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Non-linear energy accumulation buffers

Nick Mellor

Lift and Escalator Industry Association (LEIA)

Abstract Lift buffers are listed as safety components in Annex IV of EC Directive 96/16/EC on lifts. Requirements for the application and type testing of buffers, including non-linear energy accumulation buffers, are given in EN 81-1. Their function is to limit acceleration levels in the event that either the car or counterweight reaches the ends of the lift well without the normal slowing down having been effective. In this paper, lift car buffering at the bottom of the well is considered.

Of the three types of buffers commonly accepted by the main codes, both linear energy accumulation (spring) and energy dissipation (hydraulic type) buffers are readily analysed in relation to the acceleration levels of persons in the lift car and have had requirements for their application in the main codes for a long time. Non-linear energy accumulation (polyurethane or elastomeric) buffers have had requirements in EN 81 for a shorter time commensurate with the time that these types have been in common use. These, since their buffering forces are highly non-linear with buffer compression, make prediction of the behaviour of the lift car under buffering more difficult. This paper is intended to provide a simple model assessing the behaviour of the lift car once it has impacted non-linear energy accumulation buffer(s).

This model is used with a number of buffer characteristic curves and with a range of loads and buffer impact speeds, both in the free fall and assuming that the suspension remains intact, to examine the likely behaviour of the lift car after contacting the car buffer(s). A further intention is to critically examine both the average and peak accelerations derived from the model in relation to the requirements in EN 81-1.

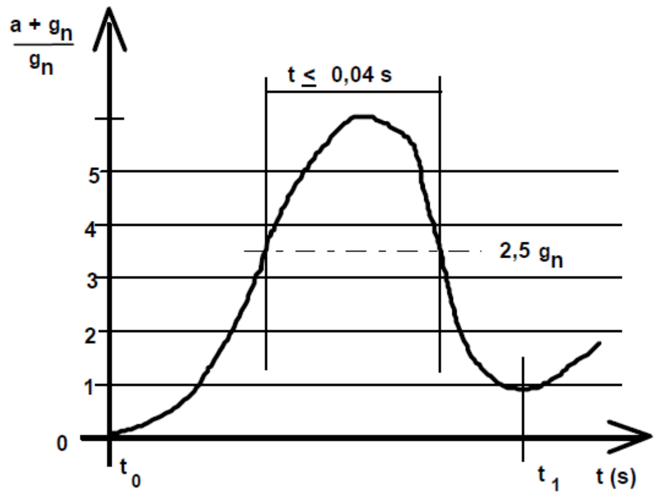
INTRODUCTION

The requirements in EN 81-1 (BSI, 2010), limiting acceleration for non-linear energy accumulation buffers (typically made from polyurethane and also called elastomeric buffers), are specified in relation to a free falling fully loaded lift car impacting the buffer at 115% of rated lift speed and are for:

- average acceleration to be not greater than 1 g_n;
- peak acceleration exceeding 2.5 g_n to be for duration not exceeding 40 mS.

EN 81-1 limits the application of non-linear energy accumulation buffers to lifts with rated speeds not greater than 1.0 m/s although further tests have been done with Notified Bodies on their application to lift speeds up to 1.6 m/s.

The requirement for the average acceleration is consistent with the maximum levels set for devices such as progressive safety gear and energy dissipation buffers. The average acceleration, as defined in EN 81-1 Annex F.5 which specifies type testing requirements for non-linear energy accumulation buffers, is measured between the first absolute minimum in the acceleration (on first hitting the buffer) and the second absolute minimum when the car comes momentarily to rest after rebound as shown in figure 1. Type testing of non-linear energy accumulation buffers is used to determine the maximum loads and speeds for a buffer type. Whilst it is clear that buffer impacts are very much more likely to be with the suspension intact, specification of the buffer requirements in this case is very much more problematic for those writing the standards or for the buffer or lift designer. Use of the free-fall fully loaded case provides a consistent basis for carrying out type testing.



t_0 = moment of hitting the buffer (first absolute minimum);

t_1 = second absolute minimum.

Figure 1 – Figure F.1 from EN 81-1 Annex F – retardation graph

A requirement limiting acceleration peaks of greater than 2.5 g_n to be no longer than 40 mS for energy dissipation buffers has been in EN 81-1 for some time having been in EN 81-1: 1977 (BSI, 1979) and before that in BS 2655-1 (BSI, 1970). The maximum acceleration of 2.5 g_n for oil dissipation buffers was present in an earlier BS 2655-1 (BSI, 1958) but that did not include for any transient peak exceeding this level. However, none of these standards had requirements for non-linear energy accumulation (polyurethane type) buffers.

Arising from buffering with the suspension intact, there are implications for acceleration levels experienced in the lift car during stops with car loading other than fully loaded. One of the objectives of this paper is to compare the average and peak accelerations with suspension intact using a range of car loads with those of the free fall case.

The method to be used to investigate the behaviour of the lift car during buffering with non-linear energy accumulation buffers is through deriving simplified equations of motion and then using these in numerical simulation. This relies heavily on being able to describe the buffering force mathematically as a function of buffer compression.

MODELLING NON-LINEAR BUFFER CHARACTERISTIC CURVES

Typical characteristics of non-linear energy accumulation buffers, as shown in the loading curve in figure 2, show very rapidly increasing forces for compressions greater than 65 – 75% of the buffer height, so the stroke is usually covered up to this range of compression. Below this point, there is a "plateau" area where the buffering force changes much less steeply.

Non-linear buffers exhibit significant hysteresis such that, when the buffer is unloaded, the force is significantly less for a given compression than the force taken to compress the buffer; shown as the unloading curve in figure 2. This characteristic of the material used in these buffers allows them to absorb a significant amount of energy when buffering.

Gill (1997) looked at how the buffer force/ deflection characteristic curves of the type shown in figure 2 could be modelled; reviewing earlier work and concluding that the buffer characteristic curve could be adequately modelled by a fourth order polynomial.

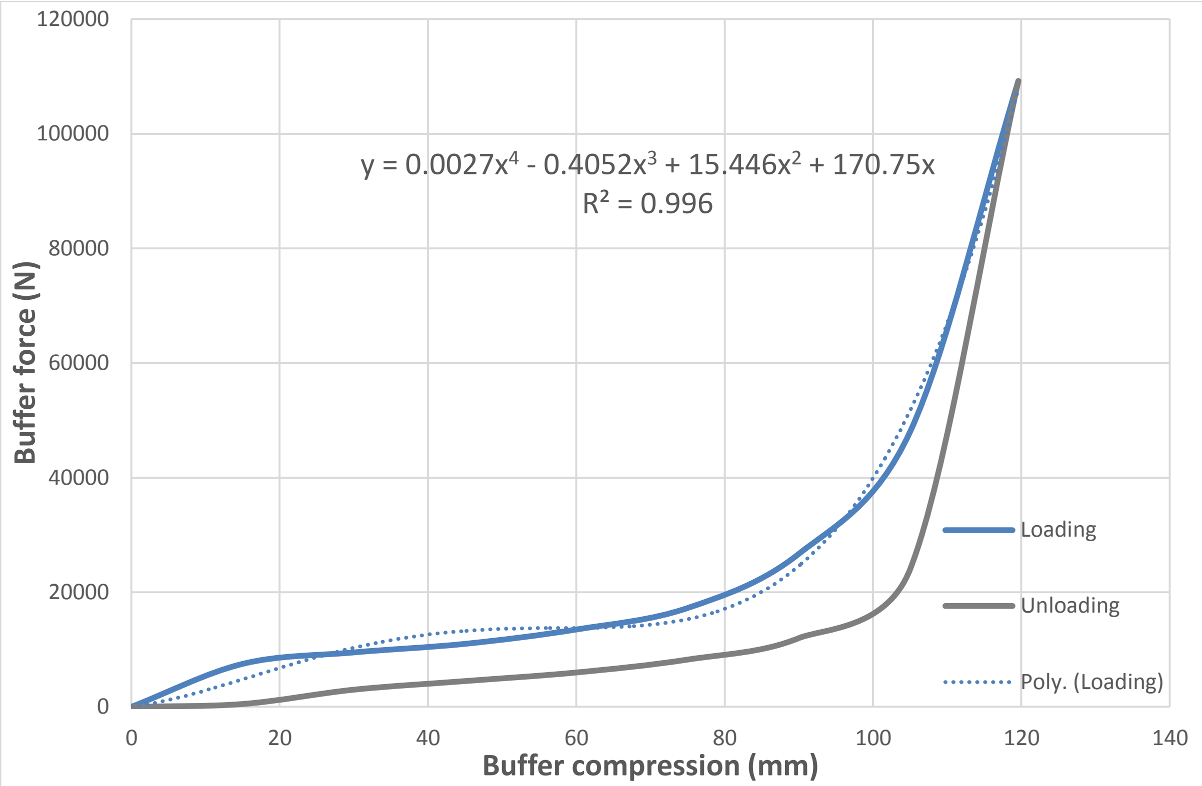


Figure 2 – Typical non-linear buffer characteristic curve

A typical buffer characteristic curve and 4^{th} order polynomial with line of best fit for the loading curve is shown in figure 2. Gill noted that the best fit would be from using a fifth order polynomial and this is shown in figure 3 below for the same characteristic curve.

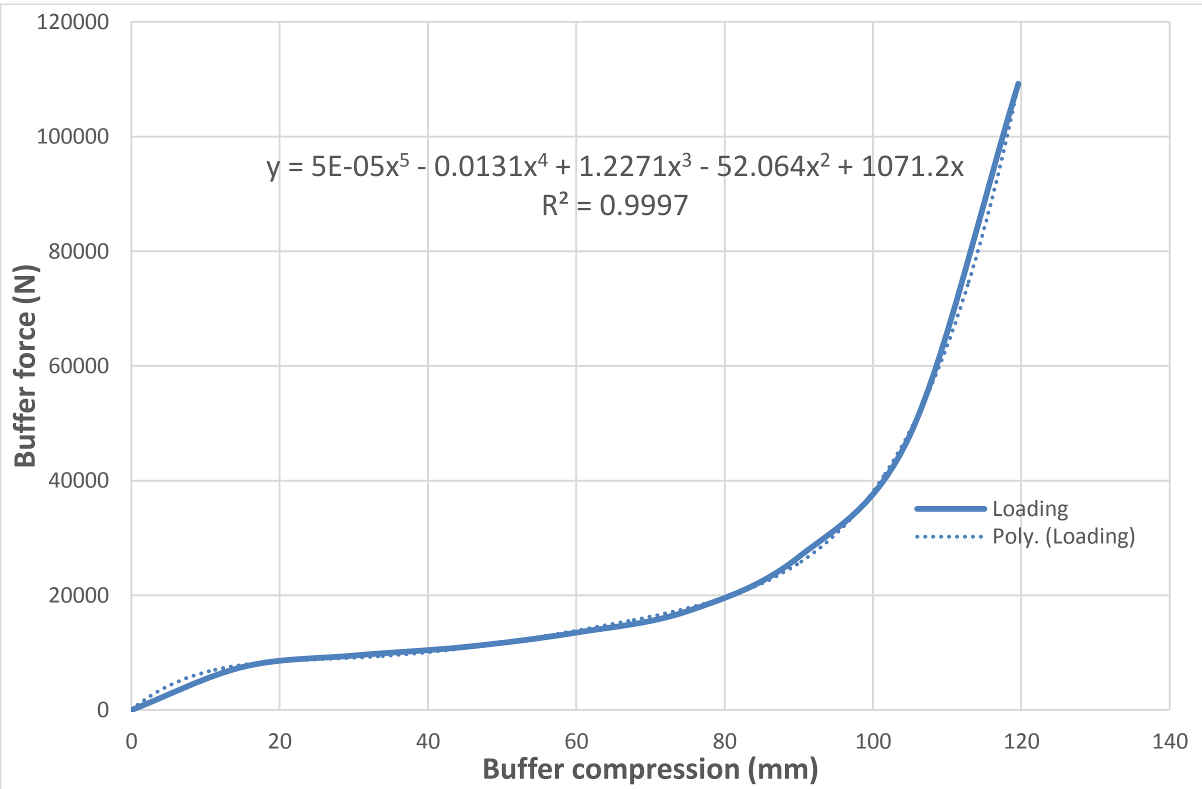


Figure 3: Typical characteristic curve and 5^{th} order polynomial fit

There is useful improvement by using a 5th order polynomial – especially in modelling small compressions, the plateau area and also the steeply rising section as the buffer becomes almost fully compressed.

As part of this work, force/ deflection characteristic curves for 18 buffers from four different manufacturers are considered for a range of rated speeds. The majority of these (16) are for rated speeds up to 1.0 m/s, one for speeds of 1.25 m/s and one for 1.6 m/s. The buffers covered a range of uncompressed heights from 80 mm to 340 mm. To enable comparison between different buffers, the characteristic curves were normalised so that compression was expressed as a proportion of the uncompressed buffer height and force was expressed as a proportion of the buffer force required for a compression of 67% of the buffer's uncompressed height.

For each buffer, the characteristic curve was first scanned and points for each curve manually selected and entered onto a spreadsheet. Having been normalised as described above, each curve was then fitted with a fourth order polynomial of the form:

Normalised buffer force:

$$y = A_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^4 \qquad (1)$$

where x is the normalised compression (proportion of the uncompressed buffer height).

Although Gill (1997) had allowed a non-zero value of A_0, in this study A_0 is set at zero to ensure that when x = 0, y = 0. A measure of how well a fourth order polynomial fits each buffer curve, the values of R^2, the regression coefficient, were noted; the worst was 0.994 indicating generally very good fits.

All 18 buffer characteristic curves are shown in figure 4. The close bunching of these shows that, irrespective of size or geometry of buffer, manufacturer or type, the buffers studied follow a very similar normalised characteristic curve. This offered the prospect of fitting a curve to all the available data points and to use this for further general investigation.

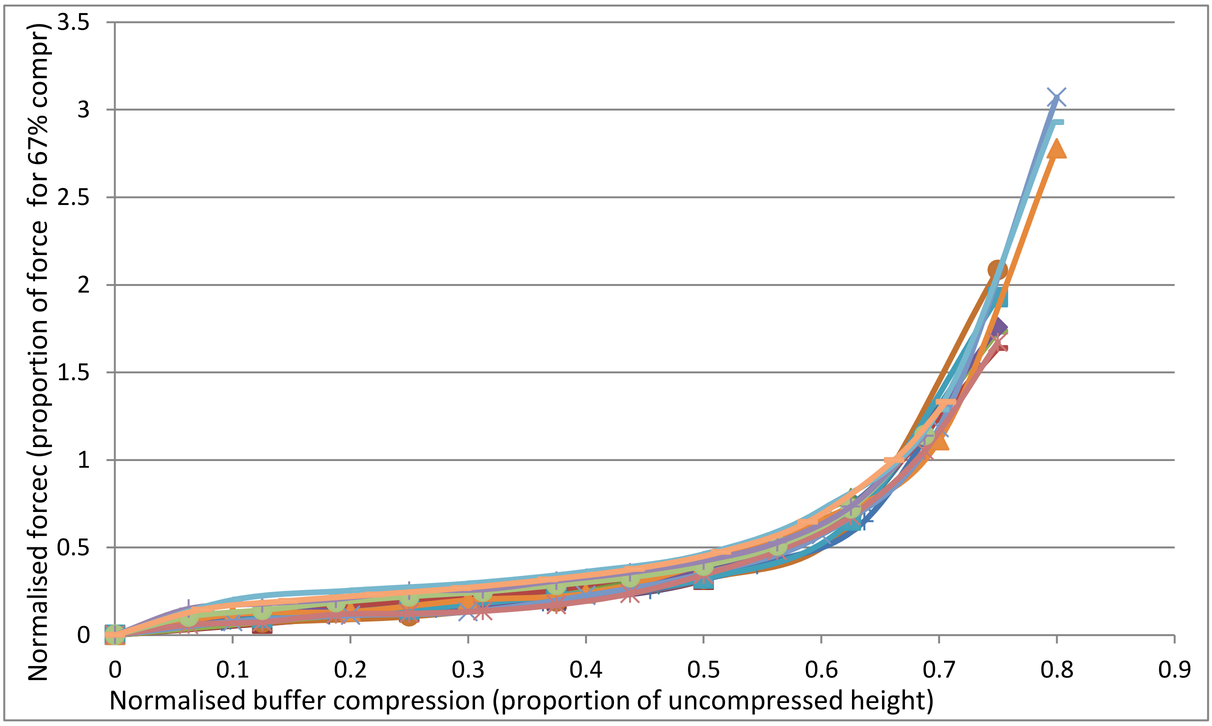


Figure 4: normalised buffer characteristic curves for 18 buffers studied

For the reasons outlined above, a fifth order polynomial was used for this curve fitting and the curve of best fit to all the data points in figure 4 was:

$$y = 2.7124x - 22.309x^2 + 87.249x^3 - 148.16x^4 + 94.62x^5 \quad (2)$$

The regression coefficient R^2 was 0.9873; a useful improvement on 0.98 for the 4th order polynomial.

Having a generalised buffer characteristic curve was of benefit because it allowed some general investigation to be done without reference to particular manufacturers or types of buffers and some general conclusions to be drawn.

ANALYSIS

For a simple analysis, the behaviour of the lift system under buffering can be analysed using Newton's second law since the lift car is influenced by its own mass, the tension if any of elements connecting it to a counterweight, and by the buffering force.

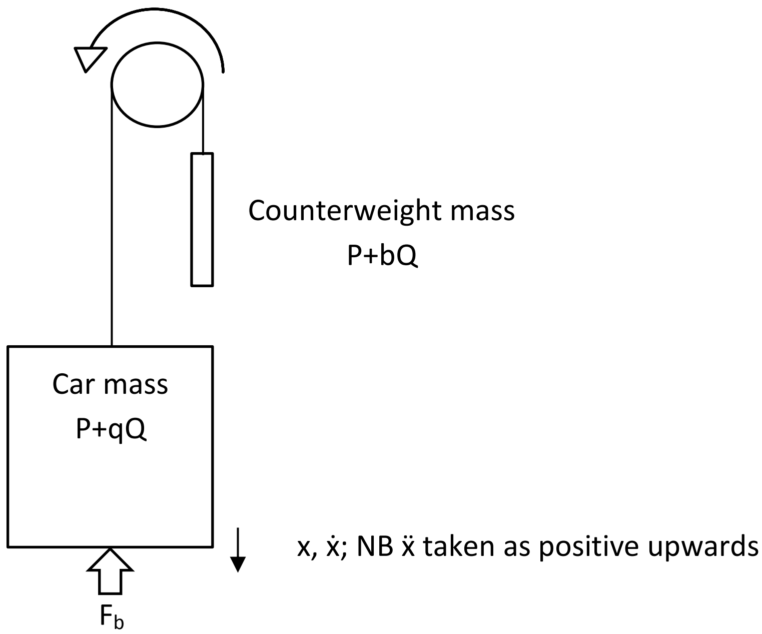


Figure 5: simplified model of car, counterweight and traction sheave

Where:

x – deflection of buffer starting from $x=0$ as the car first touches the buffer (m);

$F_b(x)$ – buffering force for deflection x (N);

R_{ct} – critical traction ratio for suspension elements over the traction sheave;

P – empty car weight (kg);

Q – rated load of the car (kg);

b – counterweight balance as a proportion of rated load;

q – proportion of car load as a proportion of rated load;

From figure 5, the motion of each of the car and counterweight can be described by:

$$\ddot{x} = \frac{F_b(x)+g_n\{P(R_{ct}-1)+Q(bR_{ct}-q)\}}{P(R_{ct}+1)+Q(bR_{ct}+q)} \text{ for } \ddot{x} \leq 1g_n \quad (3)$$

$$\ddot{x}_{car} = \frac{F_b(x)-g_n(P+qQ)}{(P+qQ)} \text{ for } \ddot{x} > 1g_n \quad (4)$$

$$\ddot{x}_{cwt} = 1g_n \text{ for } \ddot{x} > 1g_n \quad (5)$$

These would be relatively easy to solve analytically if $F_b(x)$ is a linear function of buffer compression, x. As demonstrated by the discussion of characteristic curves above, the relationship between buffer force and compression is highly non-linear over its stroke.

Fortunately, the use of numerical simulation allows for the behaviour of such systems to be investigated along with factors which might otherwise be neglected in an analytical approach. To achieve the objectives of this paper, it is necessary to present a simple model for numerical simulation. The model used includes the following:

- formula (3) for when the system remains coupled and acceleration is $< 1g_n$;
- formulae (4) and (5) for the car and counterweight for when car acceleration is $\geq 1g_n$;
- buffer reaction force modelled as a polynomial curve of best fit.

This simplified analysis makes a number of assumptions:

- The influence of the traction sheave and machine on rope tensions during the buffering stop is ignored by assuming that the electromechanical brake does not engage and that, by making Rct=1, in the equation (3), the tensions are the same on either side of the traction sheave i.e. no effects from either inertia or drive from the machine. This would be most appropriate for a low inertia machine such as a gearless machine.
- Guide friction forces and others due to friction losses in ropes, pulleys etc. are ignored. The influence of these would typically be a few percent of the out of balance load of the lift and therefore a smaller proportion compared with the average buffering force of $2g_n(P+Q)$.
- Suspension elasticity is ignored. Non-linear energy accumulation buffers are typically used in low rise lifts owing to the limitation on the maximum rated speed and so a maximum travel of 20 m can be used to assess suspension elasticity. At this travel, depending on the rope selected, factor of safety, and the overall design, the elastic rope stretch for one side would be of the order of 10 mm – 12 mm for the ropes and possibly of the order of 15 mm - 20 mm when compression springs are included. These dimensions are much smaller than the buffering distances and are likely to be important as system acceleration approaches 1 g_n and in the case that the suspension becomes taught again after a counterweight bounce. Since the latter should not happen until after the end of the initial acceleration peak, it is neglected in this paper.
- Buffer hysteresis is not considered. Buffer hysteresis is significant in modelling the rebound of the lift car during buffering and hence the second part of the acceleration peak. Since rebound speeds, and therefore accelerations, are likely to be reduced, the peak acceleration curve is likely to reduce more quickly with hysteresis effects included. These effects are not included here and would be interesting to model in future work.
- Other dynamic effects such as due to the mass and damping properties of the buffer are not modelled in this paper.

INVESTIGATION

Having modelled the buffer characteristic curves and set-up a numerical simulation, these were used to investigate the following questions:

1. For the buffers modelled, what average and peak accelerations are predicted for free-fall fully loaded cars, for both minimum and maximum specified loads?
2. For the buffers modelled, how do predicted acceleration rates for buffering with suspension intact (both empty and fully loaded) compare with the free-fall full load case?
3. For the generalised buffer characteristic curve, how do average and peak accelerations predicted vary for varying load and buffer heights?
4. For the generalised buffer characteristic curve, what are the potential implications of the changes to be introduced with EN 81-20 and EN 81-50?

RESULTS OF THE INVESTIGATION AND DISCUSSION

The results from preliminary simulation and modelling suggest the following results in relation to the questions posed above.

Peak accelerations of free-falling fully loaded cars

Simulations results for free falling fully loaded cars at the maximum rated speed for buffers and with the maximum specified loads, the peak accelerations were (with the exception of one buffer at 4.3 g_n) within a range between 6.9 g_n and 10.7 g_n; with an average for the 17 buffers of 8.9 g_n. The peak accelerations for the minimum specified loads were somewhat lower with an average of 5.0 g_n.

Of the buffers included in the study with rated speeds greater than 1.0 m/s, the buffer for 1.25 m/s showed similar acceleration rates and peaks as those at 1.0 m/s. The buffer with rated speed of 1.6 m/s actually showed the lowest peak accelerations, at 4.3 g_n, for maximum specified load (2.8 g_n at minimum specified load).

As a comparison, the simulation was run with a linear energy accumulation of the stiffest allowed in EN 81-1 (force of $4g_n(P+Q)$ for a buffer stroke of twice the gravity stopping distance). This showed a peak acceleration of 2.3 g_n i.e. as expected from an analytical approach.

It should be noted that EN 81-1 has no requirements for the level of the peak acceleration; only for its duration. These were generally within 40 mS for the maximum rated load cases but, with the minimum rated loads and lower peak accelerations, the peaks often lasted longer than 40 mS. However, the simulations were without damping losses included for the rebound behaviour; these would have the effect of slightly shortening the duration of the peak.

Implication for buffering of lift cars with suspension intact

In almost all cases, the peak accelerations with fully loaded car with suspension intact at the maximum specified buffer loads were significantly less than those for the free fall case; with an average of 6 g_n. The peak accelerations for the minimum specified loads were somewhat lower with an average of 4.5 g_n.

Peak accelerations for the empty car case close to the maximum specified buffer load were lower than the fully loaded case at 4.9 g_n average. Where the weight of the empty car was equivalent to the minimum specified load, average peak accelerations were 4.2 g_n. This clear reduction in peak acceleration for the empty car situation runs counter to the expectation of higher accelerations as would be expected during safety gear operation or even on linear energy accumulation buffers.

The explanation for this can be found in the difference in the characteristic of the non-linear buffers since, once onto the steeply increasing part of the curve, relatively small changes in the energy to be absorbed result in significantly different peak buffering forces. Since the empty car situation has significantly less energy to be absorbed compared to the fully loaded cases, the peak buffering force is reduced by more than the reduction in system mass and hence overall acceleration is reduced.

Variation of average and peak accelerations with load and buffer height

For this investigation, the generalised buffer characteristic curve derived earlier was used to explore how acceleration in the free-fall fully loaded case varied with load and buffer height. It was clear from the investigation of individual buffers that those taller relative to their rated speed showed generally lower peak accelerations. For this reason, the buffer impact speed was normalised by considering the gravity stopping distance for the rated speed as a proportion of the overall buffer height.

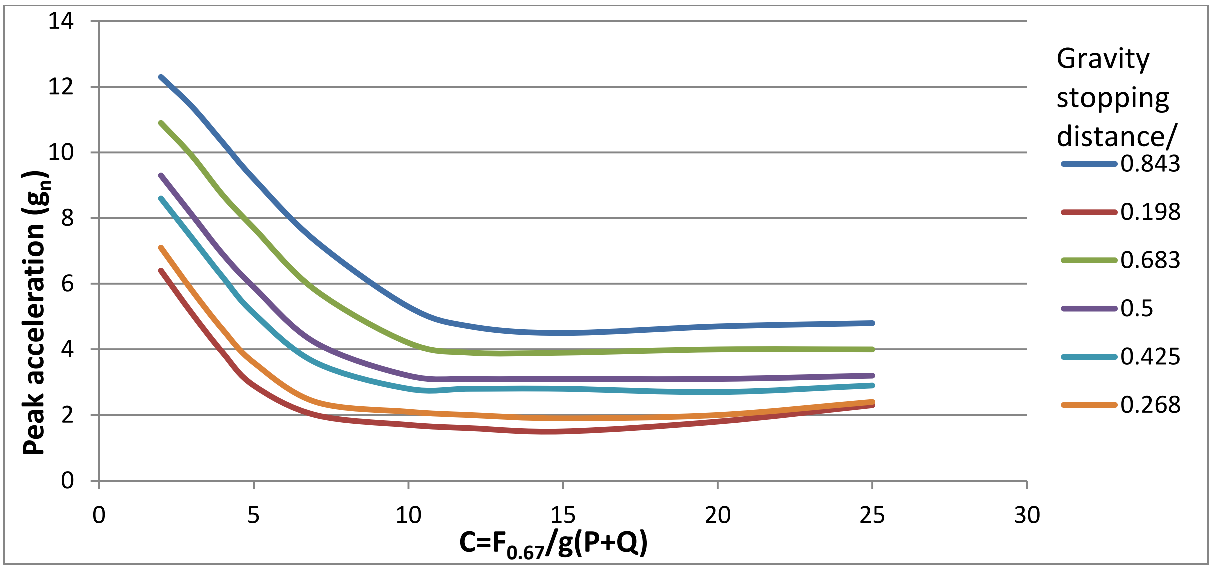


Figure 6: variation in peak acceleration with changes in load and height

A family of curves was plotted for different proportions of buffer height (equivalent to use of a buffer at different speeds) and these were plotted against variations in the ratio, "C", between the normalised buffer force (buffer for compression by 67% of the buffer's uncompressed height), $F_{0.67}$, and the load $g_n(P+Q)$ in figure 6.

The conclusions from these curves are that, if the value of "C" is small (higher rated load) then the value of peak acceleration is sensitive to the value of "C" and can be reduced significantly by increasing "C" (reducing rated load used). Thereafter, once on the flatter part of the curves, further increasing "C" has no further benefit.

A further observation is that reducing the gravity stopping distance as a proportion of buffer height (so increasing height or reducing rated speed) significantly reduces peak accelerations across the load range.

A similar influence is seen on average accelerations in figure 7; so either increasing buffering height, reducing speed or a combination of these reduces the average acceleration.

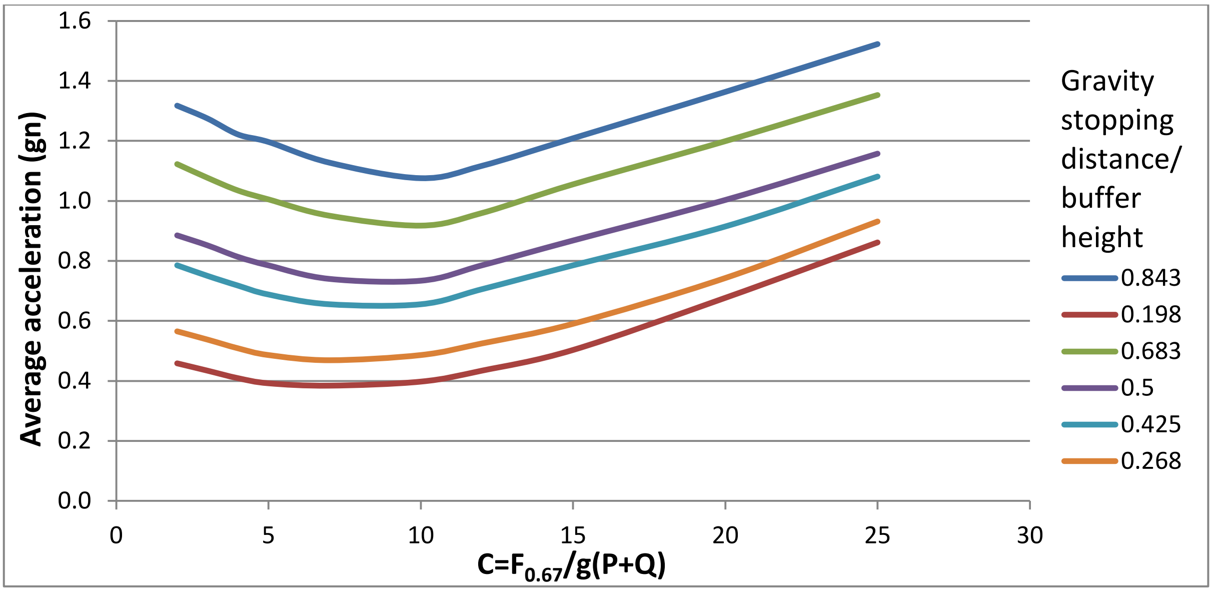


Figure 7: variation in average acceleration with changes in load and height

The results of figures 6 and 7 effectively demonstrate that there is trade-off in the value of "C" to be selected between the values of peak and average accelerations and that the requirements of meeting limits on each effectively define a working range of loads for given values of buffer height and rated load.

For the generalised buffer characteristic curve, an investigation of potential implications of the changes to be introduced with EN 81-20 and EN 81-50

The key new requirement which will be introduced by EN 81-20 will be a limitation of peak acceleration to 6 g_n for the free-fall fully loaded situation used to specify non-linear buffer requirements.

Reference to the results of individual buffer simulations described above show that, of the 17 buffers simulated, 6 would exceed this limit even at their lowest specified load; 10 would exceed this limit at their maximum specified load; and only one (the buffer with a rated speed of 1.6 m/s) would meet this limit across its specified load range.

It is therefore quite likely that many buffers, where measured peak accelerations exceed 6 g_n will need to have their load ranges revised. In the cases where this limit was exceeded across the whole load range, it is likely that reduced rated speeds would also be required. It is possible that some buffers might require new type tests.

A new requirement in EN 81-50 for type testing is for a pre-loading of the buffer within 30 minutes of the test to prevent further settlement and deviations during the test. This new requirement is because it has been found that the first impact of the buffer is not generally repeatable yet thereafter the buffer behaves in a reasonably repeatable way.

CONCLUSIONS

The work on modelling and simulation of the behaviour of the lift car buffering using non-linear energy accumulation buffer(s) allows a number of general conclusions to be drawn:

- The characteristic curves of 18 buffers of different types, manufacturers, heights, load ranges and rated speeds, were modelled by 4th and 5th order polynomials which provided very good "fits" to the curves.
- The characteristic curves of 17 buffers were used in numerical simulation of buffering of free-falling fully loaded lift cars to provide profiles of acceleration against time. These showed peak accelerations varying across the load ranges for each buffer; at maximum loads, peak accelerations averaged 8.9 g_n and some being greater than 10g_n. At the minimum specified loads, the average peak acceleration was 5.0 g_n.
- A simplified model of the lift masses was used as part of the simulation to investigate peak accelerations with suspension intact and to look at these for fully loaded lift cars at the top of the specified load range and empty cars at the bottom of the load range. In general, the fully loaded case exhibited lower peak accelerations than the free-falling case. The empty car cases showed still further reductions in peak accelerations.
- The characteristic curves for the 18 buffers were normalised for different buffer forces and heights. These showed very good correlation with each other. From these, a general buffer characteristic curve was derived which provided a very good fit and which allowed general investigations and conclusions to be drawn.
- The generalised buffer characteristic curve was used as part of the simulation to derive general graphs showing how peak and average accelerations vary with the specification of the buffer in terms of rated load and also in terms of the rated speed and buffer height. These indicate a load range bounded by meeting the requirements for both average and peak acceleration. These curves provided a basis for assessing how buffers could be brought in line with the new requirement in EN 81-20 to ensure the peak acceleration is not greater than 6 g_n.

Future work could usefully look at improvements to the results of this study by refining the model used e.g. including suspension elasticity and also by including the effects of buffer hysteresis effects.

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