# DEVELOPMENT POSSIBILITIES IN RELATION TO ECE REGULATION 66 (BUS ROLLOVER PROTECTION)

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ABSTRACT

This paper gives an analysis about the rollover process of buses in case of a standard accident simulation. International regulation requires certain strength and energy absorbing capacity of the superstructure to ensure survival space for the passengers. The kinetic energy of a rolling bus is transformed into deformation work and involving the energy losses too, an energy balance can be set up, and studied.

## 1. INTRODUCTION

International requirements for the roof strength of buses are formulated in UN-ECE Regulation 66., which is specifying a simple, reproducible „standard accident" as a test method and the requirements are related to this rollover test. Fig. 1. shows the general layout of this test: the empty bus, having no longitudinal speed rolls down into a ditch having a depth of 800 mm. The side rollover process starts from the unstable position of the bus with zero angular velocity. During this rollover, the deformation of the bus superstructure must be limited to provide a required survival space for the passengers. For the historical faith, it is interesting to mention that Reg. 66 - after some serious and tragic accident shocking the international public opinion - was born as the result of a long, ten years discussion in Geneva. (Between 1975-85). In spite of this long discussion the regulation contains a lot of contradictions, undetermined details. The ten years practice (1986-96) being the regulation in force and in use, gives the basis to the revision of Reg. 66. This study also tries to give technical arguments to this work.

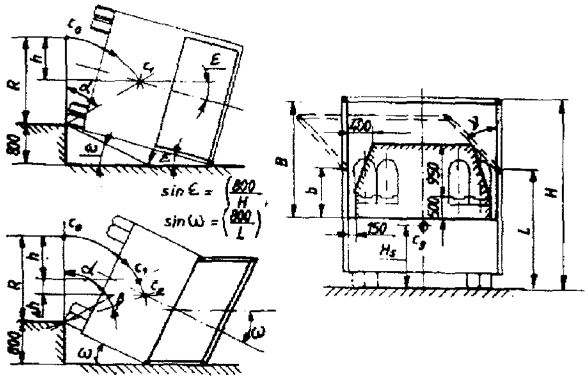


*Fig. 1. Scheme of rollover test*

## 2. THE ENERGY BALANCE

In the standard rollover accident (test) the kinetic (rotational) energy of the bus ($E_k$) is transformed partly into deformation work ($W_d$) which is absorbed by the load bearing elements of the superstructure and into a „residual" work ($W_r$) which does not influence directly the strength and deformation of the load bearing frame. The deformation work is absorbed by plastic hinges, in which the plastic deformation is concentrated. These hinges and their energy absorbing capacity [1] are the tools, the help of which the body is designed to meet the requirements of Reg.66. The kinetic energy of the bus can be given by the mass (M) and height drop (h) of CG as follows:

$$E_k = M\,g\,h = W_d + W_r \qquad (1)$$

This energy balance can be used for defining the condition of the required roof strength. The roof will not collapse, or in other words the deformation will be limited, if:

- starting the process when the cant-rail touches the ground, the kinetic energy is defined in Equ.1. by „h",
- having a certain deformation in the frame, which results further, additional height drop ($\Delta h$) of CG
- which produces further increase in the kinetic energy ($\Delta E_k$)
- and the increase of the kinetic energy is less, than the increase of absorbed deformation work ($\Delta W_d$) and residual work ($\Delta W_r$)

$$\Delta E_k = M^*\,g\,\Delta h \le \Delta W_d + \Delta W_r \qquad (2)$$

In the light of this energy balance it is interesting to study in details the followings:

- the kinetic energy as the function of the geometry of the standard rollover accident and the bus to be tested.

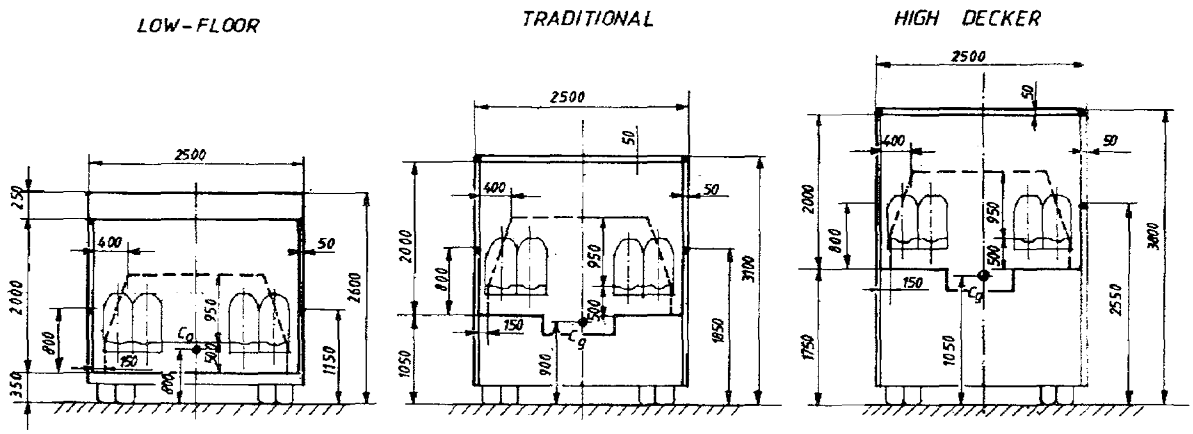


*Fig.3 Different bus categories*

- determination of the total kinetic energy
  $E_T = E_k + \Delta E_k$
- components and built up of the residual work.

3. ENERGY DEFINED BY REG. 66

3.1. Energy equations

The kinetic energy, when the bus cant-rail touches the ground can be derived by using some simplifications:

- the bus has a rectangular cross section
- the axis of rotation (determined by the tyres) is in the corner of the cross sections
- the tyres do not leave the ground (the axis of rotation) during the rollover
- the cant-rail of the body is rigid, there is no local deformation

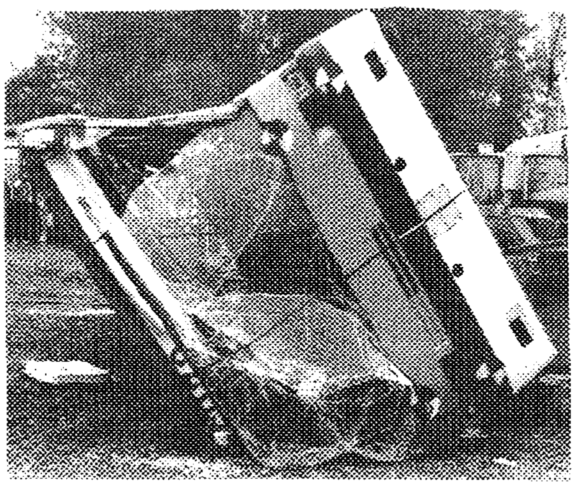

*Fig.2. Real deformations after rollover*

On the basis of Equ.1. and Fig.1, the kinetic energy may be formulated as follows:

$$E_k = Mg\left[\sqrt{\left(\frac{W}{2}\right)^2 + H_s^2} + \left(\frac{A}{H}\right)H_s - \frac{W}{2H}\sqrt{H^2 - A^2}\right] \quad (3)$$

Assuming a simplified deformation mechanism - which is realistic as Fig.2. shows - in which the deformation is characterised by four plastic hinges on one ring [2] (two hinges at the waistrail and two on the cant-rails) the deformation process can be easily described. When the cant-rail contacts the ground, the plastic hinges start to work, the rigid part of the bus body (below the waistrail) roles further and if the rings of the body (window and door pillars) are not strong enough the waistrail will also contact the ground (See Fig.1.) During this deformation process the height of the bus CG is decreasing by $\Delta h$, or in other words the kinetic energy is increasing:

$$\Delta E_k = M^* g\left[\frac{W}{2H}\sqrt{H^2 - A^2} - \left(\frac{A}{H}\right)H_s - (\cos\gamma)\sqrt{\left(\frac{W}{2}\right)^2 + H_s^2}\right]$$

It should be emphasised that M*< M while the roof is stopped by the ground, it does not moves, it does not represent kinetic energy. (M* = 0,95M seems to be a good first approximation)

3.2. Bus categories, the main technical parameters

Regulation 66. in its scope relates to the large simple deck buses (The articulated buses should be considered as two independent part of the vehicle) Let us study the existing bus categories covered by the scope of Reg.66.

3.2.1. Different floor heights.

Let us assume that the passenger compartment has constant dimension in height and width, independently from the floor height and the service circumstances (e.g. the inside height of the passenger compartment is 2000 mm and its width 2400 mm, and the cross section is rectangular, not shaped) The survival space is connected to the passenger compartment (see dotted lines in Fig.3.) These mean that the higher floor needs larger total height, increasing the floor height means: lifting upwards the passenger compartment. Fig.3. shows this phenomenon with low-floor, traditional and high decker buses. If we assume that all of these three buses have a total length of 12 m and empty mass of 10 tons, we can compare their rollover process and energy figures only on a geometrical base. In the first three lines of Table I. these three buses are compared.

3.2.2. Ranges in length, width and mass.

The length of the buses covered by Reg.66. can change between 7 m and 15 m, the width between 2000 mm and 2550 mm. In consequence of these the empty mass range is 4,5 - 13,5 tons. The two extreme configurations are the „Midi" and „Highdecker" buses. Table I. also contains the data of these two vehicles.

3.2.3. Mini and double-decker buses.

The question has been raised whether these categories could be involved into the scope of Reg.66? What are the conditions of this extension? In this case the ranges of the main parameters of the buses are further widened. Table I. contains the main figures of these categories, too.

3.2.4. The shape effect

The rectangular bus model is a rather simplified one. To get some feeling about the shape effect, Fig.7. shows a real cross section (type IKARUS 250) comparing it to the rectangular approach. Table II. compares the main geometrical parameters, showing that the kinetic energy of the real bus is less (only 86%) than in the case of a rectangular cross section approach. Also the additional kinetic energy ($\Delta E_k$) is less (only 50%) in the case of shaped cross section. The figures ($\omega$ and $\nu$) in Table II. show that the superstructure will pass the rollover test in both cases. (But taking into consideration the uncertainties in the measurement of the angles $\varepsilon$, $\omega$ and $\nu$ in case of curved cross section, and the real dimensions of plastic hinges can cause negative test result in a real rollover test)

3.3. Deformation limits created by the test method.

The rollover test - standard accident - has an essential, hidden problem: if the bus is high enough and the height of its waistrail (above the ground) is exceeding a certain value, the possible deformation of the window and door columns ($\omega$) is limited - see Fig.1. - while the waistrail hits the ground and this stops the further rotation. Having a week superstructure, this rollover test will prove it as a strong one. The survival space will be untouched because of the limited window column deformations. The problem occurs, if:

$$\omega < \nu \qquad (5)$$

The highdecker bus shown on Fig.3. has the following values: $\omega$ = 18,3° and $\nu$ = 31,6° and that means that the rollover test (or its simulation by computer) will prove the superstructure practically independently from its real strength.

3.4.Comparing the kinetic energies

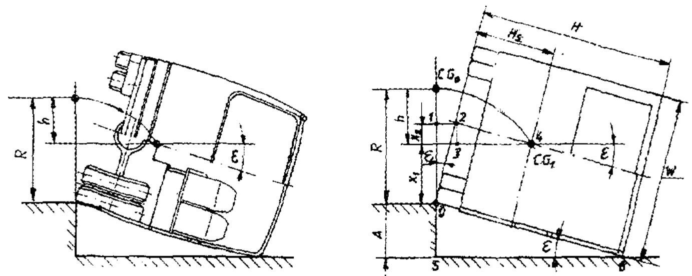

*Fig.4. Real cross section compaired*

It is interesting to compare and analyse the energy values of the buses covered by the scope of Reg.66. To make it easier rectangular cross sections are used as first approximation. Table I. contains these data. The question is whether the rollover test provides the same conditions for the different bus categories? Some general statement can be fixed on the basis of the data:

- The kinetic energy ($E_k$) of the different buses when the cant-rail hits the ground is not the same, it has a wide-range scatter. The maximum value is more than 4 times higher than the minimum. (See high decker and midi buses) The scatter is influenced mainly by three parameters: the mass (M), the total height (H) and the height of CG.
- The relative kinetic energy - when the energy is related to the mass - is proportional to the droop of CG (h). In this case the scatter is smaller, the ratio between the maximum and minimum values is 1,4. In the case of real buses (real shape) it can be 2. So it can be stated that the relative energy is also different for different buses.
- the additional kinetic energy ($\Delta E_k$) which is the result of the superstructure deformation until the waistrail touches the ground, has also the same wide-range scatter as the energy ($E_k$) itself, as well as its relative value ($\Delta h$) both of them having a ratio 4 of the max. /min. values.
- in the case of lower buses (e.g. low-floor bus) the additional kinetic energy ($\Delta E_k$) can be equal

to the original kinetic energy ($E_k$) while in the case of high deckers it is 20-25%

3.5 What is the basis of the standard rollover test?

The following question can be raised: which parameter is the same (constant, equivalent) when using the standard rollover accident specified in Reg. 66. for different bus categories. As -the result of the former analysis, it can be said:

a) the direction and the value of the impact force (on the contrail) is different
b) the kinetic energy is not the same
c) the relative kinetic energy is also different
d) the geometrical limitation of the superstructure is different that means: limited for some buses and not limited for others, depending on the strength of the main load bearing elements, rings.

The only one parameter, which is constant in the standard test is the depth of the ditch (800 mm). But this value is not related to the construction of the buses and it is not representative for the road constructions, as well. There are different real ditches along the roads, but not similar, not the same as specified in Reg.66. This is an artificial shape and artificial value. The new standard accident - which could be the basis of the rollover test must be simple as the recent test, but one or two problems listed above should be solved (should be equal for every kind of bus)

4. POSSIBLE NEW STANDARD ACCIDENTS, ROLLOVER TESTS.

Defining a new standard accident the followings should be maintained from the existing one:

- it should be a simple, reproducible rolling down by side from a standing position (without travelling speed)
- it should be a quasi static rollover: the rolling down should not have an angular velocity in the starting position (This is the equilibrium position of the bus tilting on side)

Considering the four problems listed in chapter 3.5. (a, - d,), the following standard accidents can be defined (See Fig.5.)

**A) Constant direction of reaction force** ($\varepsilon$) on the cant-rail. Having different bus heights (H) the depth of the ditch (A) should be adjusted. The required value of the force angle ($\varepsilon$) should be based on the criteria of avoiding the limited roof deformation, avoiding the waistrail to hit the ground before rings (pillars, columns) can introduce into the survival space if the superstructure is week.

**B) Constant kinetic energy level** ($E_k$) The depth of the ditch (A) can be adjusted to „h" (see Equ.1.) considering the mass (M) of the bus. This is not a realistic method: using this criteria a small midibus superstructure should absorb the same kinetic energy as a big high decker coach.

**C) Constant relative kinetic energy level.** (When the energy is related to the mass of the vehicle) This means constant drop of CG (h) until the contrail hits the ground. The required value of „h" has to also ensure the unlimited deformation of the superstructure.

**D) Ensuring unlimited superstructure deformation.** The depth of the ditch can remain 800 mm as it now exist in Reg.66. but the ground level is shaped, deepened to avoid the too early contact of the waistrail. The value of $\Delta A$ do not effect the value „h" but it can influence the value „$\Delta h$" when limiting the structural deformation.

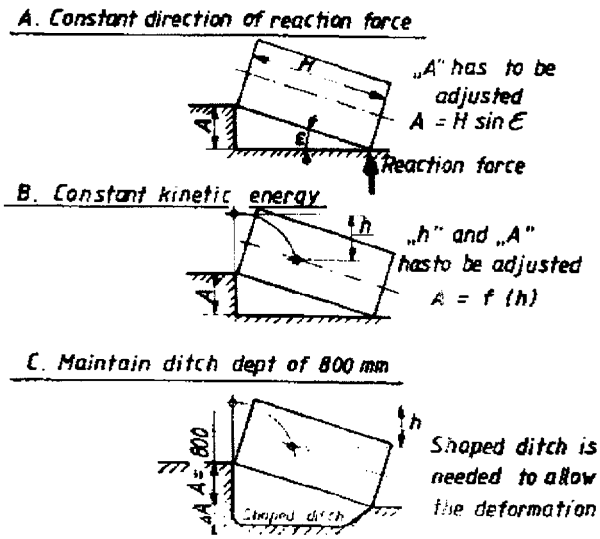


*Fig.5. Different types of rollover test*

Theoretically the best solution is the combination of „A", „C" and „D", where the deformation is not limited, the relative kinetic energy (h) and the direction of the impact force on the contrail ($\varepsilon$) is fixed. Fig.6. shows that the technical solution of the proposed new rollover tests in rather tests is rather simply, the principle and the tilting platform, developed to the existing test, can be used. That means: the modification of the test is simple and not cost sensitive.

5. RESIDUAL WORK, ENERGY WASTE

A certain part of the kinetic energy - see Equ.1. - is not absorbed by the structural deformations (more exactly that deformations which are dangerous related to the survival space) and it is gone on different paths, ways. Sometime this energy is called „energy waste", but this term is not appropriate because the higher energy waste the better for the survival space. In the followings the components of the residual work (energy waste) is analysed.

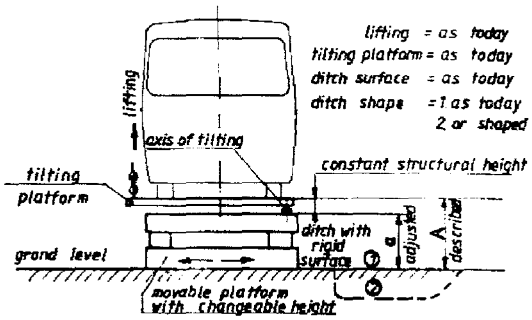


*Fig.6. Technical solution to new rollover test.*

5.1. Local wastes when cant-rail hits the ground

Along the cant-rail, when it hits the ground a reaction force is built up which - beyond causing ring (column) deformations - results local energy absorbtions, too:

- by the soil deformation an oscillation
- by the cant-rail local buckling local deformation
- friction work, while the cant-rail slips on the ground

5.2. Kinetic energy of moving further

During the rollover process the centre of rotation is determined by the wheels (by their plumb points, see Fig.1.) The reaction forces at these standing plumb points are continuously decreasing during the free rotation of the bus. The situation is changed when the contrail hits the ground. The contrail is stopped in its motion, another reaction force is built up along it and the further motion (rotation) is determined by two centres of rotation (wheels and contrail) The plastic hinges start to work, the two parts of the body have a contra rotating motion. This period of the rotation is still energy producer while the CG-s are going downward. The condition of this further motion is expressed by Equ.2. Another essential change occurs in the motion when the waistrail touches the ground:

- the whole upper part of the body (above the waistrail) stops, it does not have further motion
- the lower part of the body (below the waistrail) rotates further but its centre of rotation is changed, it is relocated to the waistrail, because the wheels leaves off, there is no more supporting force at the wheels.

This is an energy consuming motion, while the CG is moving upwards and also kinetic energy is absorbed by the working of plastic hinges. When the whole kinetic energy is consumed by the lifting of CG, a certain potential energy has been stored which starts a rotation backwards again, so a certain oscillation of the body can be observed. This oscillation is strongly damped by local deformations and slips, but this energy waste also does not influence the survival space.

5.3. Energy relations of big suspended units

The main aggregates of the bus (e.g. engine, radiator, axles) represent big concentrated masses in the body which are suspended elastically to the body through some definite points. It means:

- during the rollover (when the body hits the ground) big dynamic mass forces are created on the suspension points by the big masses, the results of which is plastic deformations around these suspension points. This means energy absorbtions without effecting the survival space
- the elastic suspension results independent oscillation of the big masses which also consumes energy
- the axles (the mass of which is 22-25% of the total mass of the empty vehicle) have long spring way (80 mm) therefor when the body hits the ground and the motion of the body is stopped in a very short time (0,1s), the axle masses can move further and their deceleration takes 0,5 s, that means their mass force effect is delayed, retarded, their kinetic energy is not absorbed by the plastic hinges but by oscillation (e.g. shockabsorbers)

All of these energy components, which are not effecting the plastic hinges have to be analysed and measured in the future, because it is very important to know the ratio of $W_r/W_d$ when making a rollover simulation by calculation. The existing Reg.66 gives a ratio $W_r/W_d = 0{,}333$

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Table I

| Bus and coach | | | | Kinetic energy | | Geometrical values | | | Angular values (°) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | M (t) | H (m) | W (m) | $E_k$ | $\Delta E_k$ | R (m) | h (m) | Δh (m) | ω | ε | β | α |
| Low floor | 10 | 2,6 | 2,5 | $5,39x10^4$ | $5,67x10^4$ | 1,48 | 0,55 | 0,61 | 44,0 | 17,9 | 26,1 | 51,1 |
| Traditional | 10 | 3,1 | 2,5 | $5,69x10^4$ | $2,33x10^4$ | 1,54 | 0,58 | 0,25 | 25,6 | 14,9 | 10,7 | 51,5 |
| High decker | 10 | 3,8 | 2,5 | $6,18x10^4$ | $1,39x10^4$ | 1,63 | 0,63 | 0,15 | 18,3 | 12,1 | 6,2 | 52,2 |
| Midi | 4,5 | 2,55 | 2,3 | $2,07x10^4$ | $2,00x10^4$ | 1,34 | 0,47 | 0,48 | 41,8 | 18,3 | 23,5 | 49,5 |
| High decker | 13,5 | 3,8 | 2,55 | $8,60x10^4$ | $1,76x10^4$ | 1,65 | 0,65 | 0,14 | 18,3 | 12,1 | 6,2 | 52,2 |
| Mini | 3 | 2 | 2,0 | $1,32x10^4$ | $1,73x10^4$ | 1,14 | 0,45 | 0,62 | 57,3 | 23,6 | 23,7 | 52,7 |
| Double decker | 15 | 4 | 2,55 | $12,8x10^4$ | $1,82x10^4$ | 1,85 | 0,87 | 0,13 | 16,0 | 11,5 | 4,5 | 58,1 |

Table II

| **Cross section** | **R** | **h** | **Δh** | **ω** | **ε** | **β** | **ν** |
|---|---|---|---|---|---|---|---|
| Regtangular | 1540 | 580 | 250 | 25,6° | 15,2° | 10,2° | 31,6° |
| Real IK 250 | 1500 | 500 | 125 | 24,2° | 15,9° | 63° | 28° |