# Track geometry for light rail systems

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## ABSTRACT

As it is known, light rail systems are characterized by their running over the streets, with semi-exclusive (or "reserved") right of way. This fact leads to the necessity of adapting the track geometry to the one existing in the streets, which sometimes leads to great challenges: strong vertical grades, horizontal circular curves with very small radius without superelevation and transition curves, vertical curves with very small minimum radius, etc.

Nevertheless, there are several good reasons for limiting track geometry parameters as far as possible due to their influence in vehicles design, in the efforts that the vehicle will transmit to the track (and, therefore, in maintenance work) and in operational and construction costs of light rail systems.

In the paper, limitations for different track geometry parameters will be analyzed, comparing recommended maximum or minimum values of each parameter established by TRB (Transportation Research Board) and by UITP (International Union of Public Transport) and explaining interesting cases, sometimes outside those limits.

The main reasons for each limitation will be exposed, either related to vehicle design, or passenger comfort, or any other physical condition.

Finally, the first conclusions of a research which is being developed by the authors in relation to track geometry parameters and construction costs of light rail systems in Spain will be presented.

## 1 INTRODUCTION

Lately, light rail transit systems are becoming increasingly important as a solution to the problem of metropolitan public transport in medium-sized cities, and as feeders for high capacity modes in bigger ones. This fact is due to their great flexibility for running over different types of streets and layouts as they can adapt to very strict conditions.

Light rail systems are characterized by their type of right of way (B), which suppose that they are longitudinally separated from other traffic by curbs, barriers, grade separation, and other physical means, but with grade crossings for vehicles and pedestrians, including regular street intersections (*1*). These grade crossings in intersections are necessary for maintaining the permeability of the city to the rest of street flows, given that light rail system runs generally on the surface, with a very good accessibility for users. This kind of design is usually known as reserved (or semi-exclusive) right of way. In any case, light rail systems can combine different rights of way in a single line, with some zones in exclusive right of way without any kind of interference with the rest of the city flows (as tunnels), other ones with reserved right of way with intersections in some points, and finally, other areas with street running without any separation from other types of street traffic.

The good accessibility mentioned above is due to:

- light rail vehicles run at street level in most part (or in the whole) of their trip, which leads to a very easy access for users. They take the public transportation system in the street, rising to the platform, which is, in general, a little higher than the curb. In this way, ascents and descents, typical of subway systems, are avoided.
- distances between stations for light rail systems are usually (in Europe) around 350-800 m. This distance is smaller than that for commuter rails (2,000-10,000 m) or for subways (1,000-2,000 m). So, access distances to stations are shorter than in other transportation modes, and users can cover them by walking in a reasonable time (5 to 10 minutes). This fact makes the system very convenient, even for short distance travelers.

Nevertheless, the fact that the vehicle runs at street level (which is, as exposed previously, very beneficial for accessibility), leads to the necessity of adapting the track geometry to the one existing in the streets, which sometimes gives rise to great challenges: strong vertical grades (rising or falling), horizontal circular curves with very small radius without superelevation and transition curves, vertical curves with very small minimum radius, etc.

Obviously, track geometry conditions are closely related to tractive and braking efforts to be required to vehicles, to their dimensions, to their structural behavior and the efforts that they will have to support, as well as to the efforts that the vehicle itself will transmit to the track (and, therefore, with maintenance work). So, a combined teamwork must be made between vehicle manufacturers and civil engineers to guarantee that the chosen light rail vehicle will be able to run over the track geometry of each installation. It is desirable that the vehicle requirements are not very severe, in such a way that a standard vehicle design can be used, instead of a customized model which will lead to higher costs.

Additionally, track geometry will have an influence in operational costs of light rail systems. This fact is a very good reason for limiting track geometry parameters as far as possible.

## 2 TRACK GEOMETRY

Main track geometry parameters will be specified in this section, highlighting recommended values established by TRB and UITP, and why each parameter must be limited. In section 4, the stricter values of main parameters for several existing networks will be shown, to point to the fact that recommended values are not always observed.

### 2.1 Track Gauge

Track gauge is one of the most important geometric parameters of track geometry. There are a lot of other parameters which are conditioned by track gauge (for example, minimum curve radius which the vehicles will be able to negotiate).

The most common value of track gauge for railroad systems is 1,435 mm, established as "standard gauge" in Bern Conference, in 1907. This value is compatible with UIC (International Union of Railways) heavy rail gauge, and it is track gauge stated by AREMA (American Railway Engineering Maintenance of Way Association) as American standard gauge. This compatibility is a good reason to use this value in light rail tracks, mainly because the procurement of track materials and track maintenance will be easier, and also because it can allow the use of those railroads in the future in track sharing, if this is a good solution for mobility problems.

So, this track gauge is the one used for most of new light rail systems, although 1,000 mm is a very common value too.

In relation to early tramway systems, there is a large variety of values for track gauge. Examples are: Rome (Italy), 950 mm; Lisbon (Portugal) old network, 900 mm; Linz (Austria) network, 900 mm; Braunschweig (Germany), 1,100 mm; Okayama, Enoshima, Fukui and Kochi, (Japan), 1,067 mm; Moscow, Volgograd, Saint Petersburg, Omsk, and a large number of Russian tramway or light rail systems with 1,524 mm (*2*).

The choice of gauge for a new light rail system can be more complicated if the local existing heavy rail system is of non-standard gauge, and either significant lengths of such existing tracks will be taken over for light rail, or heavy and light rail track sharing could be made even in the longer term.

In such situations, UITP (*3*) recommends seriously to consider the use of the existing non-standard gauge, unless it were so narrow (e.g. less than 1,000 mm) as to constrain the vehicle design unacceptably.

### 2.2 Track Horizontal Alignment

Geometric parameters of horizontal alignment are, basically: radii and length of curves, which will affect passenger comfort, as well as track-vehicle efforts, and therefore, their maintenance (for example by rail and wheel wear); superelevation, which will be related to passenger comfort according to operating speed, as well as to vehicle stability; transition curve length (in the case that they exist), which is related to superelevation gradient, and, finally, minimum straight track length between two curves, both conditioning passenger comfort an vehicle-track efforts.

#### *2.2.1 Circular Curve Radius*

Obviously, when a light rail system runs over a new created branch of the track, in a non-urbanized area, curve radii and superelevation will be settled in such a way that the maximum project speed can be achieved considering non-compensated centrifugal acceleration which can be withstood by travelers. This project speed will be limited by maximum operating velocity of the vehicle, which is usually not higher than 90 km/h, although there are some networks which run at speeds up to 100-120 km/h (i.e., Dallas light rail, by Kinki Sharyo, and model S70, by Siemens, used in Houston, San Diego and Portland, are able to operate at a maximum speed around 105 km/h).

When a light rail system runs over the streets, the layout will have to be adapted to them, and vehicle speed will be limited in the same way that it is for road vehicles (50 km/h in general, and 10 km/h in pedestrian streets, for Spain; this last value is usually raised to 25 km/h for light rail systems to avoid excessive influence in operation speed).

Minimum circular curve radius which can be negotiated in plan will specifically depend on physical characteristics of vehicle which will be used: distance between truck centers, distance between axles in the truck, the use of steering axles, the existence of physical axle between the two wheels of a wheelset, the number of articulations and their position, etc.

Even though a modified vehicle design would be able to negotiate almost any curve radius (as an example, in Lisbon old network minimum curve radius is 11 m), recommended limit values are established to avoid conditioning system operation excessively. These values are detailed in Table 1. As it can be seen, in general, TRB is a little more restrictive in horizontal curve radius, although differences are not very important. This fact is probably due to stricter restraints in street layout and space for European cities.

Real values of curve radius of light rail systems in operation nowadays can be seen in the last section of this paper. It is interesting to point the values of two modern systems as Lisbon new network, with 14.5 m, and Nottingham (United Kingdom), with 18 m (*5*).

On the other hand, in a study developed by TRB about applicability of low floor light rail vehicles in North America (*6*), it is stated that curve radius below 18 m may restrict the use of category 2 vehicles (i.e., those which use conventional motor trucks at each end and innovative trailer trucks in between them, with generally 50-75% uninterrupted low-floor area between the motor trucks); and curve radius below 20 m may restrict the use of category 3 vehicles (i.e., those which use conventional motor and trailer trucks throughout and generally have 9-15% low-floor area but may have up to 48%).

### *2.2.2 Minimum Length of Circular Curves*

According to TRB (*4*), minimum length of circular curves due to comfort will be:

$$L = 0.57 \cdot V \tag{1}$$

Where V is the vehicle speed in km/h and L is the circular curve length in m. With this equation, running over the curve will last 2 s at least. If there is superelevation in the curve, the absolute minimum value of circular curve length will be 15 m.

As an example of strict layout in relation to this parameter, Nottingham case can be pointed, with only 6 m of circular curve minimum length (*7*).

### *2.2.3 Minimum Length of Transition Curves*

The establishment of transition curves in the start and the end of circular curves is very advisable, even when they are in urban zone and they do not have superelevation. In this way, the curvature change will be gradual, and this fact will lead to improvements in comfort and reduction of wheel and rail wear. This is due to the fact that the angle of attack of the wheel when entering the curve will be lower with transition curves than without them, and so, the change of direction will be softer, and the impact between wheel and rail will be attenuated.

The clothoid is the most common transition curve. If there is superelevation in the curve, its length will be obtained according to maximum rate of change in superelevation that is allowed (see next sections), always accounting for the change in uncompensated centrifugal acceleration, which will affect passenger comfort. In other case, minimum recommended value is 20 m, and minimum absolute value is 10 m. This minimum absolute value is the one used in Nottingham light rail (*7*) and in Seville (Spain) light rail (*8*). In Tenerife (Spain) system the minimum length of transition curves is 12 m (*9*).

### *2.2.4 Superelevation*

Superelevation is used for compensating part of the centrifugal acceleration which occurs in curves. This compensation is due to the component of vehicle weight in track plan when it is inclined (i.e., when the outer rail is elevated). In this way, the passenger suffers less transversal acceleration for a given speed, or the speed can be increased keeping the value of lateral acceleration to be experienced by the passenger.

For light rail systems, UITP (*3*) recommends that the passenger does not suffer a transversal acceleration greater than 1 $m/s^2$, i.e., $0.10 \cdot g$ (where g is the gravity acceleration), the same value TRB establishes (*4*).

On the other hand, UITP recommends, for exclusive right of way, 120 mm as maximum superelevation value for track gauge of 1,435 mm (*3*), and 165 mm as absolute maximum value, while TRB recommended and absolute values are 100 and 150 mm respectively. This superelevation limit (165 mm) is set due to the problem for maintaining ballast bed if superelevation is greater, while lower values (150 or 120 mm) are imposed by passenger comfort (*3*). In case of reserved or mixed right of way, the limit will be given by layout compatibility with street alignments.

So, as it can be seen, TRB is again a little more restrictive than UITP in relation to superelevation, although differences are not big. This is probably due to stricter restraints in space for introducing a new light rail system with independent right of way in European countries, where there is a more intensive use of land. In such a situation, curve radii will often be lower, which leads to allow greater values of superelevation for keeping passenger comfort.

When running over a curve, maximum speed will be given by the following expression:

$$v = \sqrt{\left(a + \frac{g \cdot h}{1500}\right) \cdot R} \tag{2}$$

Where v is maximum operating speed (m/s); h is superelevation (in mm); a is maximum lateral passenger acceleration value (m/s$^2$); R is curve radius (in m). This expression is valid for international track gauge (with a distance between rail axis of around 1500 mm), and without accounting for suspension flexibility or track irregularities.

If maximum values of a and h are considered, the relation between speed (V, in km/h) and curve radius (in m), will be:

$$V = 5.2 \cdot \sqrt{R} \tag{3}$$

When the track is in urban zone, it is not common to establish superelevation in curves, because it is necessary to maintain a regular surface in such a way that road vehicles are able to run over it. Even where the right of way is reserved, there will be grade crossings and intersections with road traffic, in which it is compulsory to carry out this condition. This fact leads to stricter speed limitations to keep passenger comfort. Indeed, the relation between V and R in these cases will be:

$$V = 3.6 \cdot \sqrt{R} \tag{4}$$

Using these expressions, the speed limitation for a curved track with 25 m radius running over urban zone without superelevation would be 18 km/h, i.e. 15 km/h since speed limitation signals are in steps of 5 km/h. On the other hand, for a curve radius of 100 m, in exclusive right of way and with maximum superelevation, speed limit would be 52 km/h (i.e., 50 km/h).

Superelevation, if used, will increase and decrease linearly in transition curves in the start and the end of circular curves, raising and lowering, respectively, the outer rail height. Allowed maximum rate of change of superelevation should be 4 mm/m in modern light rail systems, according to UITP (*3*). In accordance to TRB (*4*), it should be such that superelevation differential between truck centers do not exceed 25 mm (for a vehicle with 7 m of distance between trucks, this will lead to maximum superelevation rate of change of 3.57 mm/m). In this way, an improvement in passenger comfort is achieved and vehicle frame twist is limited to avoid overstressing. In Nottingham light rail, maximum superelevation grade is 1 in 300, i.e. 3.33 mm/m (*7*). The same value is stated as absolute maximum for Genève (Switzerland), where recommended maximum is 2 mm/m (*10*).

These values will determine, for each case, minimum transition curve length if superelevation exists. Nevertheless, sometimes these limits are exceeded, specifically over alignments with reverse circular curves.

### *2.2.5 Minimum tangent length between reverse curves*

Generally, in railway track, minimum straight track length between two curves is set to be at least equal to that of the longest car in the trains that are going to use the track. This usually means that minimum length is around 30 m. Sometimes, distance between truck centers or between front and rear axle of the car are used, instead of longer car length.

However, it is usual to establish a comfort criterion, which sets that minimum straight track length should be such that the vehicle takes at least 2 s for running over it (*4*), in the same way that for circular curves. There are some administrations which establish smaller running times. This is the case of Genèva Public Transportation (*Transports Publics Genevoises, 10*), that sets a running time over tangent stretch of between 0.7 and 1.5 s.

Anyhow, the value that must be used is the greatest one between those from comfort and vehicle length criteria. Nevertheless, there are many situations in which these values can not be achieved, due to street layout restraints. In these cases, absolute minimum value of tangent track between curves will be given by the maximum angle which can be stood by the vehicle articulations. This can only be applied if operating speeds are below 32 km/h and no track superelevation is used in either curve (*4*).

In Nottingham light rail, minimum tangent length between reverse curves must be, at least, of 6 m, and if this is not possible, transitions of opposite hand curves shall meet at point of infinite radius (*7*).

## 2.3 Track Vertical Alignment

Geometric parameters related to vertical alignment are, mainly: vertical grades and their lengths, which will have an influence in vehicle tractive and braking performance demanded to vehicles, as well as in passenger comfort; and minimum vertical curve radii, which will determine passenger comfort, as well as efforts that must be withstood by vehicle frame.

### *2.3.1 Vertical grades and their lengths*

According to TRB (*4*), recommended limit value for vertical grades of unlimited length is 4.0%; for sustained vertical grades with up to 750 m between points of vertical intersection of vertical curves is 6.0%; while for short sustained grade with no more than 150 m between points of vertical intersection of vertical curves is 7.0%.

On the other hand, UITP (*3*) establishes that common limitations in modern light rail systems are 4.0, 5.0 or 7.0% (approximately the same values as TRB), although if fully motorized vehicles are used, they will be able to overcome vertical grades up to 10.0%. However, in planning stages it is recommended not to consider values over 4.0%, because they will lead to greater operation and construction costs.

A major reason for using steep grades is to minimize the length and cost of structures. In this sense, Tenerife light rail can be cited as an unusual example in modern light rail systems. In this case, the difference in height between Santa Cruz centre and La Laguna (the two ends of the line) has forced to use fully motorized vehicles to overcome maximum vertical grade of 8.5% in no more than 250 m, and maximum sustained grade of 7.5%. In Figure 1 the longitudinal section of Tenerife light rail line is shown to point its escarpment. In some parts of the layout it has been necessary to adopt inventive solutions, as the one which is shown in Figure 2, in which the light rail alignment has been raised in relation to the street one to avoid excessive vertical grade (14.5%).

In relation to minimum grade for drainage, TRB (*4*) sets 0.2% for direct fixation track. There are other administrations that demand values of 1.0 to 1.5%, and exceptionally, 0.5%. Sometimes a minimum grade of 0.25% is required in tunnels for removing water by a central drain.

Additionally, TRB (*4*) establishes a minimum recommended length for vertical grades of 30 m or 0.57·V (running time 2 s, in the same way of previous sections), with an absolute minimum of 12 m. However, this recommendation can be waived if street layout imposes smaller values.

### *2.3.2 Vertical curves*

Vertical curves are circular or parabolic curves located between vertical grades, which are characterized by their minimum circular radius. Minimum value of that radius must be limited due to the following two subjects:

- The requirement of keeping minimum distances from lower part of the vehicle to higher part of the track under dynamic loads or in failure conditions. These distances must be kept whether for crests or for sag vertical curves (see Figure 3). For checking this subject, the value of maximum angle which can be stood by the vertical articulation must be considered. Sag vertical curves are usually conditional on this topic.
- For restricting vertical inertial accelerations which influence passengers comfort. Crest vertical curves are usually conditional on this topic. In this sense, vertical acceleration experienced by passengers should not exceed the value of 0.2 – 0.3 m/s$^2$. Equation 5 expresses the relation between v (operating speed in m/s) or V (operating speed in km/h), with minimum vertical curve radius ($R_v$, in m), and vertical acceleration suffered by passengers ($a_v$). With this equation, the minimum radius of the vertical curve may be obtained in a simple way.

$$a_v = \frac{v^2}{R_v} = \frac{\left(\frac{V}{3.6}\right)^2}{R_v} \quad \rightarrow \quad R_v = \frac{\left(\frac{V}{3.6}\right)^2}{0.2} \approx 0.4 \cdot V^2 \qquad (5)$$

With equation 5, vertical curve radius for a speed of 50 km/h would be 1000 m, and for 25 km/h it would descend to 250 m.

UITP (*3*) establishes that the absolute minimum curve radius value for sag vertical curves is 350 m and not lower than 700 m for crest vertical curves. According to German Regulations, minimum parameter for vertical curves must not be bellow 625 m for crests and below 350 m for sags.

On the other hand, TRB (*4*) establishes as minimum vertical curve radius 250 m for sags and 350 m for crests, values that are quite a lot smaller than those of the UITP. In the case of crests, this must be due to greater values of allowed vertical acceleration to be experienced by passengers, or to stricter speed limitations for American systems, although this last reason does not seem very solid. For sags, the difference could be due to differences in typical vehicle design between European and American light rails.

If there are unusual restrictions which make necessary a very tight layout, smaller values can be achieved, although this can compromise vehicle design in a considerable way. This is the case of Amsterdam (Netherlands), with vertical radius up to 150 m.

## 3 TRACK GEOMETRY AT STATIONS

### 3.1 Track Horizontal Alignment at Stations

Both TRB (*4*) and UITP (*3*) recommend that stations have tangent alignment. In this way, excessive distances between platform and vehicle will be avoided and access to the vehicle will be easier. On the other hand, curves at stations lead to low visibility of doors by the driver, who has difficulties to control if there are passengers getting in or out, although this can be overcome by means of mirrors.

The effect of the curve at stations can be seen in Figure 4. Tangent stretch must be extended to both sides of the platform, in a minimum recommended length of 25 m, with a minimum absolute value of 15 m. Sometimes it is not possible to comply with this recommendation, and it is waived (see Figure 5 as an example).

If it is not possible to get a tangent alignment at any particular location, UITP (*3*) establishes that the radius should not be smaller than 300 m.

### 3.2 Track Vertical Alignment at Stations

Stations must be located in places with constant vertical grade (*3, 4*). This constant vertical grade stretch should be extended to both sides of the platform in a minimum length of 12 m. Recommended vertical grade at stations is 0.0%, and absolute maximum is 2.0 or 4.0%. Again, these tow conditions are waived if it is necessary (see Figure 6 and 7 as examples).

## 4 TRACK GEOMETRY PARAMETERS OF SOME LIGHT RAILS SYSTEMS IN OPERATION NOWADAYS

Extreme values of track geometry parameters of some light rail systems in operation nowadays can be seen in Table 2 and 3. Despite the recommended limitations that have been referenced along this paper, it can be seen in the table that light rail systems are able to operate in extremely tight alignment conditions. This fact makes that these systems are very flexible for introducing them over CBD along almost every kind of street.

## 5 CONCLUSIONS

Along this paper, common limit values for track geometry parameters of light rail systems have been summarized according to different recommendations. Nevertheless, due to the necessity of light rail systems for running over existing streets which have been conceived with stricter parameters, it has been shown that there are many occasions in which these recommendations are not satisfied.

If existing systems are taken into account, specially the old ones, the conclusion that light rail systems are able to operate over practically any alignment (horizontal curve radius of 11 m, vertical grades of 11.5%, etc.) can be reached. In this sense, this paper has stated the great flexibility of this kind of systems, which are able to run over really strict layouts in the event of necessity. Nevertheless, these tighter values must be avoided in new networks insofar as possible, in such a way that the following advantages are achieved:

- Increase in passenger comfort, and in service attractiveness.
- Reduction of investment and operation costs.
- Minimization of severe speed restrictions, improving in this way the commercial speed of the system.
- Possibility of using standard vehicles of current production in the market, without exceptional requirements which should have an effect on their acquisition costs, as well as on maintenance expenses and complexity.

If a comparison is made between recommended limitations to track geometry parameters established by TRB and UITP, the conclusion achieved is that the recommendations are quite similar, except for vertical curve minimum radii, in which TRB is more permissive than UITP, for the reasons stated above.

In relation to real values, it is possible that extreme values are achieved more frequently by European systems than by United States ones for new networks, due to stricter restraints in street layout and space for European cities.

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**TABLE 1 Minimum Values of Circular Curve Radius (m)**

| **SITUATION** | **TRB, 2000 (*4*)** | | **UITP, 2004 (*3*)** |
|---|---|---|---|
| | **Desired $R_{min}$** | **Minimum $R_{min}$** | |
| **Main line (exclusive right of way)** | 150 | 90 | 100 |
| **Main line in tunnel or aerial structures (exclusive right of way)** | - | 150 | |
| **Main line with embedded track (mixed traffic or reserved right of way)** | 35 | 25 | 25-20 |
| **Yard and non-revenue tracks** | 35 | 25 | - |

**TABLE 2 Extreme Values of Horizontal Track Geometry Parameters of some Light Rail Systems in Operation Nowadays**

| System | Minimum radius (m) | | Maximum superelevation (mm) | |
|---|---|---|---|---|
| | **Recommended** | **Minimum** | **Recommended** | **Minimum** |
| **Toronto, old network (Canada)** | 35 | 18 | - | |
| **Denver (USA)** | 152 | 25 | 101 | 152 |
| **Philadelphia, old network (USA)** | 22.5 | | - | |
| **Lisbon, old network (Portugal)** | 11 | | - | |
| **Lisbon, new network (Portugal)** | 14.5 | | 45 | |
| **Barcelona (Spain)** | 25 | | 0 | |
| **Tenerife (Spain)** | 26 | | 100 | |
| **Seville (Spain)** | 25 | | - | |
| **Rouen (France)** | 30 | | 160 | |
| **Dusseldorf (Germany)** | 25 | | 165 | |
| **Dublin (Ireland)** | 25 | | 120 | |
| **Nottingham (United Kingdom)** | 18 | | 36 (Shared ROW) | 143 (Segregated ROW) |
| **Genève (Switzerland)** | 150 (Main line) | 80 (Main line) | 70 | |
| | 50 (At stations) | 20 (At stations, with right hand curve, for visibility in right hand doors) | | |
| **Sheffield (United Kingdom)** | 25 | | 150 | |
| **Croydon, London (United Kingdom)** | 25 | | 15 (Segregated ROW. To allow track to conform to the highway camber) | 150 (Independent ROW) |
| **Docklands, London (United Kingdom)** | 40 | | 150 | |
| **Manchester (United Kingdom)** | 25 | | 35 (Grooved track) | 150 (Ballasted track) |

**TABLE 3 Extreme Values of Vertical Track Geometry Parameters of some Light Rail Systems in Operation Nowadays**

| System | Maximum vertical grade (%) | | Minimum radius in vertical curves (m) | |
|---|---|---|---|---|
| | Rec. | Min. | Rec. | Min. |
| **Toronto, old network (Canada)** | 5.2 | | - | |
| **Denver (USA)** | 3.5 | 6.0 | - | |
| **Philadelphia, old network (USA)** | 5.0 | | - | |
| **Lisbon, old network (Portugal)** | 14.5 | | - | |
| **Lisbon, new network (Portugal)** | 6.0 | 7.5 | - | |
| **Barcelona (Spain)** | 7.5 | | 500 | |
| **Tenerife (Spain)** | 7.5 | 8.5 (Length < 250 m) | 700 (Sag)<br>1000 (Crest) | 500 (Sag)<br>700 (Crest) |
| **Seville (Spain)** | 1.56 | | 2500 | |
| **Rouen (France)** | 7.0 | 8.0 (Length < 250 m) | 350 (Sag)<br>700 (Crest) | |
| **Dusseldorf (Germany)** | 4.0 | | 500 | |
| **Dublin (Ireland)** | 6.0 | 8.0 (Length < 250 m) | 350 (Sag)<br>700 (Crest) | |
| **Nottingham (United Kingdom)** | 6.7 (Maximum grade at platforms) | 8.5 (Maximum grade elsewhere) | 300 (Sag)<br>500 (Crest) | |
| **Genève (Switzerland)** | 3.0 | 6.0 (Maximum length 80 m) | 1000 (Sag)<br>1500 (Crest) | 300 (Sag)<br>300 (Crest) |
| **Sheffield (United Kingdom)** | 10.0 | | - | |
| **Croydon, London (United Kingdom)** | 9.0 | | 1000 | |
| **Docklands, London (United Kingdom)** | 6.0 | | - | |
| **Manchester (United Kingdom)** | 5.56 | | - | |

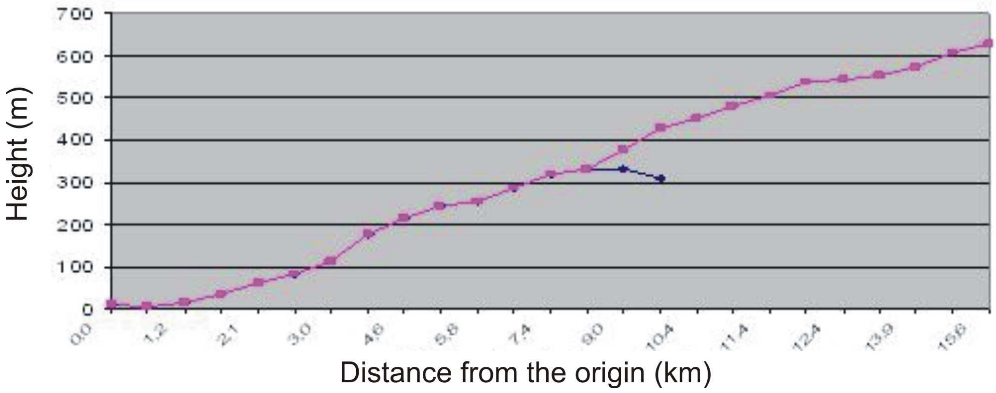

FIGURE 1 Longitudinal section. Tenerife light rail. Source: (*11*)

FIGURE 2  Light rail alignment raised from street one. Tenerife light rail.

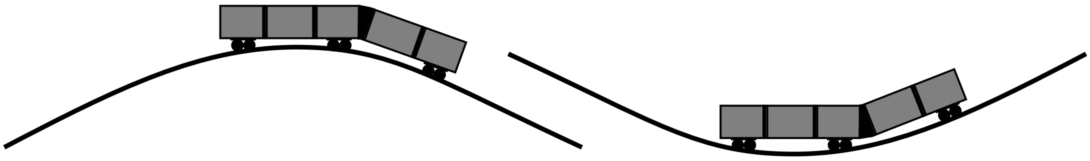

FIGURE 3 Effects of vertical curves over vehicle geometry.

**FIGURE 4 Effects of horizontal curves at stations. Zurich (Switzerland) light rail.**

**FIGURE 5 Station in which tangent tract is not extended to both sides of the platform. Tenerife light rail.**

**FIGURE 6 Vertical grade of 7.5% at station. See the detail of staggered seats in the shelter. Tenerife light rail.**

**FIGURE 7 Station located in a sag vertical curve. Tenerife light rail. Source: (*12*)**