THE SEVERITY OF BUS ROLLOVER ACCIDENTS

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ABSTRACT

The most dangerous bus accident is the rollover. An accident statistics - collected by the author containing more then 300 accidents - shows that the average casualty rate is 25 casualties/accident. There are four major injury mechanisms in a rollover which may endanger the occupants: intrusion, projection, total and partial ejection. Different ways of protection may be used to avoid these kinds of injuries, which are shown in the paper. The severity of a rollover accident may be specified on two different ways: one is based on the number of casualties (this is mainly used by the public opinion) and the other one evaluates the circumstances of the rollover (turn on side is less severe than roll down into a precipice) The severity is a basic parameter when specifying the protectable rollover accidents (PRA) in which the occupants may be and shall be protected. This severity limit may be defined on the basis of the accident statistics mentioned above and on the basis of in depth analysis of real world rollover accidents and different rollover tests. These methods are used and discussed in this paper. All bus passengers using different bus categories (traditional buses, high decker tourist coaches, double deckers, and small buses) shall have the same safety level which shall be guarantied by international regulation. This paper is a contribution to the international effort specifying a general regulation about the safety of buses in rollover accidents.

INTRODUCTION

In case of buses the rollover is a rather rare accident type. In Hungary, during a 5 years period (1978-1982) among 1803 bus accidents (as a total) 22 rollovers have been reported [1] this means 1,2%. In this statistics the small buses were not considered. Some other statistics are compared to this figure [2] and the rate of rollover in bus accidents was found in the range of 1-8%. The casualty rate (number of casualties per accident) in rollover accident is around 25 and in frontal collision – which is the second most dangerous bus accident type – this figure is around 17. The difference is even stronger, when comparing the fatality and serious injury rate together: this figure is at least 15 or more, (see Table 5) for rollover and 9 in case of frontal collision.
Since the mid of '70-s the protection of the passengers in bus rollover accidents is a strong effort in the UN-ECE regulatory work. The existing ECE regulation R.66 – which describes a required strength of the superstructure in a specified rollover test – relates only to large, single deck buses, e.g. the small buses, double deck coaches are excluded from its scope. To define the required protection level for all bus categories, to specify the same (similar, equivalent) safety for all kind of bus occupants, at least the following questions should be analysed and answered:

a) In which kind of rollover accidents (group of accidents) shall be the bus occupants protected? The protection generally means to provide high level probability of survival and to reduce the casualty risk.
b) What are the general requirements to protect bus occupants, to provide the required safety level?
c) How to specify the requirements of the approval (approval test) for all bus categories?

Every bus rollover accident is unique, different from the others. But there are certain regularities which can help to answer on the questions above. Theoretically there are two essentially different rollover processes for buses:

- The bus is rotating around an axis being perpendicular to the vertical longitudinal central plane of the bus. This can happen, if the road has a sharp curve close to a precipice. One accident is known belonging to this type of rollover, happened in Rome, 2005. Only 1-2% of the rollover accidents belong to this type of rollover.
- The bus is rotating around a longitudinal axis being parallel with the main longitudinal axis of the bus. This is the general way of rollover, the so called lateral rollover, at least 98% of the rollover accidents belong to this group. The safety requirements and the approval tests of ECE Reg.66 are based on this type of rollover as it is shown on Fig.1.

This paper – similarly to the international regulatory work – deals only with the second type of rollover. To reduce the number and severity of casualties, the following main injury mechanisms shall be considered:

- **Intrusion**. Due to large scale structural deformations and the loss of the residual space, structural elements intrude the body of the occupants or crash them.

- **Projection.** Due to the uncontrolled movement of the occupants inside the bus, their body impacts the structural parts of the passenger compartment.
- **Complete ejection.** During the rollover process the occupants could be ejected through the broken or fallen windows and crushed by the rolling bus.
- **Partial ejection.** During the rollover process parts of the passenger's body come contact with outside surface and can be strongly scratched or parts of the body (head, arms, chest) get under window column or waist rail and are pressed by it.

Figure 1. Lateral rollover test

CATEGORIZATION OF ROLLOVER ACCIDENTS

To specify those rollovers (rollover groups) in which the passengers shall be protected, the first step is to define characteristics groups of rollovers. The following categories may be used:

a) **Turn on side** ¼ rotation. The bus generally slips a certain distance on its side and finally stops. Level difference is practically 0

b) **Turn into a ditch.** The rotation is between ¼ and ½ .The depth of the ditch is not more than 1,5 m, but it can stop the further rotation

c) **Rollover from the road.** More than ½ rotation, but not more than 2. The level difference between the road and the ground, where the bus finally stops is not more than 10 m.

d) **Serious rollover.** More than 2 rotations. The level difference between the road and the ground, where the bus finally stops is more than 10 m.

e) **Combined rollover.** The rollover is followed by a fire, or before the rollover a severe frontal collision occurred, or after the rollover the bus falls into a river or lake, etc.

Sometimes category "b" (turn into a ditch) is listed either in category "a", or category "c".

Categories "a", "b" and "c" may belong to the protectable rollover accidents (PRA) and it is a realistic public demand to assure high level survival probability for the bus occupants in these kinds of rollover. One of the most important requirements is that in PRA-s the bus superstructure shall have certain strength to avoid its collapse or large scale deformation, to avoid the intrusion type casualties. It has to be mentioned that the 2 rotations and the 10 m level difference in category "c" are not theoretical, but practical figures. There were more real accidents (as well as full scale rollover tests) validating these figures. It is important to emphasize that the approval test specified in R.66 can assure an appropriate strength for the superstructure to survive this type of rollover.

SPECIAL ROLLOVER STATISTICS

Based on the Hungarian media reports (TV and radio new, newspapers, journals, internet, etc.) the collection of information started in 2000 and the results of this work were published many times.

Table 1.
Summary of rollover statistics

Number of accidents	338
Number of countries involved[1]	65
Total number of	
- fatalities	4054
- serious injuries	1029
- light injuries	977
- injuries without classification	2594
- reported "many injuries"	21 times
Type of rollover (severity)	
- turned on side	64
- rollover from the road	127
- serious rollover	74
- combined accident	73
Category of the bus rolled over	
- C I. (city, suburban)	7
- C II (intercity, local,	34
- C III (tourist long-distance)	130
- Double decker	16
- Small bus [2]	67
- School bus[3]	9
- Other (worker, pilgrim, etc.)	8
- unknown	67
Deformation of superstructure	
- serious deformation[4]	61
- slight deformation[5]	82
- no information	195

Footnotes to Table I.

(1) countries may be involved as manufacturer, approval authority, operator or the scene of the accident.
(2) in the media reports this category is called: minibus, microbus, small bus, midi bus, club bus, ambulance bus, etc. without exact specification
(3) in many cases children, students were transported by normal coaches, these accidents are counted as coach accidents.
(4) serious deformation means the damage of the survival space, (the collapse of the superstructure obviously belongs to this category).
(5) slight deformation means that the survival space very likely is not damaged in the rollover accident.

The last presentation shown and analysed on the last EAEC Congress in Belgrade (2005) was based on 222 rollover accident happened worldwide reported by the Hungarian media [3]. Meantime this statistics has been increased, the new version contains already 338 accidents. Table 1. gives a summary of this statistics analysing the 338 accidents from different point of views.

Table 2.
Rollovers in three major regions.

Regions	Before 2001	2001-2003	2004-2006(3)	Total
Hungary	10	39	45	94
Europe(1)	30	29	32	91
World(2)	18	59	76	153
Total	58	127	153	338

(1) without Hungary
(2) without Europe
(3) only the first 9 months in this year

Table 2 shows the distribution of these accidents among three interesting regions.
It is interesting to mention that the rates of the accident types (their severity) in this statistics strongly depend on the region of the accident. An example: a "turn on side" of a minibus without fatalities is reported by the Hungarian media only if it happened in Hungary, but it is not news if it happened in Brasilia or China. This is proved by Table 3. The conclusion of this effect is that the more severe rollover accidents are over-represented in this accident statistics considering the whole world.

Table 3.
The rates of accident types in the regions

Regions	Turn ed on side	Rollover from the road	Serious roll-over	Comb. roll-over	total
Hungary	45 48%	43 46%	0 0%	6 6%	94 100%
Europe(1)	18 20%	40 44%	13 14%	20 22%	91 100%
World(2)	2 1%	43 28%	59 39%	49 32%	153 100%
Total	65 19%	126 37%	72 21%	75 23%	338 100%

(1) without Hungary (2) without Europe

Remarks to Table 3.

- This statistics is projected by the Hungarian media. It means that the Hungarian figures are almost complete (90-95%), so it may be said that it is a representative sample from Hungary.
- Assuming a proportional figure in Europe, based on the fleet sizes of buses (18.000 in Hungary and 500-550 thousand in Europe) the estimated number of the rollover accidents in Europe could be in the range of 380-480 rollovers/year. If so, the European figures in this statistics cover only 2-4% of the total, which is not representative sample. It may be said that it is a useful, usable signal from Europe.
- The rollovers outside Europe may be used as individual information, but they can be involved into the statistical evaluation of certain questions, special aspects.

Table 4. summarizes the number and the rate of PRA-s in this statistics.

Table 4.
The rate of PRA-s in the regions.

Regions	All rollover accidents	PRA	
		number	%
Hungary	**94**	**88**	**94%**
Europe(1)	**91**	**58**	**64%**
World(2)	**153**	**45**	**29%**
Total	**338**	**191**	**57%**

(1) without Hungary
(2) without Europe

Remarks to Table 4:

- In Hungary the 94% of the rollover accidents belong to PRA (No big mountains, precipices, all rollover accidents are reported even if there was no fatality, no serious injury, etc.) As it was said before, this statistics is representative, related to Hungary
- Related to Europe, this rate is 64% but it is obvious that the Hungarian media do not report the less severe rollover accidents from Europe.
- Considering countries having more and bigger mountains, too, the estimated rate of PRA-s is between these two values, probable closer to the Hungarian one. It seems to be a reasonable estimation that 80-85% - as an European average – of the rollover accidents belong to PRA.
- In other words, if we can provide high level probability of survival and reduce the casualty risk in PRA-s, the passenger protection will be significantly increased in rollover accidents of buses.

THE ROLLOVER PROCESS

It is important to see clearly the rollover process, the factors influencing this process and to understand the problem of severity in case of rollover.

Start of the rollover

The start of the rollover process mechanically is simply and more or less similar in all accidents. A turning moment (M) starts the process (see Fig.2.) which may be generated on two ways:

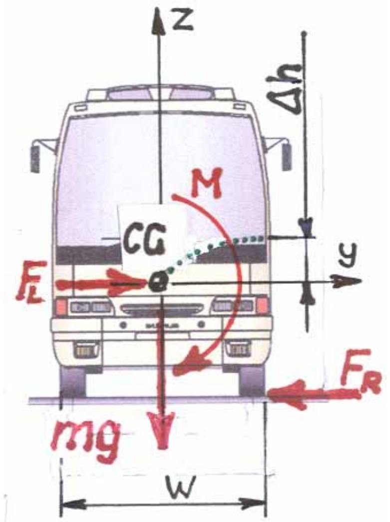

Figure 2. Turning moment and other parameters.

a) If the one side wheels of the bus run into the air, no vertical supporting forces on these wheels, the turning moment M is:

$$M = mg\frac{w}{2} \qquad (1)$$

b) If lateral mass force (F_L) – due to a sharp curve or lateral slipping on icy road – is acting in the CG of the bus, lateral friction forces as reacting forces (F_R) are acting on the wheels. The rotations starts around the axis running trough the wheel foot points, if the turning moment is big enough:

$$M = m\,g\frac{w}{2}\mu \rangle\, mg\frac{w}{2} - hF_L \qquad (2)$$

and the kinetic energy of the bus is enough to elevate the CG into the unstable position:

$$E_{kin} \rangle\, mg\Delta h \qquad (3)$$

In these equations
- m is the total mass of the bus
- μ is the friction coefficient
- g is the gravitational constant
- w is the extended track (see Figure 2.)

If there is no friction (μ = 0) there is no turning moment, no rollover, only slipping away. Bigger friction coefficient bigger turning moment. The friction coefficient, more exactly the reaction force (F_R) could be increased by certain circumstances (see Figure 3.)

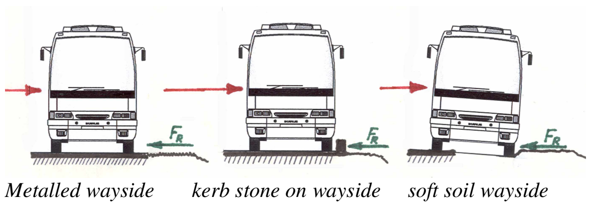

Figure 3. Increasing of the reaction (friction) force

The simplest rollover is the "turn on side", with ¼ rotation. This is the end of the first part of the rollover process. This happens on a horizontal (or closely horizontal) ground, see Fig.4. The bus slips on its side, the reaction (friction) force (F_R) is acting on the sidewall. The possible axis of the further rotation A_r is at the cantrail. No further rotation, if the kinetic energy of the bus can not elevate the CG into the unstable position (Δh). The sliding will be stopped by the friction (energy consumption), finally the bus will be laying on its side.

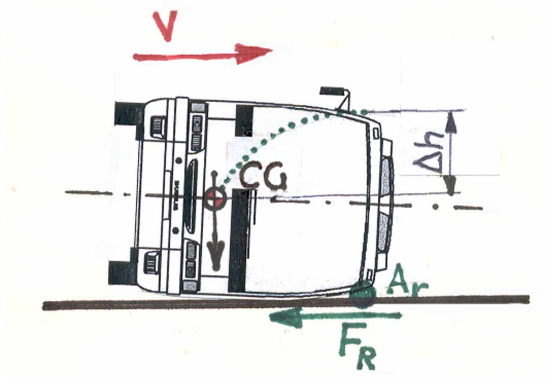

Figure 4. Turn on side.

The further motion in rollover

Studying the further motion of the bus – after turn on side – two essentially different processes may be distinguished:

- Energy consuming process, when the kinetic energy of the bus is decreasing by the energy absorption of the friction work, by the deformation work (structural and/or local) and by the elevation of the CG, etc. This process leads to stopping the further rotation of the bus.
- Energy generating process, when the kinetic energy of the bus is increasing by the drop of the CG (e.g. sliding or rolling down on a slope) If the energy generated by the drop of the CG (ΔE_g) is bigger than the energy absorbed by the friction and deformations (ΔE_a):

$$\Delta E_g \rangle\, \Delta E_a \qquad (4)$$

the motion of the bus (sliding or rotation) will continue.

The further motion of the bus depends on the surroundings (general geometry of the scene of the accident, soil properties, locality of the ground, etc.) and on the properties of the bus (shape, CG position, stiffness of the superstructure, etc.) Let us consider the two essential influences.

General geometry of the scene

To understand the effect of the general feature of the scene of the rollover, let us presume the same starting position: the bus already turned on its side and is sliding on its side crosswise. Figure 5. shows examples about the possible general geometry of the surroundings. Different surroundings, different further motion of the bus, different severity in the rollover process.

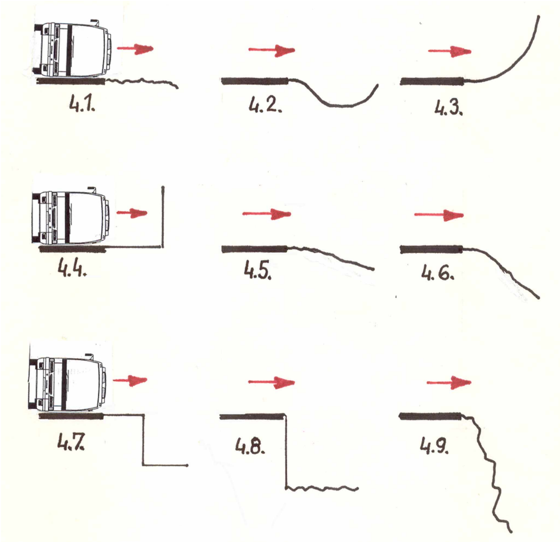

Figure 5. Examples for the general geometry of the surroundings.

Explanation to Figure 5.

4.1. horizontal ground with different surface
4.2. ditch with different shape
4.4. wall like object wayside
4.5 slight slope with different length
4.7. step like level difference
4.8. level difference with water, down
4.9. precipice with different depth

Stiffness of the superstructure.

There are two major aspects. The first is the general stiffness (or strength) of the superstructure having two alternatives: the superstructure is strong enough, no considerable deformation in the standard rollover described in the regulation ECE-R.66, or the superstructure is weak, large scale structural deformation or collapse occurs (see Fig.6/a) The other one is the local stiffness of the cantrail (outside corner between the roof and sidewall) which may influence the further rotation (see Fig.6/b.)

When studying the further motion of the bus in a rollover accident, it has to be recognized that the surroundings and structural stiffness have common effects, too. [3]

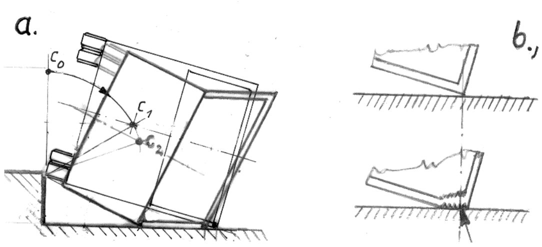

Figure 6. Stiffness of the superstructure

SEVERITY OF ROLLOVER ACCIDENTS

It is interesting and important to specify the severity of bus rollover accidents, at least to specify a "dividing line" between the severe and not severe accidents. It is obvious that the regulatory work should concentrate on the not severe accidents, in which the passengers should be protected, the safety level should be enhanced. There are two different approaches in the common practice when talking about the severity of bus rollovers:

a) Based on the number and severity of casualties. More casualties, more severe accident. The material losses are also considered. The real rollover process does not play role in this approach. A turned into a ditch accident – if the roof collapses and there are many fatalities – is called a severe one in this case.
b) Based on the rollover process. In chapter 3, the list of the different rollover accidents represents an order of the severity, the PRA-s are not severe accidents, but the combined and serious rollovers are severe. This approach does not count the casualties, if an empty bus rolls down on a slope having 20 m level difference and no casualty (because it was empty), the accident is a severe one.

These two approaches sometimes are mixed, and sometimes both approaches specifies an accident as a severe one, or both of them as a non severe one. From the view point of the regulatory work the second approach is more useful, because well defined technical requirements may be derived on the basis of this approach. As it was said earlier, the PRA-s specify those group of the rollovers in which the bus occupants shall be protected, so the dividing live is between PRA-s and the severe rollover accidents (serious and combined rollovers)

It is difficult to check, whether the recently used approval test is adequate to separate the strong superstructure from the weak one, to meet the demand of the public, to assure the required safety for the passengers at least in the PRA-s. A slow feedback can be found from this accident statistics, even if this statistics does not give direct information about the efficiency of the approval of buses regarding ECE-Rg.66. Very few information are available, whether the bus having a rollover accident was approved on the basis of R.66 or not. But indirectly an interesting comparison may be done. As it was defined above, PRA-s cover those accidents in which the passengers should be protected, the survival space (SS) shall be maintained. It has to be underline that the required strength of the superstructure helps to avoid the intrusion type injuries, to reduce drastically this type of fatalities, but it is less effective in the projection and ejection type injuries. Among the 388 rollover accidents there are 191 PRA-s and among these accidents there are 142 in which we have information about the behaviour of the superstructure: 82 accidents did not cause damage in the SS and in 60 accidents the SS was harmed, including the total collapse, too. An interesting comparison is shown in Table 5., in which the casualty rates (casualty per accident, CR) are given for four kinds of rollover accident groups:

– All the 388 accidents giving a very general average
– PRA-s in which the passengers should be protected
– PRA-s in which the SS remained intact (studying the pictures, photos, videos available)
– PRA-s in which the SS damaged, the superstructure collapsed.

Table 5.
Casualty rates in rollover accidents

Considered rollovers	Number of events	Casualty rates (CRi)				
		CR_{Fa}	CR_{Si}	CR_{Li}	CR_{Ns}	CR_{AC}
All rollovers	338	12,0	3,0	2,9	7,7	25,6
PRA-s	191	5,5	2,6	3,7	6,3	18,1
SS intact	82	0,9	1,9	4,3	3,6	10,7
SS damaged	60	13,4	6,7	4,2	10,2	34,5

In Table 5.
CR_{Fa} = fatality rate
CR_{Si} = serious injury rate
CR_{Li} = slight injury rate
CR_{Nc} = rate of not specified injuries
CR_{Ac} = all casualty rate

Remarks to Table 5:

- Dealing with the casualty data in this statistics we have to be careful. The fatalities are acceptable statistically (as reported from the scene) and also the total number of the injuries, but their real severity is questionable. The number of the serious injury is strongly underestimated.
- The fatality rates clearly show the essential importance of the SS. If the survival space is damaged, the fatality rate is higher with one order (15 times) compared to the unharmed SS. The rates of the serious injuries show also a significant difference (3,5 times higher)
- On the basis of these statistical data it may be said that the casualty risk of intrusions can be drastically reduced by the requirement of the intact SS, by the required strength of the superstructure.
- It is interesting to mention - on the basis of Table 5. - that the slight injury rates are not closely related to the kind of rollover groups. It may be assumed that this type of injuries are caused mainly by projection (the inside collision of the passengers) when they are leaving their seats, seating position during the rollover process. The main tool to reduce this kind of injuries could be the use of seat belts. (It has to be emphasized that the seat belt can reduce the number of fatalities and serious injuries, too, and also the ejection of the passengers.)

When starting to work with R.66 (in the mid of '70s) one of the most important and long discussed question was to find on appropriate standard approval rollover test. At that time there was no clear idea about the PRA-s, but there was a demand for a "good" approval test which separates the strong superstructures from the weak ones. Figure 7. shows three kind of rollover tests used in Hungary.

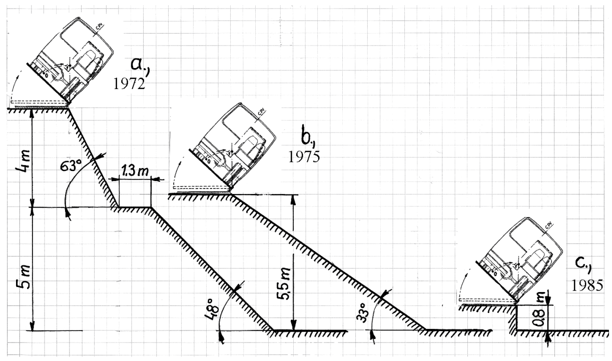

Figure 7. Different rollover tests, used and proposed by Hungary

This test series gave a good possibility to compare their results because the same bus types were used, altogether 8 full scale real rollover tests were carried out [4] The most severe test is – producing the most severe dynamic impact load on the cantrail – the version "c", which, at first glance seems to be the less severe one. Test "b" separated also the weak superstructure (see Figure 8.) from the strong one. Figure 9 shows the same test with the same bus type in which two reinforcing safety rings were installed and the survival space remained intact during the test, the superstructure did not collapse. But the comparison with the test "c" – using the same weak and reinforced buses – showed that the reinforced bus needed some further reinforcement at the rear part of the superstructure (see Figure 10.)

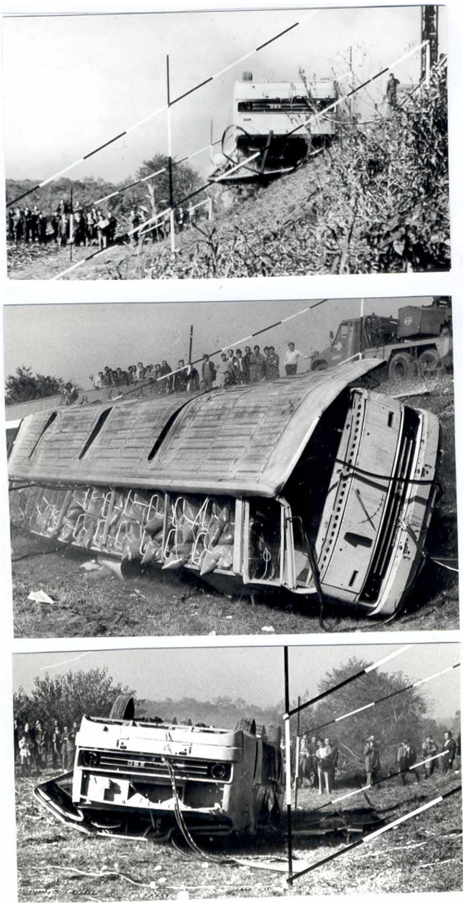

Figure 8. Rollover test with weak superstructure

Figure 9. Rollover test with reinforced superstructure

week superstructure

reinforced superstructure

Figure 10. Comparison with test "c"

Many real rollover accidents proved the effectiveness of the recent approval rollover test described in R.66. which is the same as the version "c" on Figure 7. Some examples are shown on the next figures Figure 11. shows the result of a rollover accident, which happened on a slope very similar to the version "b" on Figure 7. after 1,5 rotation. The level difference was around 6 m, the superstructure was "original", that means without reinforcement. After two steps reinforcement (and approval according to R.66) this reinforced bus had a rollover accident on a slope given in Figure 12. The level difference was around 9-10 m, the number of rotation 2 ¼ and after this accident no significant deformation could be observed on the superstructure. [5] (see Figure 13.)

Figure 11. Result of real rollover accident (Superstructure not reinforced)

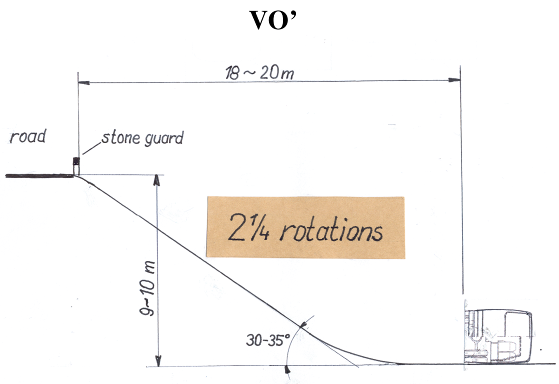

Figure 12. The scene of the rollover accident

Figure 13. After rollover no significant deformations

Another bus type – also approved according to R.66 – may be seen on Figure 14. after a rollover accident slope, number of rotation ¾, the level difference is around 5-6 m. An interesting test was published by Volvo [6] With an approved bus, having the required strength of superstructure a rather severe rollover test was carried out on the slope shown on Figure 15. After 3 ¼ rotations – the level difference was 17-18 m – the survival space remained intact, the intrusions were avoided. Nine dummies were used in this test, 7 of them had 3pts safety belt, 2 of them were without belt. The belted dummies remained in their seats, (no projection type injury) but the two unbelted dummies flew in the passenger compartment and had untraceable motion. According to our definition, this rollover accident is out of the PRA group (more than 2 rotations, more than 10 m level difference) it belongs to the severe rollovers. But having the required strength of superstructure and wearing seat belt, the survival probability of the occupants is strongly increased even in severe rollover accidents, too.

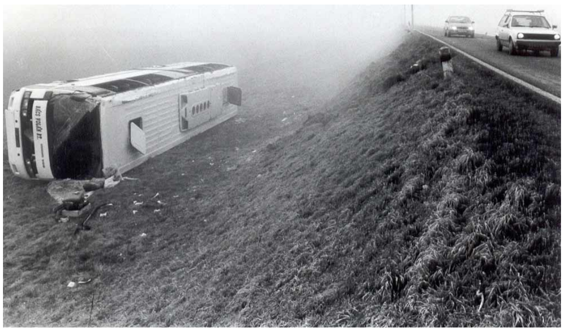

Figure 14. Rollover accident of an approved bus type

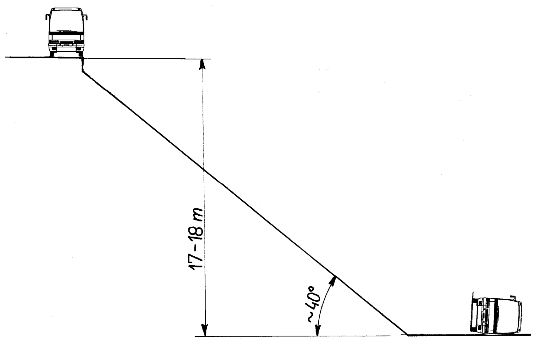

Figure 15. VOLVO's rollover test

TWO EXAMPLES

Thinking about the severity of rollover accidents, it could be interesting to study in details the following two accidents.

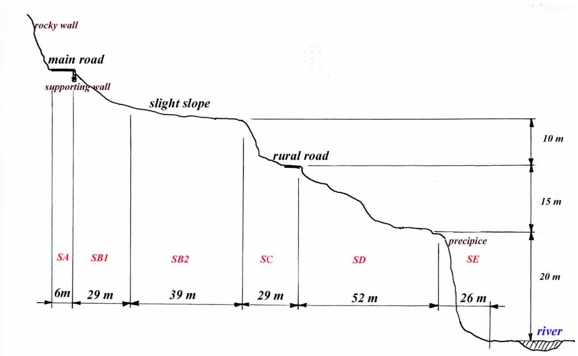

Figure 16. The path of the rollover

Switzerland, Grand St.Bernard Pass, 17.04.2005

HD tourist coach, 27 occupants on board rolled down from a mountain road The result: 12 fatalities, 15 serious injuries, 4 of them were in life danger. The path of the rollover process is shown on Figure16. Next to the road there was a 60-70 m long slight slope on which the bus had 6-7 rotations. After that a steeper section came, finally a 20 m deep rocky precipice completed the path of the bus. The final position and the completely collapsed roof can be seen on Figure17. Asking the question: was it a severe accident? – both approaches give positive answer, yes it was. But a detailed study proved [3] that if the bus should have had a strong superstructure which did not collapse at the first impact, the bus could slip away on the slight slope and stop before the steeper section. Of course certain injuries could happen in this case, too, but perhaps both approaches could say: no, it was not a severe accident.

Figure 17. Final position of the collapsed bus

Hungary, Balatonszentgyörgy, 10.07.2002

The HD tourist coach, 51 occupants on board, run into a roundabout with relatively high speed (The driver did not recognize the situation, it was gloom, night.) After uncontrolled manoeuvre the bus turned on its side, slipped away on the double-way roundabout 20-25 m and hit the other side of a ditch next to the roundabout. (see Figure18.) The roof structure completely collapsed as it may be seen on Figure19. The result: 20 fatalities, 17 serious injuries and 14 slight injuries. [7] The tip over (turned on side) is the less severe rollover based on the 2nd approach. But the first approach says, it is a very severe accident. But if the superstructure should have had the required strength, both approaches could say that this is not a severe accident. The public opinion says: it is unacceptable that in a similar accident (tip over) the casualty rates are so high. And that is the goal of the international regulatory work: to increase the safety, to avoid this kind of results in PRA-s.

Figure 18. The ditch, in which the bus landed

Figure 19. The collapsed roof structure

CONCLUSIONS

- The protectable rollover accidents (PRA) in which the bus occupants shall be protected may be and shall be defined.
- Every individual rollover accident is strongly influenced by the surroundings, the general geometry of the scene, but the process is similar for all bus categories.

- The severity of the rollover should be defined on the rollover process itself and not on the measure (number) of the casualty figures.
- The survival space concept and the belonging existing requirements are very effective. Statistical data prove that the all casualty rate is 3 - 4 times lower, the fatality rate is lower with one order (10 times) when the survival space remains intact in a PRA.
- There are four important injury mechanisms which should be considered enhancing the passenger safety in rollover. The most dangerous one is the intrusion, when due to the large scale structural deformation structural parts intrude into the passenger, or compress them (lack of the strength of superstructure)

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