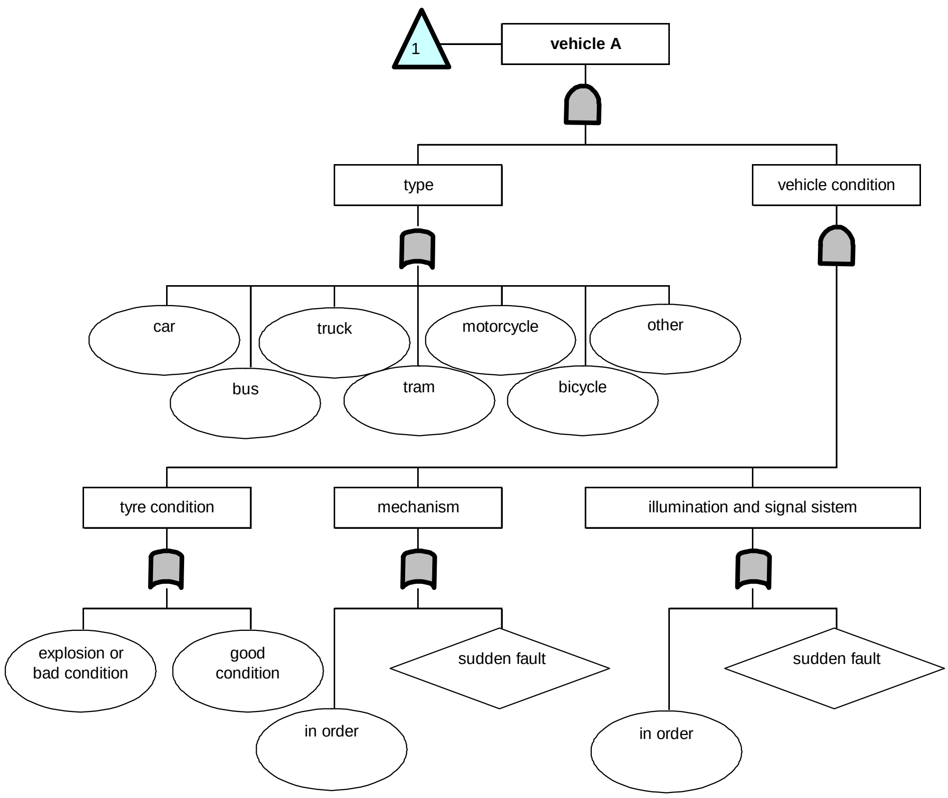
This is the reason why the events between top and base events are grouped in the above-mentioned categories: vehicle - man - working - road environment.
Then, man and his vehicle are marked with A for vehicle presumably causing the accident (on the basis of scene of the accident survey) and with B for the second vehicle involved.

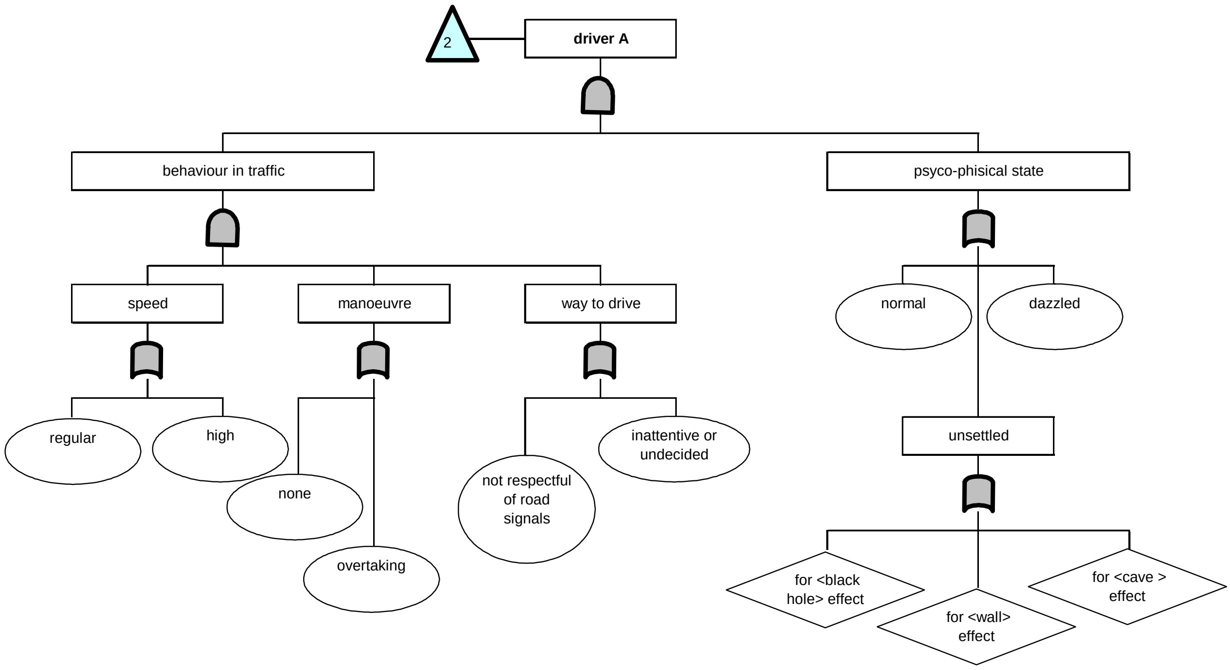
Unlike the other locations, in this one we consider the road tunnel effects on the driver, causing an unsure state speed.
Particularly we name:

- <black hole> effect, the exploration difficulty past entrance fornix, because of the different conditions of the road tunnel brightness - natural (outside) and artificial (inside);
- <wall> effect, the induction to the trajectory changes in approaching the road tunnel and to the speed, because of the short distance between the portal piers and the road side;
- <cave> effect, the going on of drive conditions in an above and sideways bounded environment.

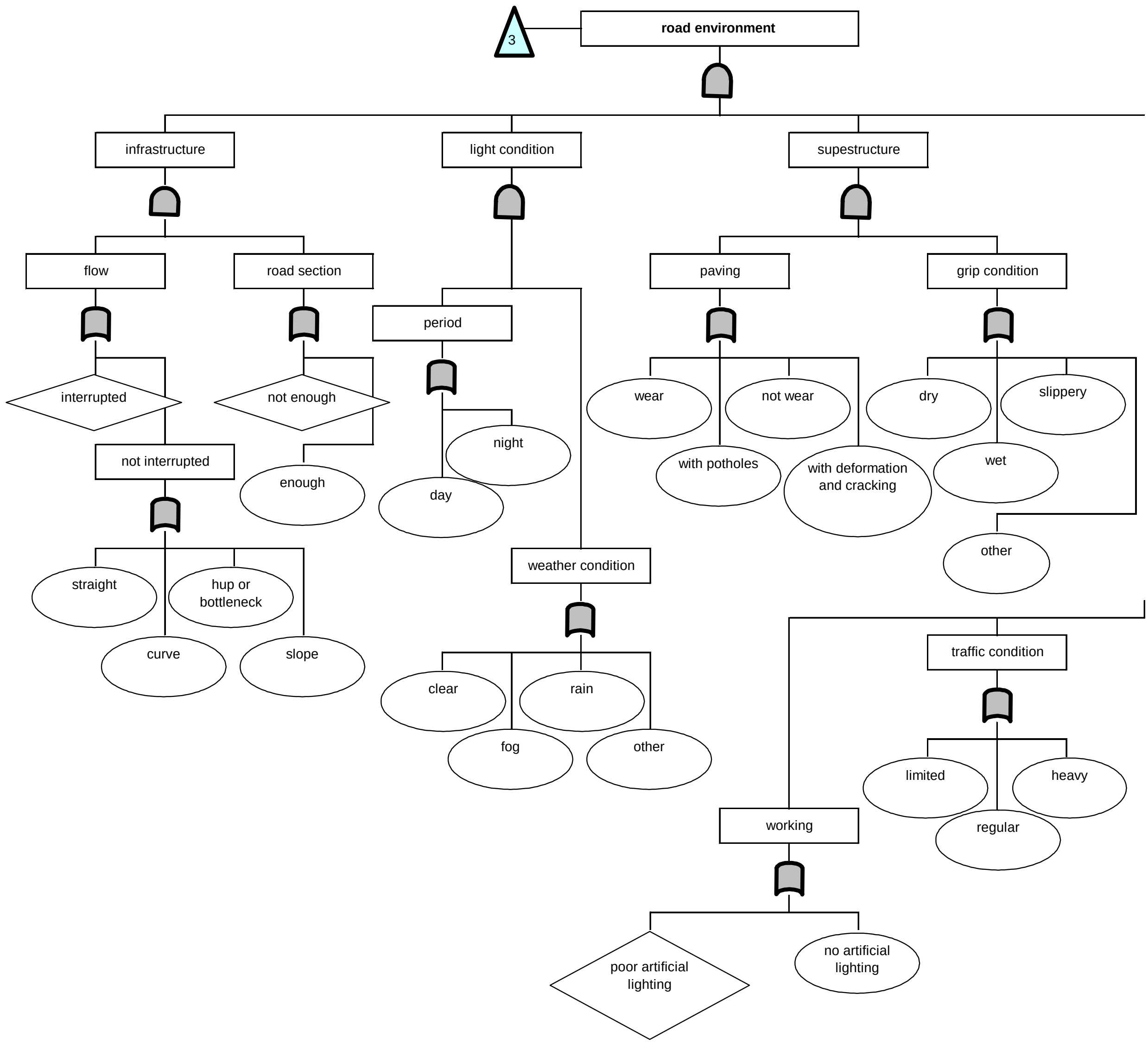
1. Fault Tree for bumper-to-bumper crash in two-way road tunnel



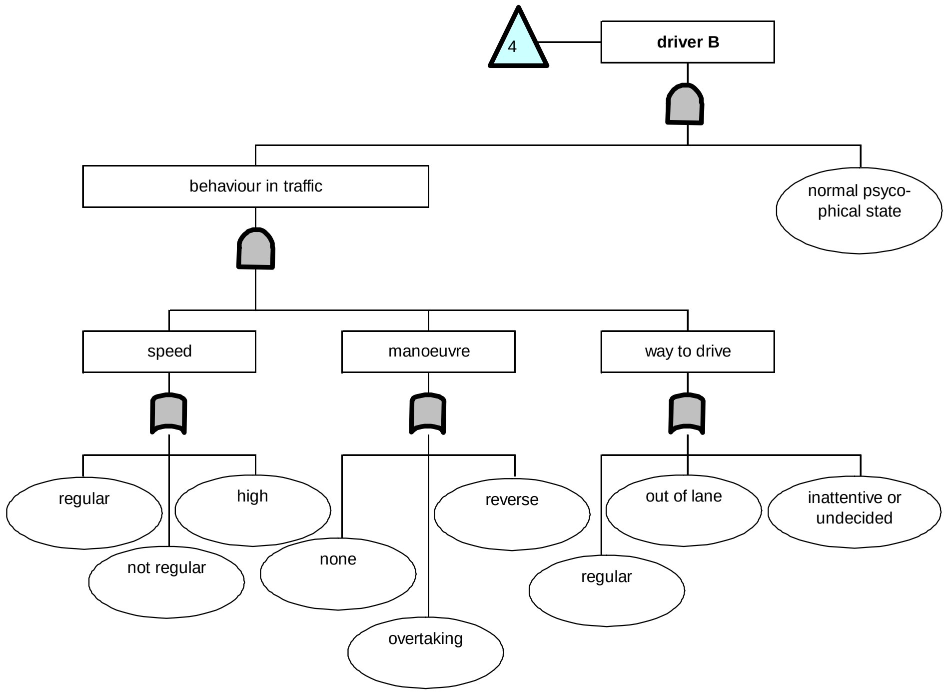


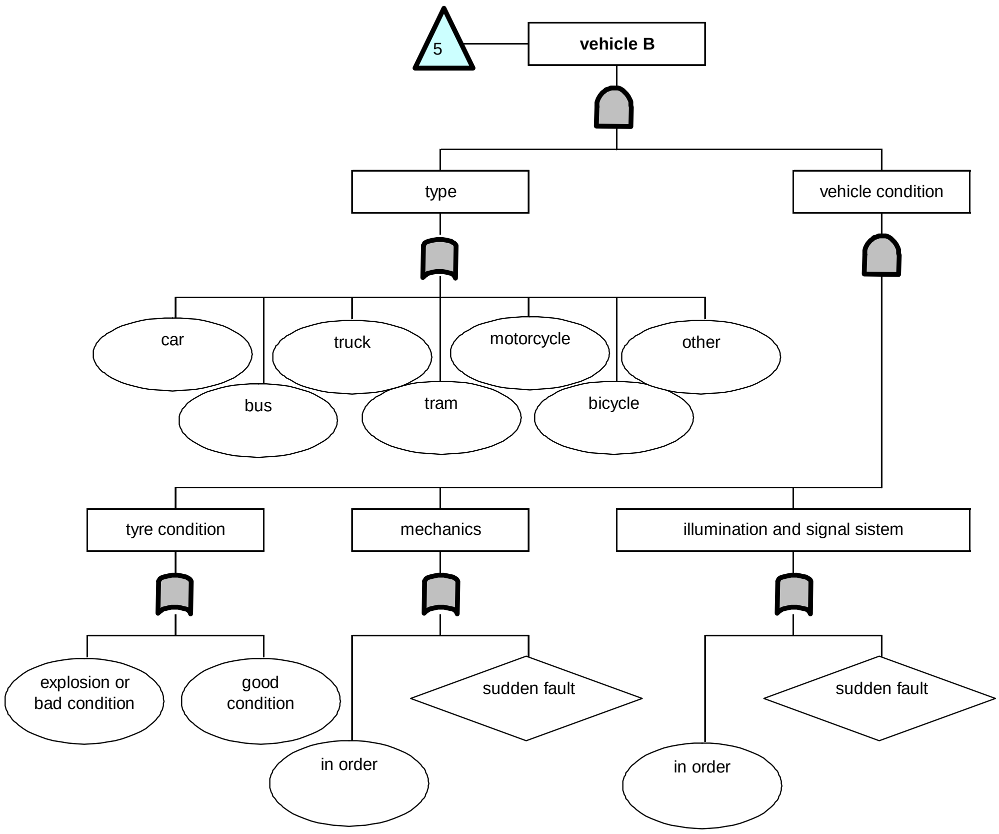


2
driver A
behaviour in traffic
psyco-phisical state
speed
manoeuvre
way to drive
normal
dazzled
regular
high
none
overtaking
not respectful of road signals
inattentive or undecided
unsettled
for <black hole> effect
for <wall> effect
for <cave > effect

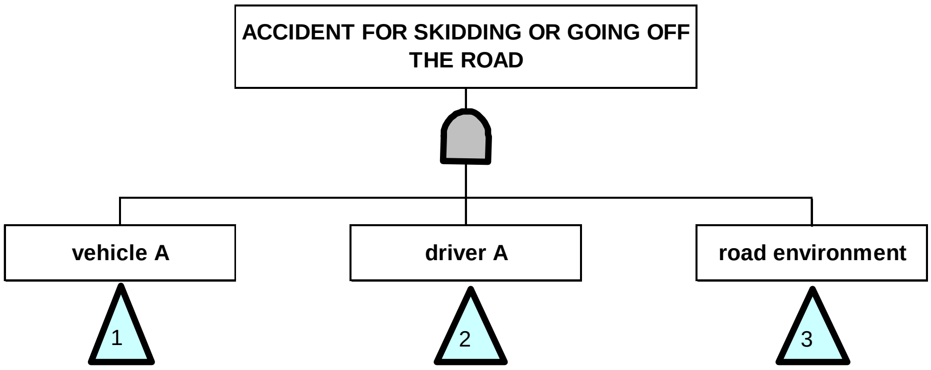


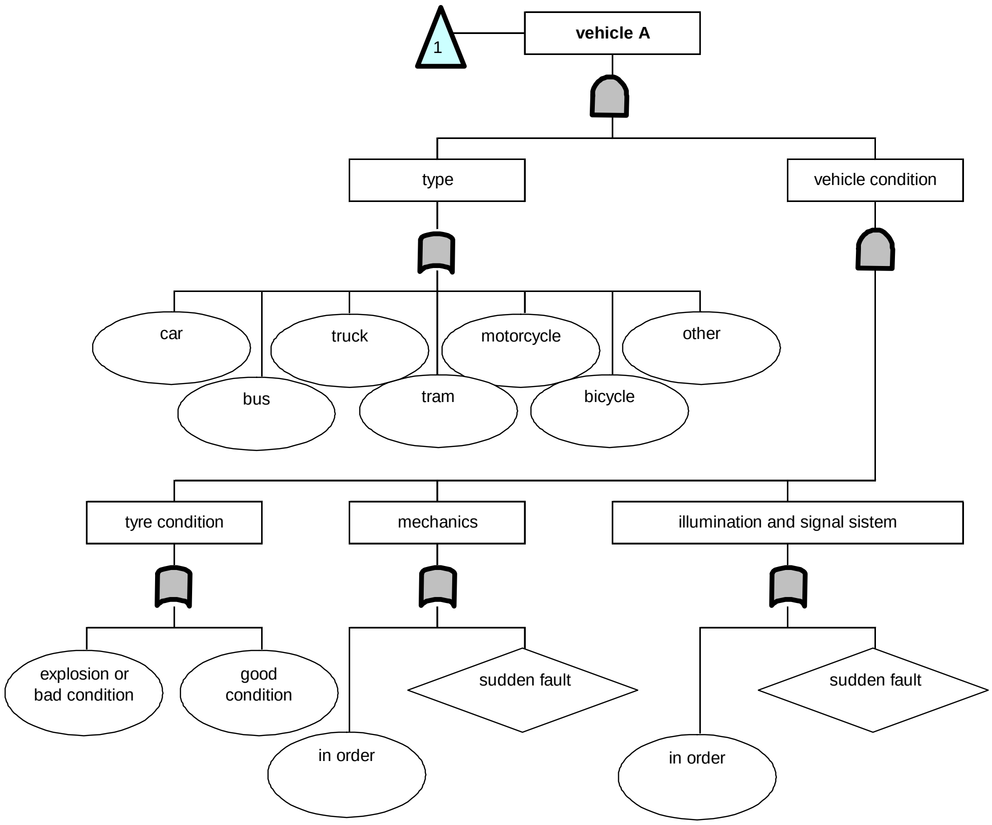
3
road environment
infrastructure
light condition
supestructure
flow
road section
period
paving
grip condition
interrupted
not enough
night
day
wear
not wear
with potholes
with deformation and cracking
dry
slippery
wet
other
not interrupted
enough
weather condition
straight
hup or bottleneck
curve
slope
clear
rain
fog
other
traffic condition
limited
heavy
regular
working
poor artificial lighting
no artificial lighting

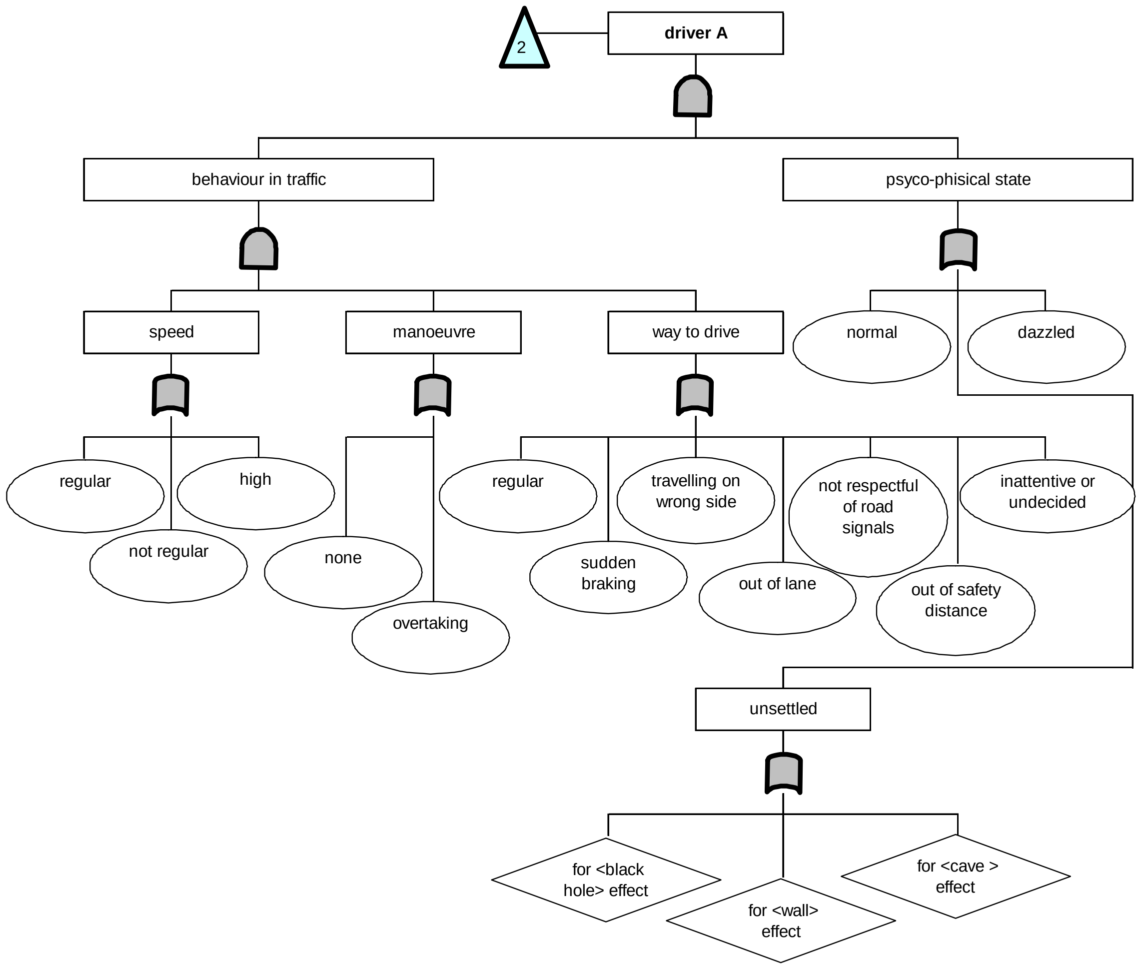

4
driver B
behaviour in traffic
normal psyco-
phical state
speed
manoeuvre
way to drive
regular
high
not regular
none
reverse
overtaking
out of lane
inattentive or
undecided
regular


5
vehicle B
type
vehicle condition
car
truck
motorcycle
other
bus
tram
bicycle
tyre condition
mechanics
illumination and signal sistem
explosion or
bad condition
good
condition
sudden fault
in order
sudden fault
in order

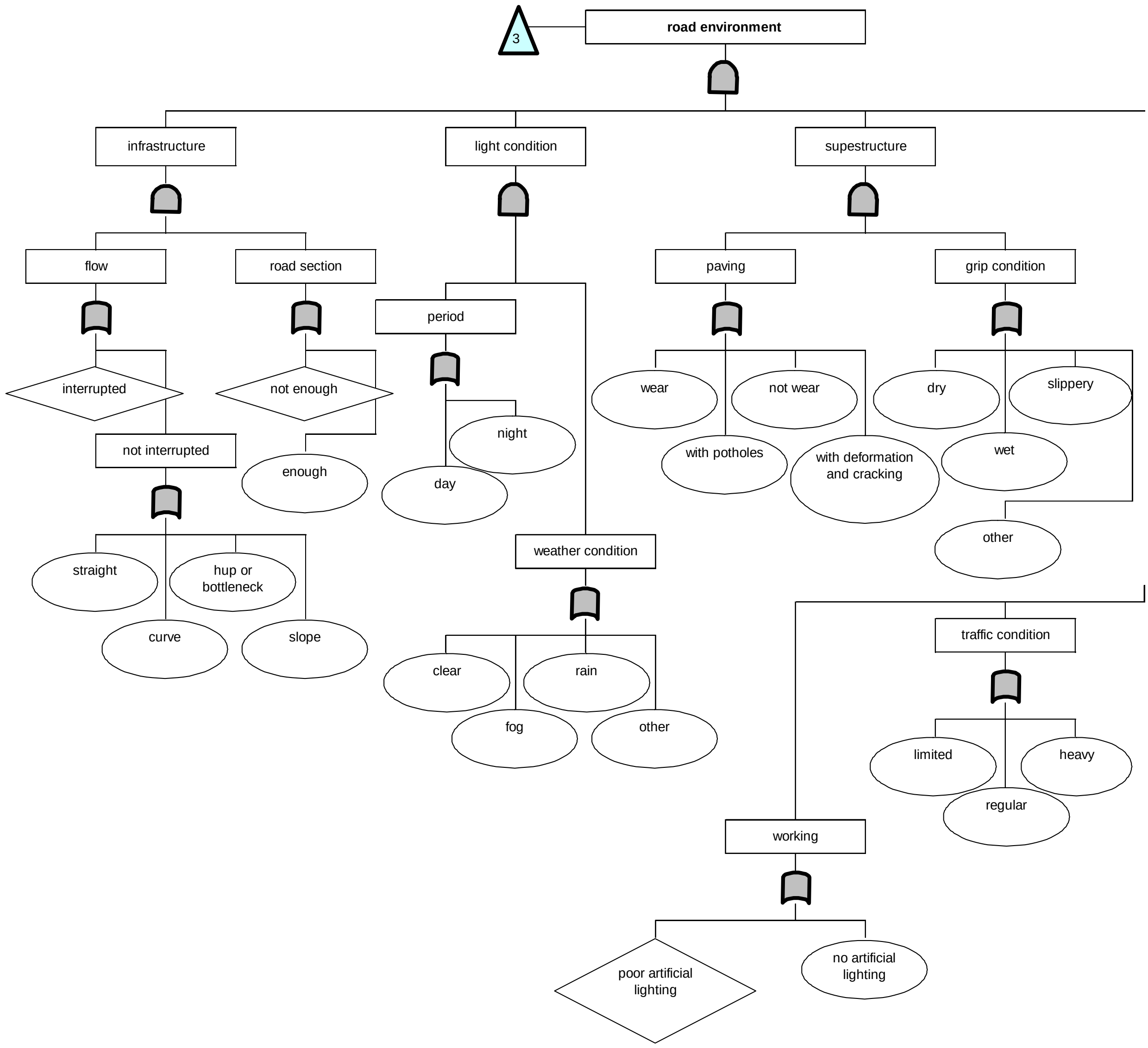
2. <u>Fault Tree for accident for skidding or going off the road crash in two-way road tunnel</u>



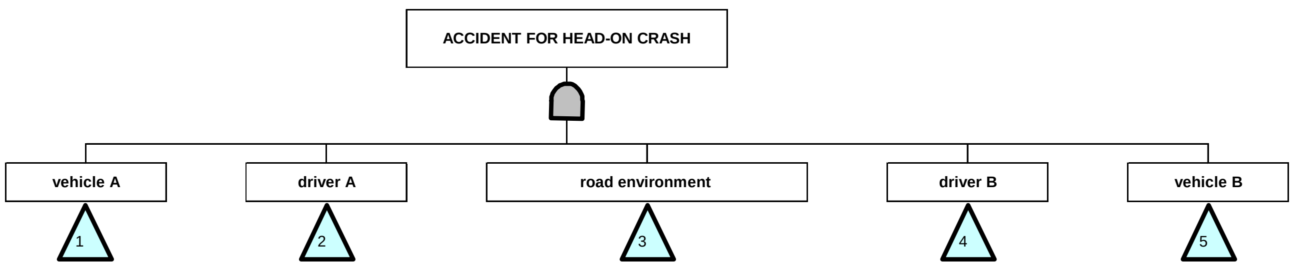


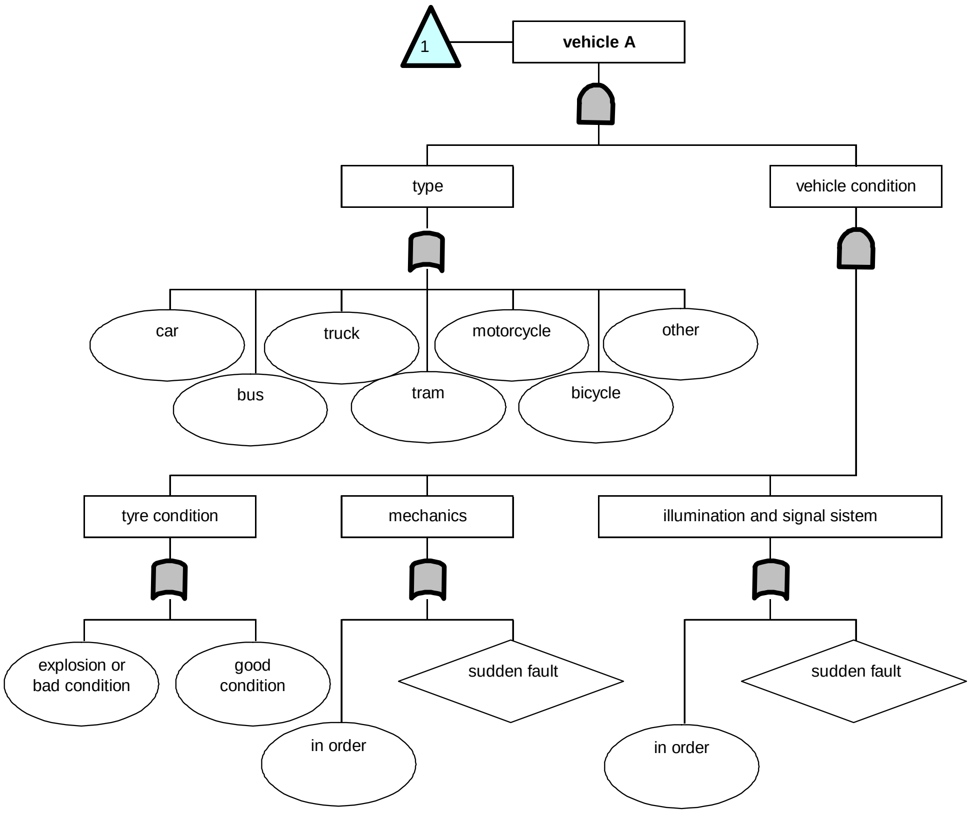


2
driver A
behaviour in traffic
psyco-phisical state
speed
manoeuvre
way to drive
normal
dazzled
regular
high
not regular
none
overtaking
regular
travelling on wrong side
not respectful of road signals
inattentive or undecided
sudden braking
out of lane
out of safety distance
unsettled
for <black hole> effect
for <wall> effect
for <cave > effect

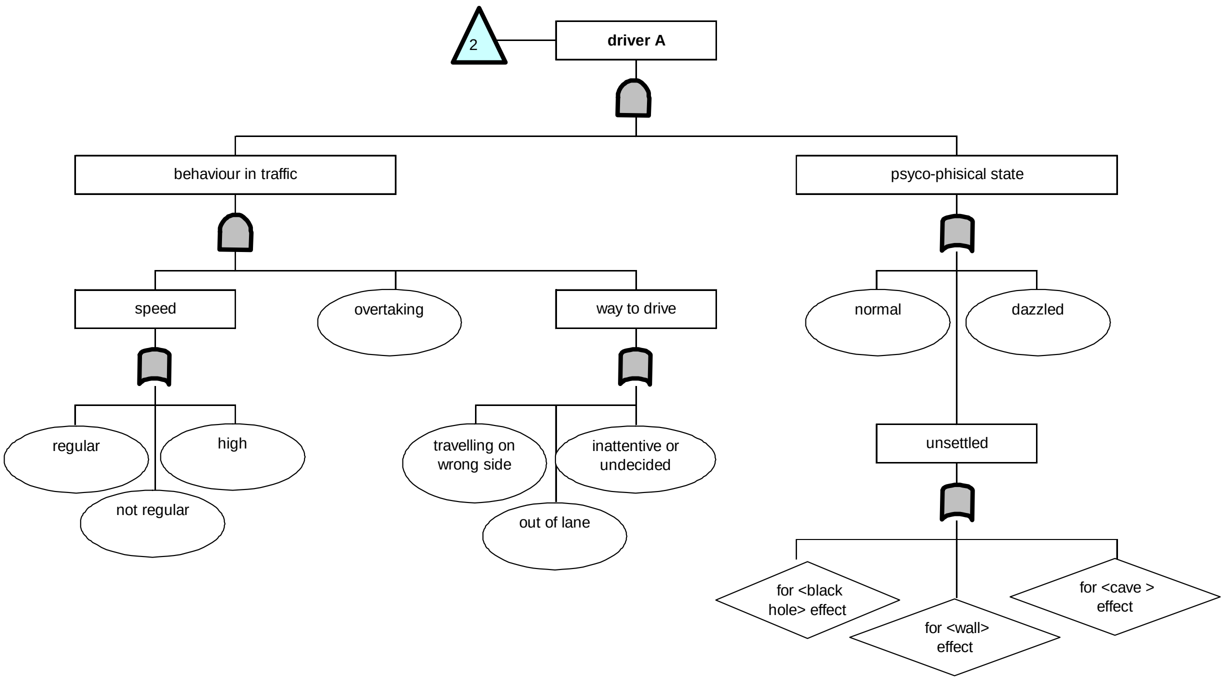


3. Fault Tree for head-on crash in two-way road tunnel

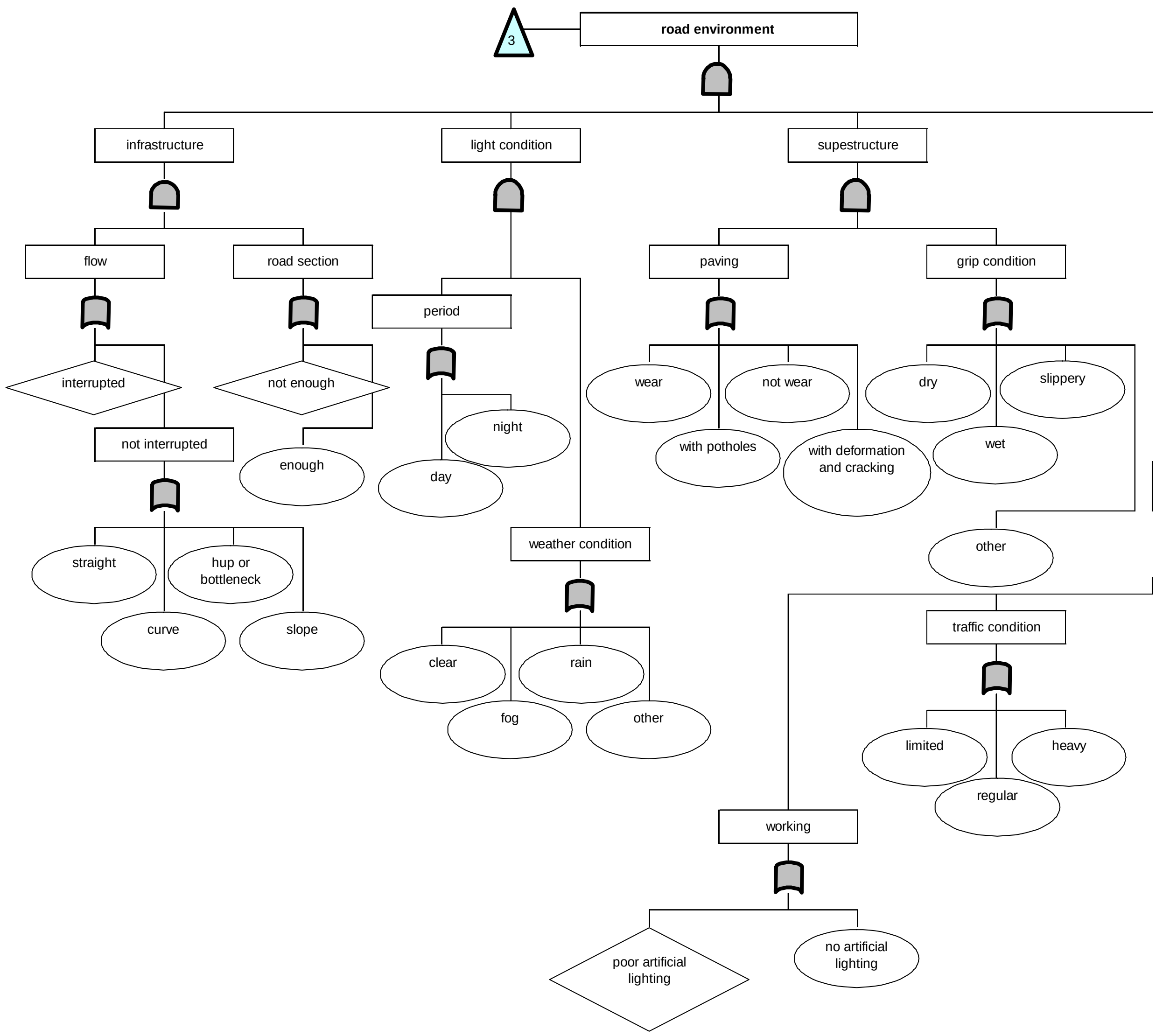


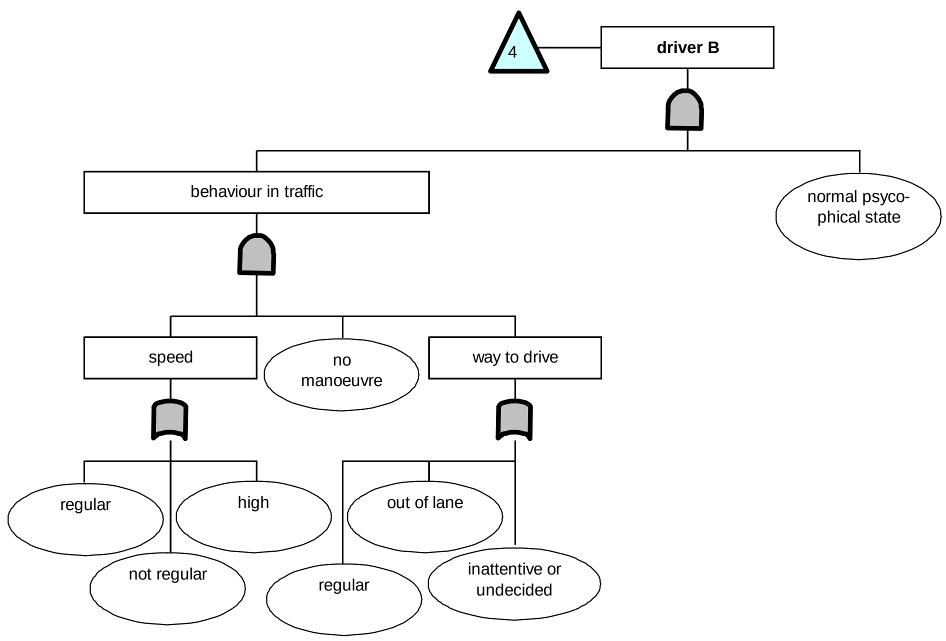


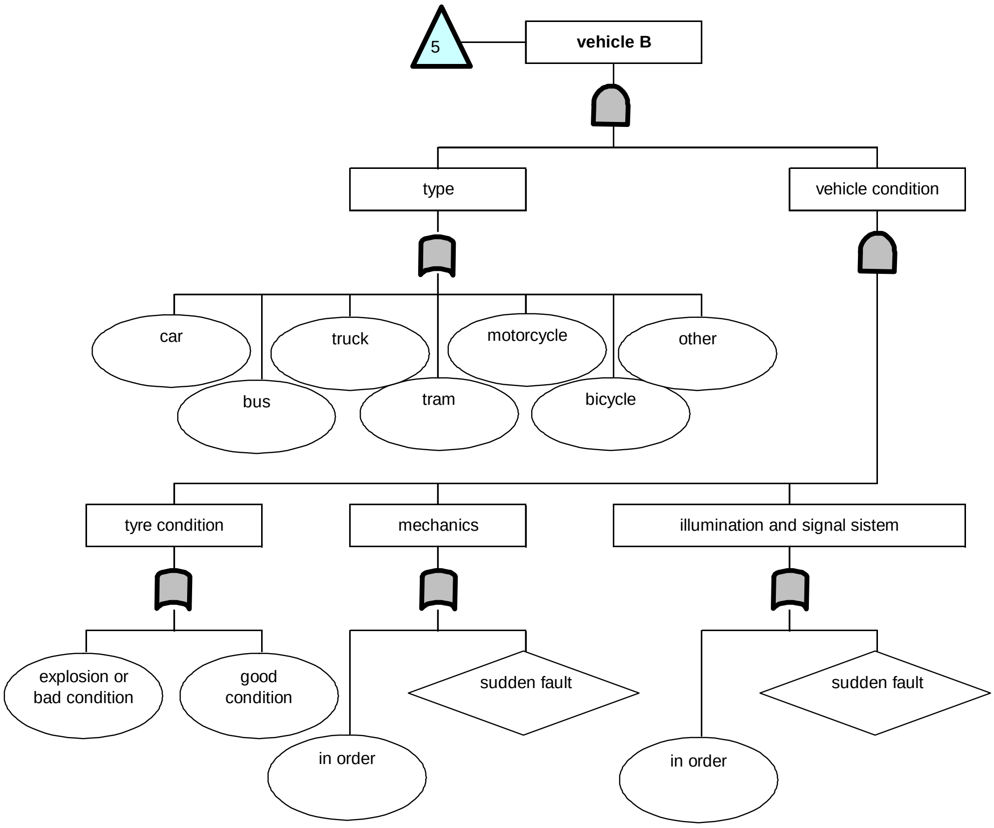
1
vehicle A
type
vehicle condition
car
bus
truck
tram
motorcycle
bicycle
other
tyre condition
mechanics
illumination and signal sistem
explosion or bad condition
good condition
sudden fault
in order
sudden fault
in order



2
driver A
behaviour in traffic
psyco-phisical state
speed
overtaking
way to drive
normal
dazzled
regular
high
not regular
travelling on wrong side
inattentive or undecided
out of lane
unsettled
for <black hole> effect
for <wall> effect
for <cave > effect


3
road environment
infrastructure
light condition
supestructure
flow
road section
interrupted
not enough
not interrupted
enough
straight
hup or bottleneck
curve
slope
period
night
day
weather condition
clear
rain
fog
other
paving
grip condition
wear
not wear
with potholes
with deformation and cracking
dry
slippery
wet
other
traffic condition
limited
heavy
regular
working
poor artificial lighting
no artificial lighting


4
driver B
behaviour in traffic
normal psyco-phical state
speed
no manoeuvre
way to drive
regular
high
not regular
out of lane
regular
inattentive or undecided



As explained up to now, after structuring the fault trees necessary to physical reality <representation>, the methodological procedure plans reality <reconstruction> through going up from detected base events with qualitative assessment.
It's necessary the following different finding of statistical data for this purpose (also resorting to general nationwide survey):

- disaggregated and/or aggregated data about having accidents on the total network (because of disaggregated data unavailability for road tunnels);
- geometrical and structural data on a wide sample of the analysed road tunnel;
- statistical data on presence and typology of systems in the analysed road tunnel;
- statistical data on the streams of traffic size in the analyzed road tunnel sections.

In the course of our research programme baked by P.O.N. financing, we are making an application extended to all road tunnels on directly managed or controlled (motorways in concession) by A.N.A.S. italian network.

CONCLUSIONS

This study shows development and use possibilities of complex systems control methods (typical of engineering industrial fields), in the road technique.
The theoretical basis of this planning has showed (in the last 50 years) a satisfactory validity in many science-application sectors, on condition to specialize the general patterns for the peculiar features of each study problem.
It will be possible, for the object of the methodological planning proposed up to this point, to achieve a precise numerical formulation only after studying in-depth all aspects of the fault trees created for the studied road tunnel. So, will be able to assign the simple frequencies to the base events and to go up these trees and the complete procedure quantitatively.
The final purpose this study (this note is only a first informative communication) are interpretation of the system man-vehicle- road environment concerning the road tunnel (where services management gathers unusual prominence) and its modelling to support an experimental (really physical and virtual) research started in the Department of Transportation Engineering “L.Tocchetti” - Naples University “FedericoII” .

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