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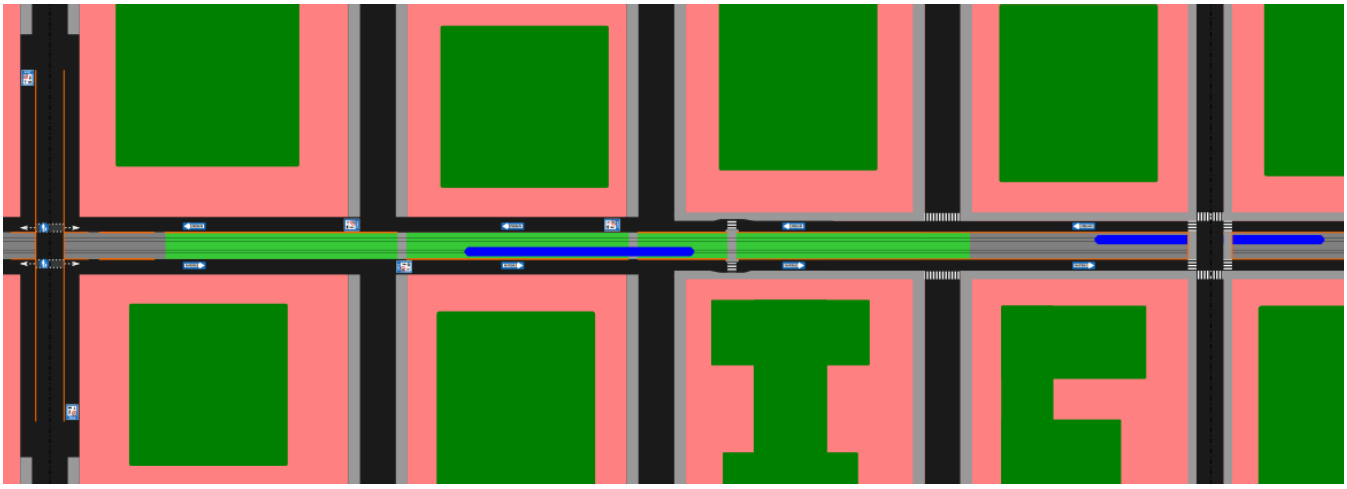
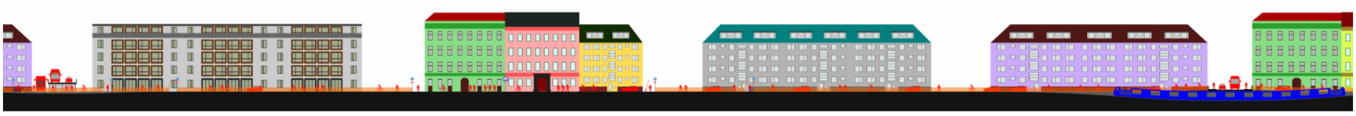
LCRT

Low-clearance Rapid Transit

Fast, reliable high-performance urban transport at moderate costs for the city budget





Generalized Feasibility Study

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1. Introduction and Initial Situation

1.1. Basic Idea

The aim of the concept „Low-clearance Rapid Transit“ (LCRT) is urban rail transit combining optimally the cost advantages of a tram and speed and reliability of a metro. Compared to existing rapid tram concepts, the following innovative factors contribute to this goal:

- The LCRT line is running mainly on street level (preferably divided from the surrounding area by fences or railings), instead of a track alignment continuously above or below street level, crossing roads are passed under via separated underpasses.
- Underpasses are realised only for major crossroads (at about 250 – 400 m distance between them), crossing minor streets are cut for motorized vehicles but equipped with protected level crossings for pedestrians.
- LCRT-vehicles are of significantly lower overall height than conventional tram or metro vehicles, so underpasses can be constructed much easier.
- Next to the underpasses, not only the LCRT track is lowered, but also the street surface is elevated, so the underpass ramps get shorter and the construction masses are reduced.

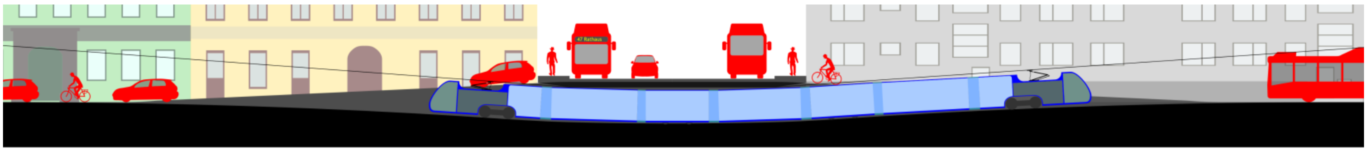

Figure 1: Illustrative representation of an LCRT underpass

1.2. Initial Situation: Average Speed of Different Tram and Metro Models

The idea of a “fast tram” or “prioritization” of the tram against the individual traffic isn’t new. Already a long time, these solutions are proposed in order to achieve quality similar to a metro at much lower costs. Anyway, they didn’t reach the popularity of “real” metro lines by far.

In order to quantify the effectiveness of these measures for public transport speed improvement, 39 exemplary route sections in Vienna and other central European cities were compared concerning length, travel time and number of stops. These examples were divided into the following four groups:

- Tram in mixed traffic with cars: tram lines mainly using tracks, which serve at the same time as driving lanes for individual traffic
- Tram with own track segregated from car traffic: tram lines without longitudinal car flow on its track, but with crossing car traffic basically at every street crossing (distance between crossings according to the local building structure)
- Fully grade-separated rapid tram: tram lines with consequently level-free routing on tracks without any contact to car traffic
- Metro: classical metro lines with accordingly big trainsets, train control system and mainly elevated or lowered track alignment.

In order to neutralize the effect of different average distances between stations, a time loss of 35 seconds per stop has been assumed. This contains not only the stop itself, but also time losses for deceleration and acceleration compared to passing the deceleration and acceleration distances with average operational speed.

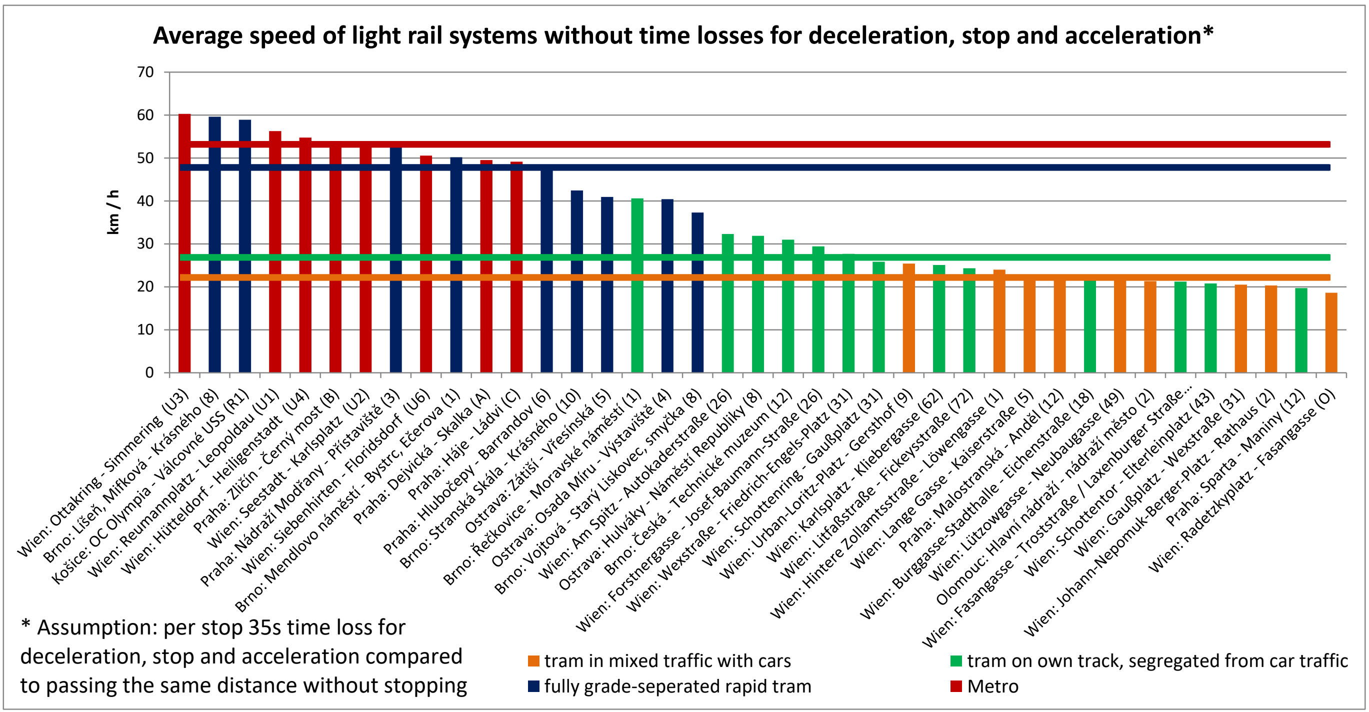

Figure 2: Average operational speed without time losses for stops for metro and tram of various characteristics in Vienna and other central European cities

The calculated average operational speed values for the compared examples are shown in Figure 2 the average for metro lines is 53 km/h and for fully grade-separated rapid trams 48 km/h, on the contrary for the tram on own, segregated track 27 km/h and for the tram in mixed traffic even only 22 km/h. It turns out, that the time savings potential of segregated tracks (avoiding cars on the track only between crossings) is much smaller, than that of fully grade-separated lines (avoiding cars on the track anywhere). On some line sections, existing rapid tram solutions as for example in Praha or Brno achieve similar speed as metro systems. However, these lines usually do not pass historically grown neighbourhoods, but they either connect satellite towns that had from the start been planned including the rapid tram line, or follow natural barriers like the Vltava river in Prague. Once the public transport users approach the city centre, they have to accept either low average speed or changing from tram to metro. This disadvantage was probably crucial for the decision to replace the only real rapid tram in Vienna, the tram line 64, by an extension of the metro line U6: Despite the running time on the grade separated line section is the same, the metro extension provides the opportunity of a fast continuation of the journey throughout the city center without changing. While in newly built up suburban areas with generous public space, average tram speed could be increased as well by better priority systems or the use of railway-type level crossing protection systems, the comparison of the average operational speed shown above clearly indicates poor effectivity of traffic signal prioritization: In densely built-up areas with intense traffic, a rigorous prioritization according to the principle of “stopping only at stations” could work theoretically, but in reality it is either politically inacceptable or tram tracks are obstructed anyway by cars which enter the crossing area without enough free space in front of it.

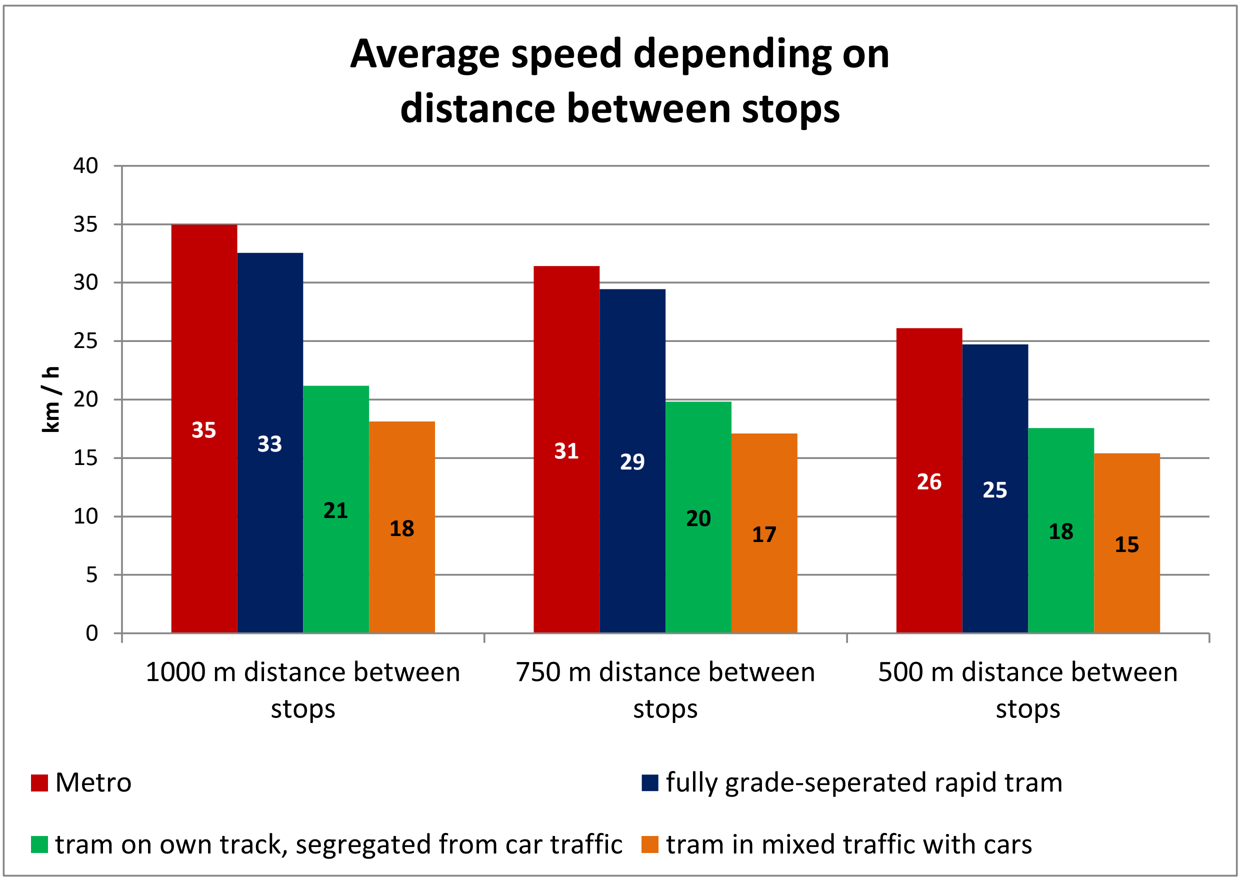

Figure 3: Average speed including time losses for stops depending on the average stop distance, deduced from the examples in Figure 2.

In Figure 3 there are shown average speeds including time losses for stops, which were calculated according to the distance between stops and the average operational speed identified before.

A similar classification of mass transit systems by separation from individual traffic and achievable speed has been carried out by the International Tunnelling Association[1]:

- "Complete separation", corresponding to the categories "Metro" and "fully grade-seperated rapid tram" as mentioned above, leading to operating speeds (including stops) of 30-60 km/h
- "Substantial separation", corresponding roughly to the category "tram on own track, segregated from car traffic" mentioned above, with priority at intersections, leading to operating speeds of 20-30 km/h
- "partial or no separation" corresponding roughly to the category "tram in mixed traffic with cars" mentioned above, with or without priority at intersections, leading to operating speeds of 12-15 km/h.

Since the rolling stock demand at given intervals is inversely proportional to average speed and turnaround times at terminal stations, running time savings and increased punctuality (thanks to avoided obstructions on tram lines) represent a significant potential for cost reductions: According to the difference in average speed displayed in Figure 3, even in case of 40-100% higher costs per vehicle the rolling stock costs would still be less than those of conventional trams and driving personnel costs are cut as well.

1.3. Application areas of LCRT

Depending on the city's size and existing means of public transport, LCRT can fulfil the following tasks:

- New LCRT network in addition to an existing tram network: In medium-sized cities, which are according to the state of the art too small to generate demand and funding for conventional metro, LCRT is a fundable alternative to create a superior public transport system with higher speed and longer distance between stations.
- Speeding up existing tram lines: If there is no demand for a new superior public transport system, because of inadequate city size or a sufficient existing metro network, existing tram lines can be converted into LCRT lines in order to reduce travel time at unchanged distances between stations.
- New tram network in addition to a bus network: For cities which have until now only a bus or trolleybus network, the increased attractiveness of LCRT can lead to the decision in favour of an urban light rail system
- Additional metro lines: In metropoles with an existing conventional metro network, additional lines can be established as LCRT lines instead of conventional metro lines. The cost reduction can be used for realising a higher network density.
- Urban express lines: A special option of higher network density is the completion of an existing metro network by the next speed level: further lines with even longer distance between stops, achieving even higher average speed. Such LCRT lines could cross the whole city or lead tangentially along the suburbs and would stop only at junctions with other metro or commuter railway lines. These urban express lines could provide travel times which are competitive to urban highways even in off-peak-hours.
- Tram-train-systems: For the following reasons, the LCRT concept is particularly suitable for suburban light rail solutions with or without shared use of standard heavy-rail infrastructure:
    - In contrary to existing regional railways or extra-urban trams, which usually either pass outside the villages or cross them very slowly because of many level-crossings, LCRT can directly reach the core of the village with higher speed at appropriate costs.
    - A common problem of many tram-train-concepts are different capacity requirements between the city centre and the suburbs: If the suburban line sections are running on tracks, which are shared with standard railway trains, there are often no shorter intervals feasible than 15-30 minutes. Because of these relatively long intervals, each individual vehicle would need higher capacity, than compatible with length restrictions in mixed-traffic urban tram operation[2]. In the opposite, if there are short intervals, but also short platforms on the suburban part of the line and suburban trains shall continue via a metro line, they might get overcrowded[a]. In both cases, flexibility and cost-efficiency of the LCRT would be helpful: Train length isn't restricted by building structure and road compatibility and capacity improvement by additional lines through the city centre is more fundable, than in case of conventional metro lines.

  In case of a tram-train application, on suburban line sections, the maximum speed should be 80-100 km/h instead of 60 km/h. Whether the underpasses should also be dimensioned for this speed limit should be decided individually with regard to local conditions.

[a] This problem would occur e.g. in case of the (technically feasible) connection of the Vienna-Baden light rail with the metro line U6.

Compared to various types of conventional metro lines, the application area of LCRT can be characterized as follows:

- If it is possible to build an elevated metro, LCRT can be realized as well
- LCRT is nearly always a substitute for a cut-and-cover-metro
- LCRT cannot achieve the same degree of freedom concerning track alignment, as a bored metro tunnel

About the suitability of different urban structures for the realisation of LCRT lines see chapter 4.

1.4. Task and structure of this study

The first task of this study is to investigate, which forms of LCRT could be reasonably realized:

- Parameters of vehicles and track alignment, e.g. height and width, slope, vertical and horizontal curve radii as well as velocity
- Geometry parameters of roads and public space to be redesigned in the course of LCRT construction
- Optimization approaches concerning vehicle technology and track guidance
- Arrangement and track topology of interchange stations

Another task of the study is a qualified estimation as a range of costs concerning construction and specific parts of operation of the LCRT-lines compared to conventional trams and metros.

In the field of technical conception, there are in some cases developed several solution approaches simultaneously, some of them with big uncertainties about technical feasibility and positive or negative influences on costs. The cost estimation is always based on a rather conservative main variant where low risk of misjudgement was assumed. The other variants represent alternative solutions, which might facilitate realisation at lower costs, but also might turn out to be infeasible.

In order to keep effort and timescale for this study realistic, it does not deal with any concrete lines or networks in real cities, but it refers to usual framing conditions and expectable costs per line or track length. Standards and regulations as well as examples of track or road parameters were taken mostly from Vienna and other central European cities.

2. Technical Feasibility and track / road geometry parameters

2.1. Height difference between LCRT line and crossroad

The overall height difference between the LCRT line and the intersecting road has to be reached by ramps elevating the crossroad and lowering the LCRT line. It is determined by the following parts (ranked by importance):

1. Inner height of the vehicle
2. Roof thickness and height of rooftop equipment
3. Catenary height including electrical clearance
4. Vehicle floor height
5. Thickness of load-bearing structure, crest and road pavement
6. Thickness of the track structure

In the following paragraphs, for all parts of the overall height difference, there are deduced those values which will be used for cost estimation (see section 2.10.2) as the main variant as well as there are discussed alternative technical solutions, which could eventually help to achieve more favourable values.

2.1.1 Inner height

The intended internal height of the vehicle is **200 cm**, as usual for double-deck railway carriages[3] and significantly better than double-deck buses (192 cm on the lower floor, 170 cm on the upper floor[4]). The Austria tram regulation states a minimum inner height of 195 cm, in the seated area 170 cm[5].

2.1.2 Roof thickness and height of rooftop equipment

A significant part of the reduction of clearance height is achieved in the roof area: Classical high-floor trams had various technical devices as electric converters or air conditioning placed under the floor, low-floor trams have them placed on the roof. In case of LCRT vehicles, all these equipment has to be placed on the same height range as the passenger's compartment: Either in separate sections at the vehicle's ends, or distributed into residual volumes under seats, in corners under the roof or similar. The remaining roof thickness is about **5 cm**. In contrary to conventional trams, it does not matter, if the relocation of electrical devices leads to increased vehicle length, because thanks to the complete grade separation, there are no such restrictions of the vehicle's length as apply for trams in mixed traffic.

2.1.3 Catenary height including electrical clearance

A further, significant part of the reduction of clearance height is achieved between the upper end of the vehicle and the ceiling of the underpass as this gap is also reduced to **5 cm**. For the problem of missing space for catenary and electrical clearance compared to conventional trams there are proposed different solutions:

2.1.3.1 Main variant with two pantographs at the vehicle's ends

According to the main variant, the vehicle isn't equipped with one pantograph above the passenger compartment, but with two pantographs, which are located above the end sections, carrying technical units. These utility sections are lower than the passenger sections, so the completely lowered pantograph does not exceed the height of the rest of the vehicle. In the area of an underpass, there is a neutral, permanently deenergised section, so there is no voltage on those parts of the overhead lines, which are too low to comply with requirements of electrical safety. If the underpasses are short enough resp. the vehicle long enough, one of the two pantographs is at any time in contact with an active overhead line. For reasons of electrical safety, the lower parts of the pantograph are isolated and diodes ensure, that there is no voltage on the second, lowered pantograph.

If longer tunnel sections should be required, they must be equipped with conventional catenary and sufficient tunnel height.

2.1.3.2 Alternative solutions

Apart from the main variant described above, the following alternative solutions concerning energy supply are imaginable:

- Use of a state-of-the-art catenary-free tram system: high-capacity electric energy storage (chemical batteries or supercapacitors) or ground-level power supply (APS by Alstom)
- Safety extra-low voltage catenary in the underpass section: A voltage of not more than 60 V DC is considered as non-hazardous to humans, so no regulations apply concerning minimum height or other means of protection against touching. Compared to a usual tram catenary voltage of 600 V, the available power is reduced down to 10% if the same current limit is applied. If

underpasses and stations are arranged in an appropriate way, vehicles can pass the underpass section by momentum and the reduced voltage instead of a completely zero-voltage section can be used for auxiliary power users in order to save battery life. In case of an unexpected stop of the LCRT vehicle in the reduced voltage section, 10% of the usual power is still enough to leave the underpass over an average slope of 4-5% at 10 km/h[6]. Indeed, a higher current limit and thus more available power in the underpass section is considerable, if a wider catenary cross-section with more contact surface between catenary and pantograph is applied.

- Minimum variant of energy storage, based on coasting through the neutral section by momentum too: In order to avoid a blocking of the whole line because of a vehicle, which stopped unexpectedly in the underpass, vehicles should be equipped with a small auxiliary battery, serving only for rare cases of slow movement out of the underpass.
- Use of trolley poles: Trolley poles as formerly used for trams and still used for trolleybuses can swivel over the edge of the vehicle, so the power lines of the two tracks can run close together in the highest part of the tunnel ceiling, where it is easier to fulfil the minimum height above the bottom of the underpass (resp. above top-of-rail). Furthermore, with trolley poles it is easier to bridge the big height difference between the vehicle's roof and the catenary outside of underpasses.

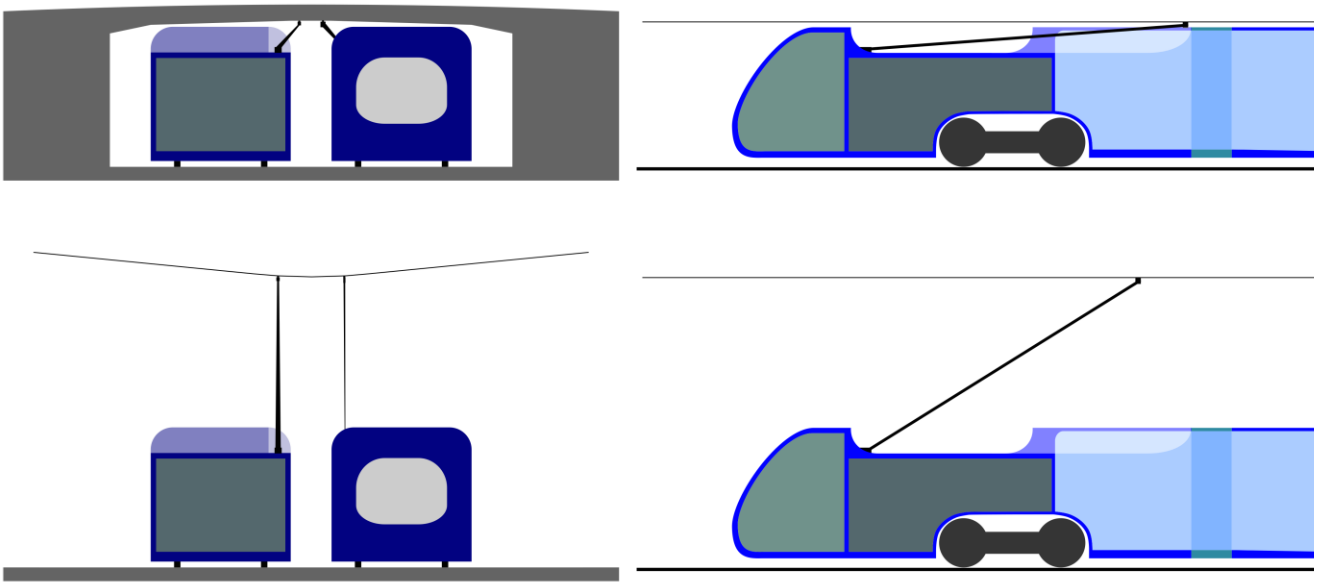

Figure 4: Deployment of trolley poles in an underpass with 2,5 m power line height (upper images) and outside an underpass with 5 m catenary height (lower images)

Although trolley poles mounted on the left side of the vehicle (in case of right-hand traffic) would make best use of the ceiling height of underpasses, a more complex combination of pantograph and trolley pole on the right side of the vehicle would allow to place the trolley close to the buildings on short beams. So masts in the road can be avoided, saving costs and maximizing the useable cross-section of the road. Compared to a central trolley mounted on the adjacent buildings by wires, there is less pulling force on the wall anchors and there are better conditions for the use of turnable ladders by the fire brigade or landing of an emergency helicopter.

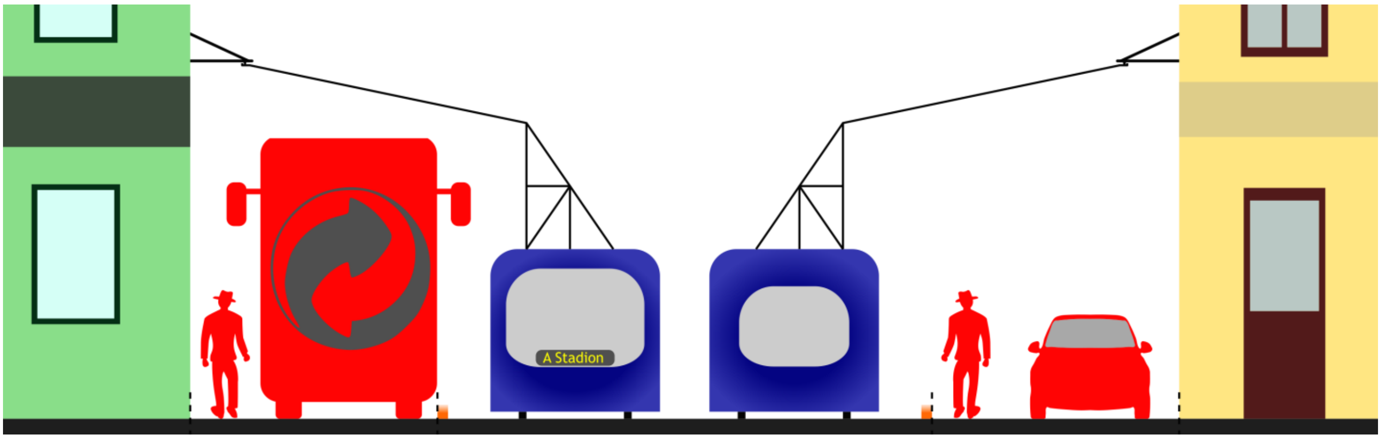

Figure 5: Combination of pantograph and trolley pole with trolley alignment close to the buildings.

2.1.4 Floor height according to applied running gear technology

After reducing the vehicle's internal height to some acceptable level and elemination of the necessary height for catenary, pantograph and technical devices, the floor level above top-of-rail remains as the crucial factor for the overall clearance height. Currently applied low-floor-technologies for tram vehicles can be divided in the following three groups:

1. Constructions with continuous wheelset axles achieve (at least above bogies or other running gear) no lower floor height than about 450mm above top-of-rail. On the other hand, such running gear is still quite similar to that of conventional high-floor-trams and has favourable characteristics concerning manufacturing costs and wear[7].
2. Most low-floor trams have, at least near entrances, a floor height of 300-400 mm above top-of-rail. In case of such a floor height, between the body's underneath and the rails there remains enough space for components like the following examples:
    - Bogies or other running gear without continuous wheelset axles, but with some kind of bogie frame, connecting the single wheels directly (not via the car body)
    - Rods, which influence the radial positioning of bogies or single wheels depending of the angle between car body sections
    - Pivot joints between adjacent sections with wheel-less sections, carried by the adjacent sections (the pivot joint has to transmit not only longitudinal forces, but also the weight of the section)
3. A floor height of not more than about 200-250 mm above top-of-rail along the whole vehicle is only possible, if there aren't any further components between the car body's bottom and the rails. This criterion is fulfilled by the Siemens "ULF" tram type, operating in Vienna and Oradea, using some kind of portal wheelsets consisting out of two single wheels between the car body sections. The fact, that this solution is rarely applied outside the Viennese home market of the manufacturer is an indication for serious disadvantages, presumably relevant additional costs for production and operation.

2.1.4.1 Main variant

As the main variant, a floor height of **350 mm** is assumed, a value which is achieved by trams of different manufacturers, although not compatible with continuous wheelset axles.

2.1.4.2 Alternative solution with running portal wheelsets

The disadvantages of the portal wheelsets could be reduced if only non-driven, running axles are realized as portal wheelsets, so there is no space demand for motors and transmission in the area of the portal wheelsets and wear and tear of the small wheel is reduced as there are no driving forces, and less weight and braking forces on them.

In order to achieve satisfying tractive performance, two sub-variants are possible:

- If the solution with portal wheelsets shall contribute to a lower clearance height compared to the main variant, driven wheels can be situated only below the end segments. There, conventional high-floor bogies can be applied, because above them, there is no passenger compartment, but various technical devices, so a reduction of the internal height of the vehicle is unproblematic in this area. The share of the vehicles weight resting on driven axles can be improved by placing heavy components in the end segments and making the overhang as long as possible, but anyway, the maximum vehicle length is limited by the tractive force of the running gears below the end segments.

- If the solution with portal wheelsets shall contribute to a more inner height at same clearance height, as a compromise portal wheelsets and driven wheelsets with slightly higher floor can be alternated. As an example, significant sections of 210 cm inner height at a minimum inner height of 200 cm could be realised this way, facilitating the door mechanism as well.

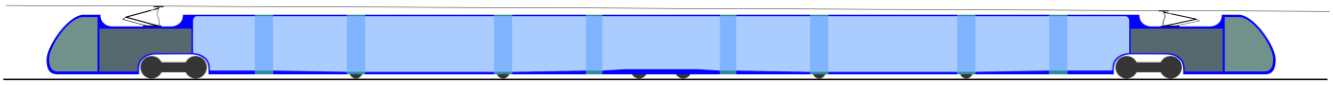

Figure 6: Vehicle version with driven high-floor bogies under the end segments, a driven four-wheel running gear in the middle and a total of four non driven portal wheelsets. In the area of the non-driven portal wheelsets, floor height is 25 cm and inner height is 210 cm, above driven wheels, floor height is 35 cm and inner height is 200 cm.

2.1.4.3 Alternative solution with lateral aisles around running gear

In order to make conventional wheelset axles compatible with a very low floor height, in the area of the running gear, seats can be arranged in the center of the vehicle, whereas between the seats and the side wall there are aisles on both sides of the seats. There are two sub-variations of this solution:

1. With two benches, arranged back-to-back along the vehicle, there can be generated more coherent space for the running gear to be arranged below it. On the other hand, because of the space necessary for the feet of the passengers, there remains less usable aisle width.

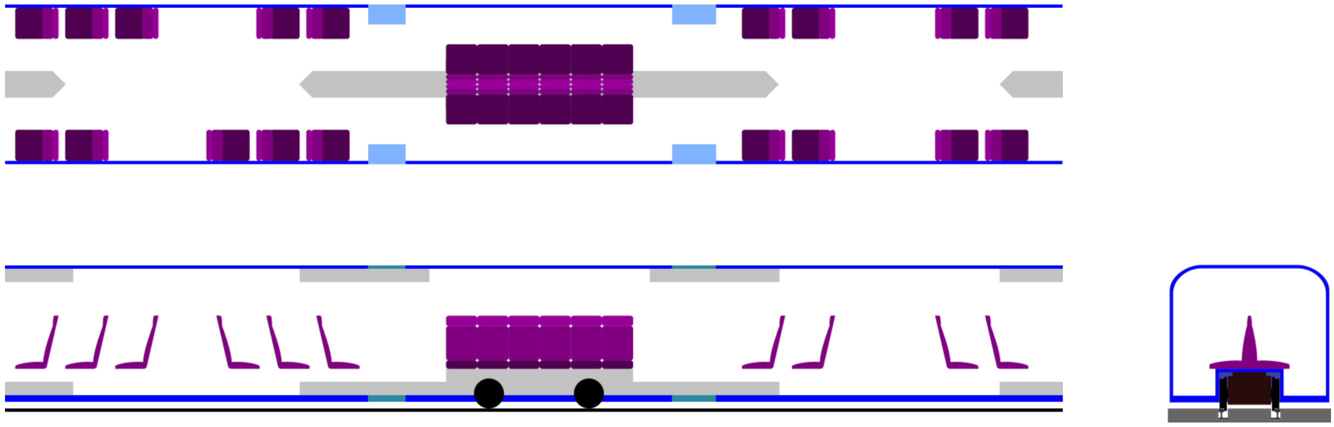

Figure 7: Vehicle version with lateral aisles and longitudinally arranged, central benches above the running gear at 760mm gauge and 2,4 m vehicle width. Grey: Restrictions of the passenger compartment's height in the center of the vehicle because of running gear and pivot joints between car body sections.

2. If above the running gear there are arranged two seat groups arranged back-to-back transversely to the vehicle's longitudinal axle, between them, in the foot area, there is less space for running gear and the wheels must be arranged exactly below the benches. On the other hand, the aisle width is not affected by passengers' feet and the whole seat groups including the floor between them can be slightly elevated in order to provide space for bigger wheels.

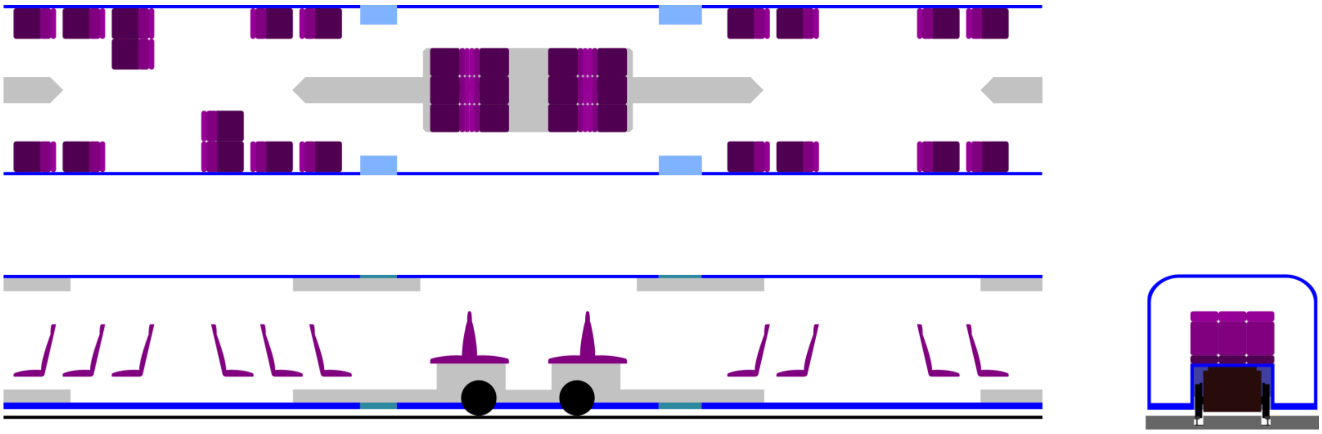

Figure 8: Vehicle version with lateral aisles and transversally arranged, central benches above the running gear at 1000 mm gauge and 2,6 m vehicle width. Grey: Restrictions of the passenger compartment's height in the center of the vehicle because of running gear and pivot joints between car body sections.

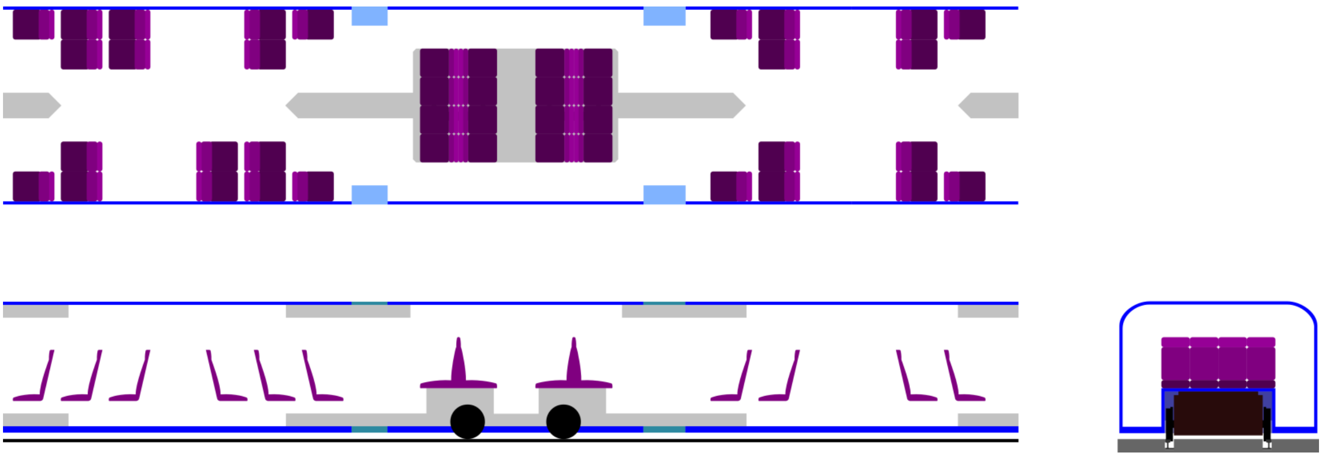

Figure 9: Vehicle version with lateral aisles and transversally arranged, central benches above the running gear at 1435 mm gauge and 3,1 m vehicle width. Grey: Restrictions of the passenger compartment's height in the center of the vehicle because of running gear and pivot joints between car body sections.

In order to achieve an appropriate width of the aisles, only certain combinations of gauge and vehicle width are possible (see Table 2). Furthermore, this solution is not suitable for classical bogies, but only for running gears, which do not significantly turn against the car body.

In case of a construction as a multi-articulated vehicle with wheel-less car body sections, also in the area of the pivot joints, there can be realised two lateral aisles, because there might be a need for more space for the pivot joint in the middle, which has to transmit the weight of the wheel-less section to the adjacent ones (also shown in Figure 7 until Figure 9).

The framing conditions for the choice of the vehicle width are described in Table 1:

Reference dimensions, vehicle versions and partial widths											Overall width (m)
Usual widths of tram vehicles (m)											2,2 - 2,65
Width of metro vehicles and long heavy-rail cars											2,6 - 2,9
Width of short heavy-rail cars (or multi-articulated trainsets with short sections)											2,9 - 3,15
Versions with benches above rolling gear in the middle of the vehicle	Alignment of benches above running gear	Benches above running gear		Partial widths							
		Width (m)	Number of seats	Wall thick-ness (mm)	Lateral aisle (mm)	Wall thickness + gap + wheel (mm)	Max. gauge (mm)	Wall thickness + gap + wheel (mm)	Lateral aisle (mm)	Wall thick-ness (mm)	Result: overall width (m)
	longitudinal	1,3	2	50	700	170	760	170	700	50	2,6
	transversal narrow	1,1	2	50	600	170	760	170	600	50	2,4
	transversal medium	1,3	3	50	600	150	1000	150	600	50	2,6
	transversal wide	1,8	4	50	600	182,5	1435	182,5	600	50	3,1
Pivot joint with limited height of the passengers compartment in the middle of the vehicle		Partial widths									Result: overall width (m)
		Folding bellows (mm)		Aisle (mm)		Load-bearing pivot joint (mm)		Aisle (mm)		Folding bellows (mm)	
		300		600		400		600		300	2,2

Table 1: Possible width of the vehicle depending on framing conditions and applied construction

In principle, wider vehicles have the advantage of more capacity at given length and also less costs per seat, whereas more narrow vehicles are more suitable for narrow road cross-sections where there might not be enough space for a wider track, segregated from car traffic. Furthermore, for the solution with lateral aisles, the minimum vehicle width depends on the gauge: A usual tram vehicle width of about 2,5m is feasible maximally up to metre gauge. If the vehicles should run on standard gauge (1435mm), their minimum width is 3,1m – just suitable for a multi-articulated heavy-rail vehicle with short sections, but too wide for existing tram lines. If there is no need for compatibility with existing tram or railroad sections, there are two arguments for a more narrow gauge compared to conventional tram or metro lines: First, the lower centre of gravity of LCRT vehicles reduces the risk of capsizing in curves. Second, if the track is more narrow, it becomes easier to allocate it not directly above cables, sewers and other pipes. (See also 2.4 and 2.10.2)

2.1.5 Thickness of load-bearing structure, crest and road pavement

The examples in Table 2 were used as an orientation for guide values of a realistic thickness of the load bearing structure of the underpass. As far as in these examples, a very low thickness would not be as useful as in case of the LCRT concept, a rather optimistic assumption of **30 cm** for further calculations was made. The intended vertical radius on the crest of 120 m (see 2.2.1) means, that the top of the crossing road above the middle of the LCRT line is about 3 cm higher, than the road surface above the outer edge of the LCRT vehicle. Additionally, 2 cm road pavement thickness was calculated, leading to an overall thickness of crest and pavement of **5 cm**.

Bridge name	Bridge span (m)	Width (m)	Panel thickness (cm)	Remarks
Underpass of the A13 motorway feeder road next to the landfill „Europabrücke“ of the Brenner base tunnel construction site	6,5	5,5	40	5-year temporary construction with edge beams of unknown dimensions
Unteralpe bridge	6,2	4,6	40	Steel concrete serving directly as pavement, edge beam about 10 cm above pavement level (estimation according to photograph)
Griesbachbridge Telfs (Enlargement)	4,96-5,27	unknown	35	Balustrade on top, 57 cm high edge beam (probably downwards)
Kinzachbach bridge	3	10,5	25-30	Width including 0,6 m wide edge beams on both sides, additionally 15 cm asphalt pavement
Beam bridge JSK 300	Up to 9	scalable	29	Modular bridge
Railway bridge: steel concrete / panel construction	not defined – absolute minimum value		40	High axle loads as usual for heavy rail
Railway bridge: steel construction, compound panel or filler beam decks	7	not defined	39	

Table 2: Examples for panel thickness of bridge structures of similar size as the LCRT-underpasses. Sources: bmvit[8], Swietelsky[9], BH Innsbruck[10,11], Jansons Bridging[12], ÖBB-Infra[13,14]

2.1.6 Thickness of the track structure

Despite the thickness of the track structure is not relevant for the level difference between the crossing road surface on the upper part of the underpass and the top of rail of the LCRT track in the lower part of the underpass, a reduced thickness of the track structure can contribute to lower costs because the whole underpass construction becomes lower and when applying variable track thickness, the underpass ramps can be shortened. For the main variant, a conventional tram track structure with about 180 mm rail height has been assumed, some alternative solutions with less track thickness are explained in 5.2.

2.1.7 Summary: total height difference and cross-section of the underpass

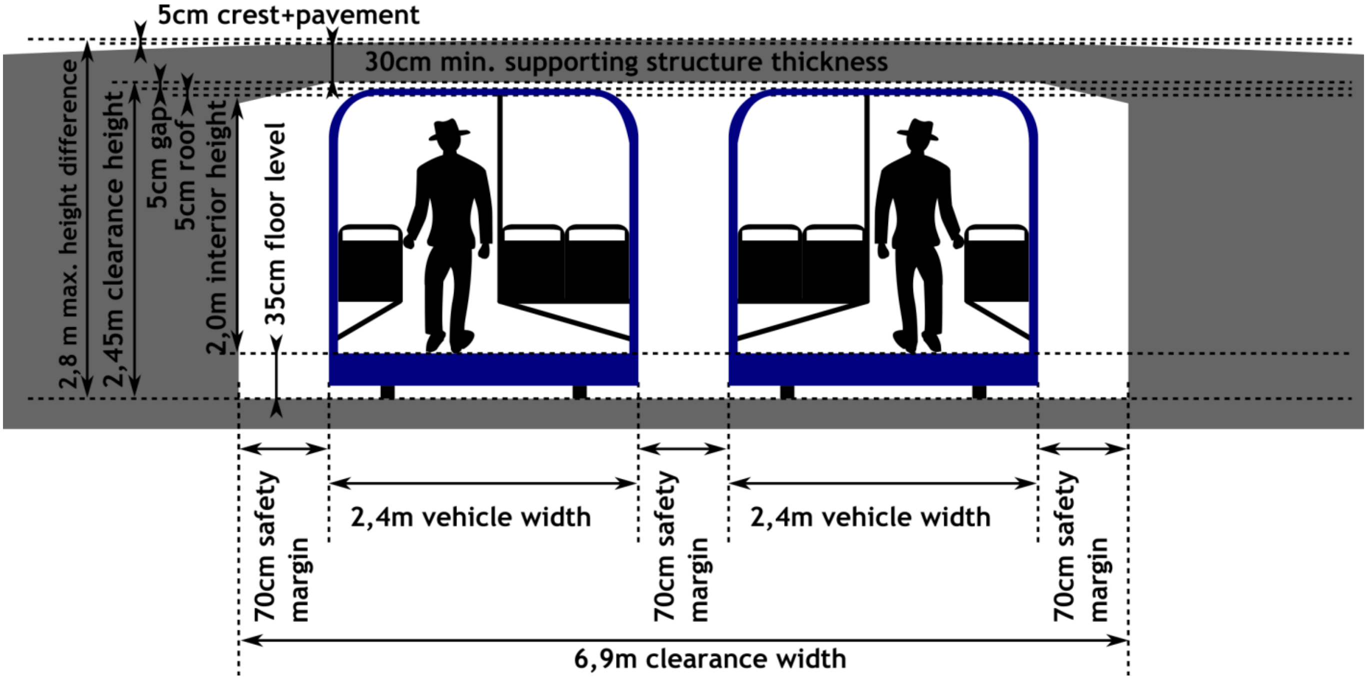

Figure 10: Cross-section of the vehicle and the underpass clearance

According to the main variant described above, the total height difference from top-of-rail to the peak of the crossing road's surface is **2,8 m**. Concerning the width, rather narrow vehicles (**2,4 m**) were assumed. Between the vehicles and beside it, a safety margin of **0,7 m** is compulsory, particularly in the underpass, but not necessarily along the full height of the vehicle[15].

The whole cross-section of the underpass is shown in Figure 10.

2.2. Alignment parameters for the LCRT line

2.2.1 Vertical radii on crests and in hollows

2.2.1.1 Visibility

In contrary to the dimensioning of vertical radii of the crossing roads, consideration of visibility conditions is not necessary for the LCRT line, because of the possibility to use a train control system. The ability to stop within sight distance is required only in the area of pedestrian level crossings (see 2.7).

2.2.1.2 Vertical acceleration and ride comfort

The vertical acceleration which appears in the vehicle while running over crests and hollows and reduces the perceived weight of passengers on the crest and increases it in the hollow, represents a basic indicator for feasibility resp. acceptability of the geometry of the underpass ramps. For magnetic levitation lines, German legislation[16] states a maximum vertical acceleration 0,6 m/s^2 on the crest and 1,2 m/s^2 in the hollow, probably representing acceptable values in the meaning of passenger comfort, particularly for short travel times. For wheel-rail-systems, legal limits concerning vertical curves resp. accelerations depending on speed differ significantly between countries. Whilst similar limits as for maglev tracks count on the crest, the vertical acceleration limit in the hollow isn't so much higher in case of railway and tram lines[17,18]. With regard to the fact, that the acceleration in the hollow does not represent a risk of derailment (in contrary to the acceleration on the crest), and the additional forces on wheel and rail are marginal compared to different axle loads or the load on the outer wheel and rail in case of horizontal curves, we can assume, that a vertical acceleration of 1,2 m/s^2 is technically feasible in case of a newly designed rail-wheel-system. Vertical accelerations between 1,2 and 1,5 m/s^2 are also mentioned as a limit for human well-being relating to elevators[19,20,21].

In order to gain further orientation values about usual and acceptable vertical accelerations in public transport, the following acceleration measurements were carried out using the app „Accelerometer Acceleration Log“[22] and a Sony Xperia X F5121 smartphone:

- 9 Measurements along the urban public bus route 11 A in Vienna between the stops „Forsthausgasse“ and „Dr.-Adolf-Schärf-Heim“ (including an underpass below the “Nordwestbahn” railway line)
- 6 Measurements along the urban public bus route a A in Vienna between the stops Haltestellen „Lisztstraße“ and „Am Modenapark“ (including the short, steep ramp between Marokkanergasse street and Salesianergasse street)
- 2 Measurements along the urban public bus route 57 A in Vienna between the stops „Stiegengasse“ and „Haus des Meeres“ (including the slope between Joanelligasse street and Kaunitzgasse street)
- 2 Measurements along the tram route 1 in Brno between the stops „Mendlovo náměstí“ and „Výstaviště“ (including the bridge over Křížkovského street)
- 2 Measurements on an escalator (Stops „Museumsquartier“ and „Taborstraße” of the Viennese U2 metro line, both upwards)

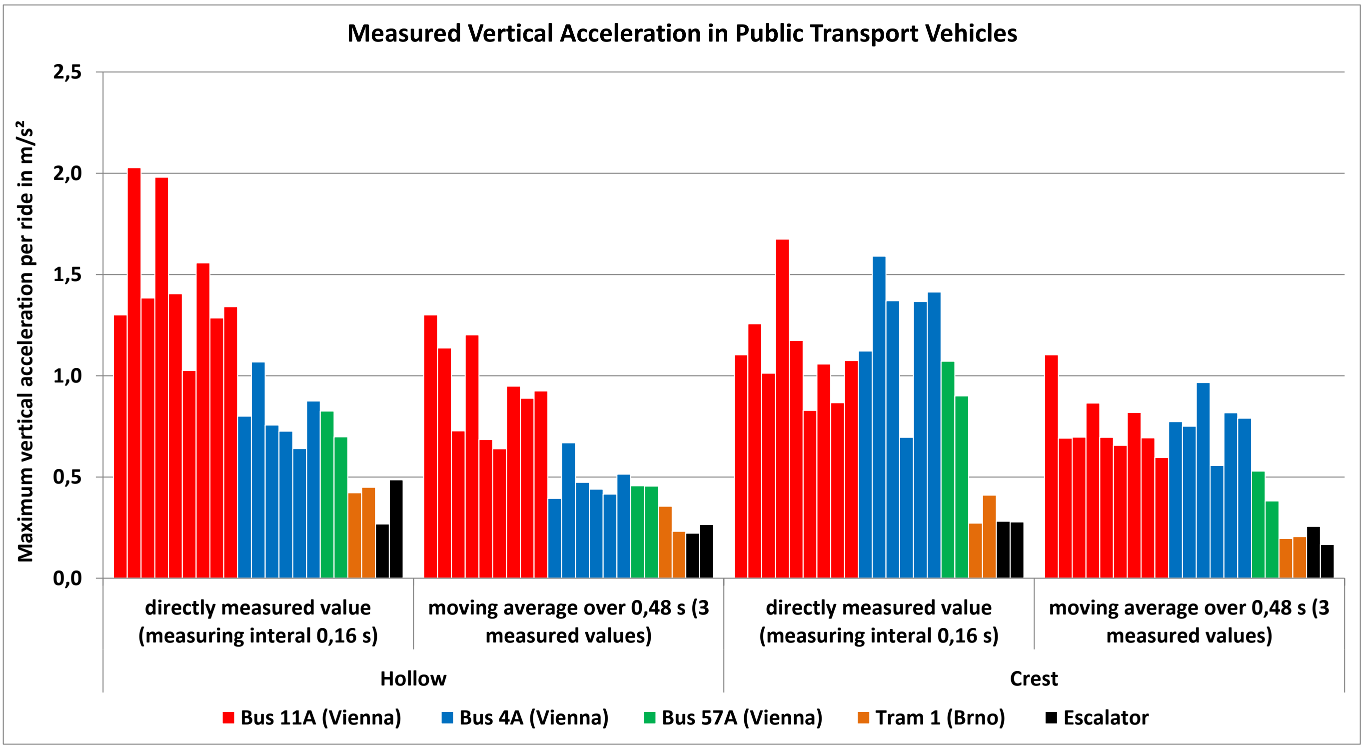

Figure 11: Maximum measured vertical acceleration in various public transport vehicles. Several bars of the same colour represent several measurements on the same line

The measured vertical acceleration values shown in Figure 11 confirm the researched range of values, despite the difference between crest and hollow is less than stated in the German maglev regulation[23]. More relevant than the directly measured values should be the moving average over three measurements (about half a second), which balance point loads because of uneven pavement. According to the author's perception, the vertical accelerations weren't spectacular to feel, the driving style was always comfortable and careful.

Although measurements and sources relating to elevators suggest less difference between crest and hollow, the main variant follows the limits of **0,6 m/s²** on the crest and **1,2 m/s²** in the hollow because of the following considerations:

- The vertical acceleration on the crest, leading to the feeling of the stomach moving upwards, is more uncomfortable, than the weight increase in the hollow.
- The vertical radius of the hollow is much more cost-relevant: a bigger hollow radius makes the deeper part of the underpass longer, increasing excavation volume and construction efforts according to more depth. A bigger crest radius increases only the length of the shallow upper part of the ramp.

2.2.1.3 Inclination change rate and stability for standees

Passing a crest or a hollow leads not only to a negative or positive vertical acceleration, it also changes the inclination of the vehicle's floor against the horizontal plane. The change of the this inclination angle per time effects the stability of standing passengers in a similar way as a jerk in the meaning of changing horizontal acceleration, leading to a change of the resultant of gravity and inertia forces. A longitudinal or transverse jerk of 0,7 m/s^3 as defined as a limit value in the Austrian tram regulation[24] is equivalent to an inclination angle change of 4,1 degree per second[b].

2.2.1.4 Vertical radii according to design speed

The intended standard speed for the design of LCRT lines is **60 km/h**. At this speed, the maximum vertical radius on the crest following the maximum vertical acceleration is **463 m**, in the hollow, the maximum admissible inclination change rate leads to a vertical radius of **234 m** (according to the maximum vertical acceleration it would be nearly the same: 231 m).

2.2.2 Longitudinal slope

Table 3 shows the maximum and average longitudinal slopes of the LCRT line depending on the part of the total height difference of 2,8 m (see 2.1), that is achieved by lowering the LCRT track (the residual part has to be achieved by elevation of the crossing road).

Depth of the underpass (m)	Ramp length (m)	Maximum longitudinal slope	Average longitudinal slope
0,5	26	3,8%	1,9%
1,0	37	5,4%	2,7%
1,5	46	6,6%	3,3%
2,0	53	7,6%	3,8%
2,3	57	8,1%	4,1%
2,8	62	9,0%	4,5%

Table 3: Ramp length, maximum and average longitudinal slope depending on the depth of the underpass

The critical factor for the feasiblity of the proposed ramp geometry is not the maximum, but rather the average slope, because the length of the train is similar to the length of the whole ramp, so the adhesive friction and gravity forces affecting the whole vehicle are determined by the height difference, distributed over the whole ramp. Limit values for the longitudinal slope of tram tracks are e.g. in Vienna 5% as standard value and 6% for exceptional cases[25], thus both steeper than the average longitudinal slopes of the LCRT underpasses.

2.2.3 Horizontal curve radii, superelevation and achievable speed

In contrary to the vertical curvature of the LCRT track, which are designed to be passed through with full line speed, horizontal curves require speed restrictions: Similar to a metro that is realized as an elevated track or a cut-and-cover-tunnel, the route cannot pass below building blocks but has to be aligned with such curve radii, that can be accommodated within road space.

[b] Effects of the interference between the changing angle of the vehicle's floor and vertical and horizontal accelerations had been neglected.

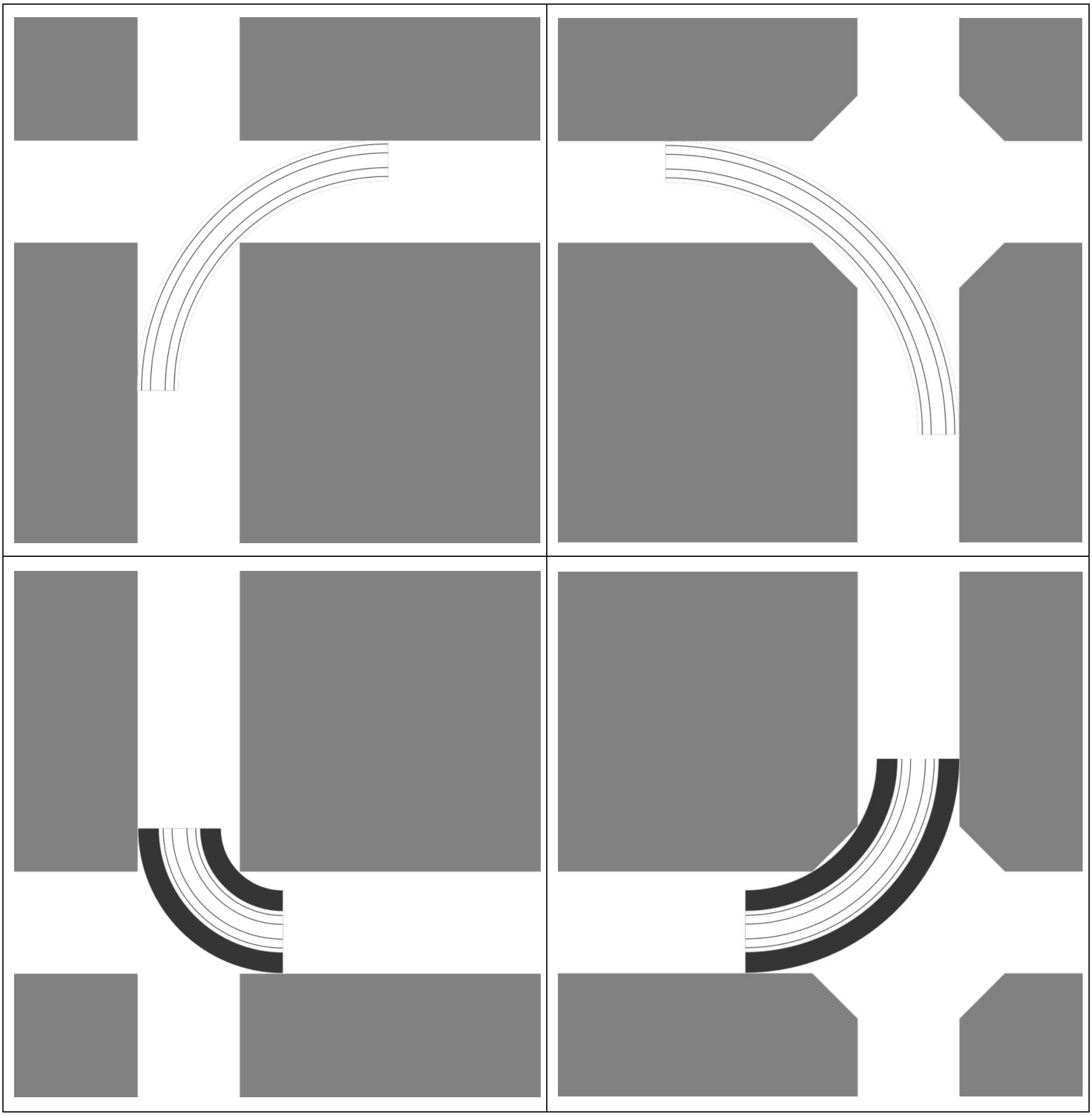

Figure 12: Various feasible curve radii without and with parallel traffic area (upper/lower row) and without and with chamfering of building edges (left/right column)

Feasible curve radii depend not only on the road width, but also on the factors, shown schematically in Figure 12:

- Many buildings have chamfered edges, facilitating a bigger curve radius
- Compared to concentric circle segments of the LCRT tracks and parallel lanes on both sides it is possible to realize significant bigger curve radii, if the whole road width is used in such way, that the LCRT line gets as close to the neighbouring buildings as possible in terms of safety margin. With regard to the accessibility of the concerned building, such a construction seems feasible only, if the curve is aligned as a relatively deep underpass with building entrances above the track (see also 2.5.4).

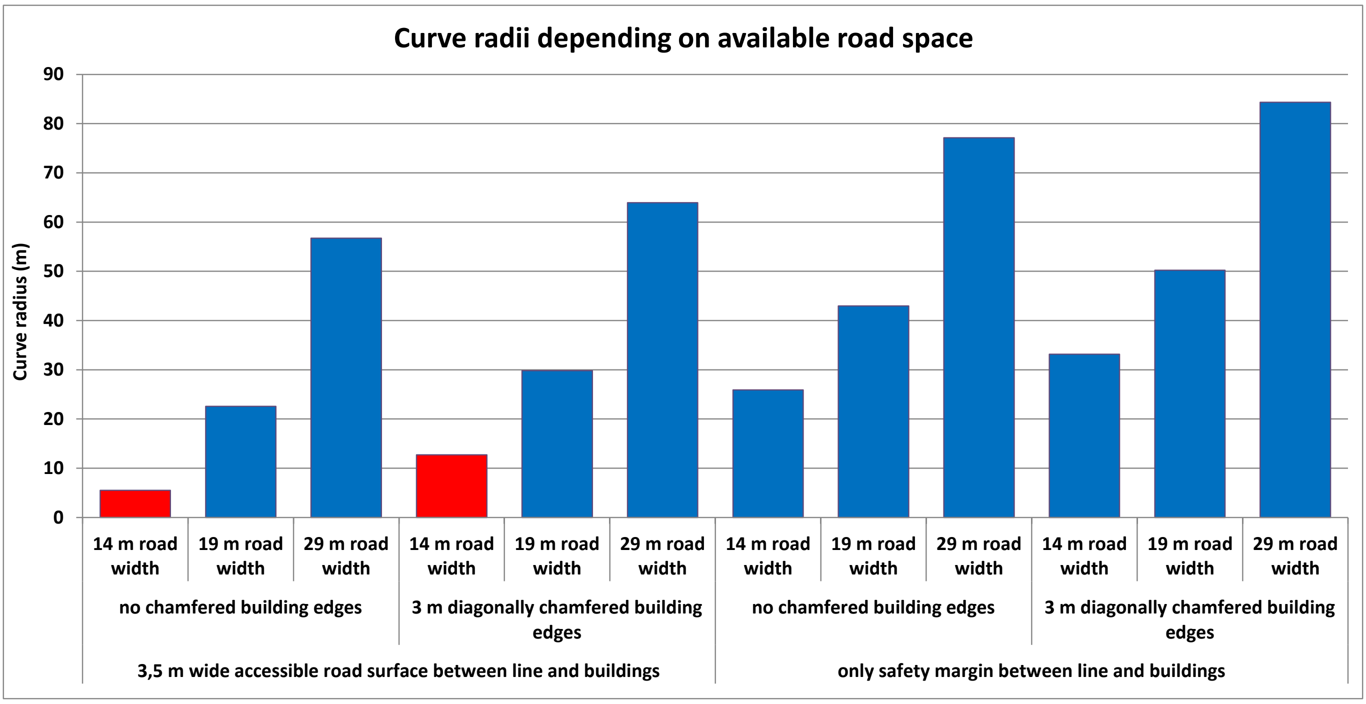

Figure 13: Possible curve radii of the inner track of a double-track LCRT line depending on road width and further circumstances

The effect of the two factors mentioned above as well as different road widths (according to model road cross-sections as described in 2.9) is shown in Figure 13: The highlighted lower extreme values seem to be generally infeasible as modern tram vehicles and –networks usually have a minimum curve radius of 18 m[26,27]. Minimum curve radii of existing metro networks are in a range from 27-40 m in exceptional cases of historic elevated or cut-and-cover-networks with strong dependency of the road network over 60 m in older up to 270 m in modern networks, constructed partly by the use of boring technology[28,29,30].

The admissible curve speed at given curve radius depends on the maximum permitted unbalanced lateral acceleration and on the superelevation, which is in case of LCRT compared to conventional trams facilitated by separation from road traffic. Austrian tram regulation[31] states the following limit values of unbalanced lateral acceleration:

- 1,0 m/s^2 for „on-road“ tracks
- 0,654 m/s^2 for „off-road“ tracks

Presuming the same stability for standing passengers in a vehicle when stopping in an elevated curve as in a vehicle passing passing the curve with maximum allowed speed, the admissible superelevation is equal to the inverse tangent of the permitted unbalanced lateral acceleration divided by the acceleration of gravity. Figure 14 shows the absolute superelevation (height difference between outer and inner rail) when applying the higher or the lower limit value of unbalanced lateral acceleration and when applying the full or only the half admissible angle of superelevation.

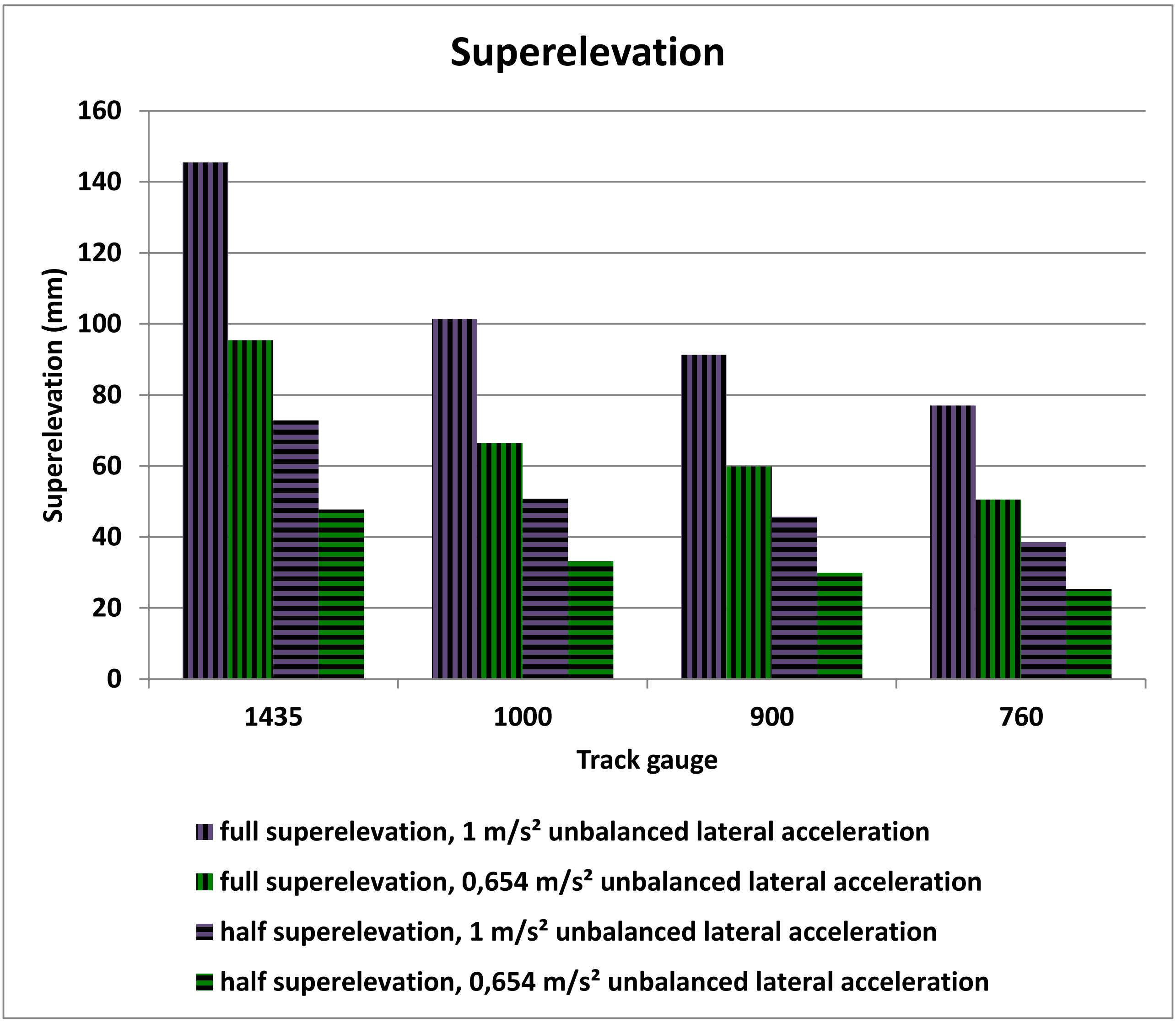

Figure 14: Superelevation (height difference between outer and inner rail) depending on gauge width, permitted unbalanced lateral acceleration and application of the full or the half admissible superelevation

The calculated dimensions of superelevation are realistic, for heavy rail lines in Germany (standard gauge 1435 mm) the maximum permitted superelevation is 160 mm for ballast tracks and 170 mm for ballastless tracks[32].

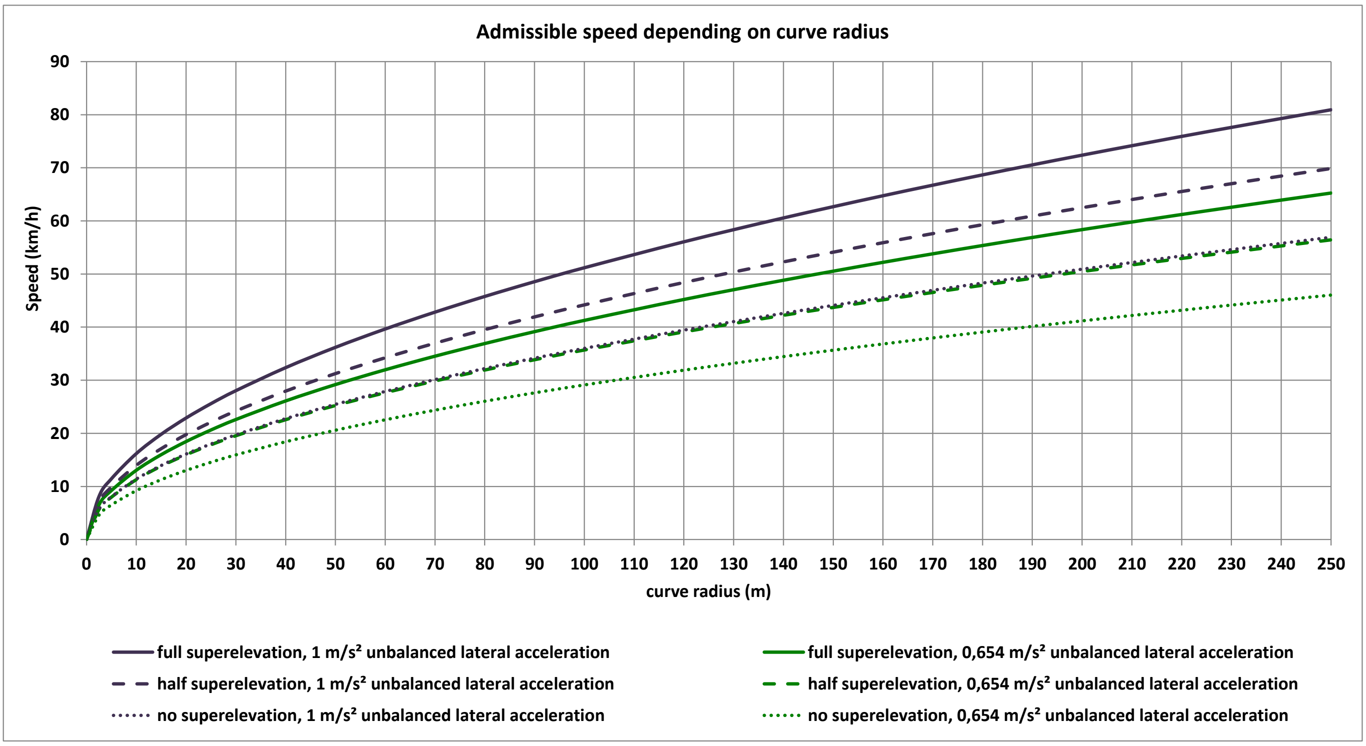

Figure 15: Admissible speed depending on curve radii, superelevation and unbalanced lateral acceleration

The influence of curve radius, superelevation and the permitted unbalanced lateral acceleration on the curve speed is shown in Figure 15: The feasible speed in the worst case is slightly more than the half of the best case speed, the difference caused by the two different limit values for unbalanced lateral acceleration is about the same as the speed difference between full vs. half superelevation or half vs. no superelevation.

For further dimensioning, the upper limit value for unbalanced lateral acceleration (1 m/s^2) was applied for the following considerations:

- According to the definitions in the Austrian tram regulation[33] LCRT might be classified as an „off-road" tram, because it "runs solely on a separated track", but with regard to the overlap of safety margin and road profile in the area of truck rear view mirrors (see 2.9), the passenger level crossings and the restrictions in track alignment at street level, LCRT should be rather classified as an "on-road" tram, which "adapts with its constructional and operational facilities to the character of road traffic".
- Furthermore, 1,0 m/s^2 unbalanced lateral acceleration isn't unusual even in long-distance rail services with much longer travel times and comfort requirements[34].

Concerning the admissible superelevation, further calculations were carried out applying an optimistic scenario, based on full superelevation, and a pessimistic, based on half superelevation. The pessimistic scenario takes into account potential obstacles for the realization of optimal curve geometry, particularly transition curves and superelevation ramps or incompatibility with the vehicle geometry (too long carbody segments or insufficient flexibility of joints between them).

For the estimation of travel time increase caused by curves, the optimistic and pessimistic assumptions described above are combined with various assumptions concerning road geometry as shown in Figure 13. Furthermore, the travel time increase was calculated for different train lengths (50 m, 100 m or 150 m) separately.

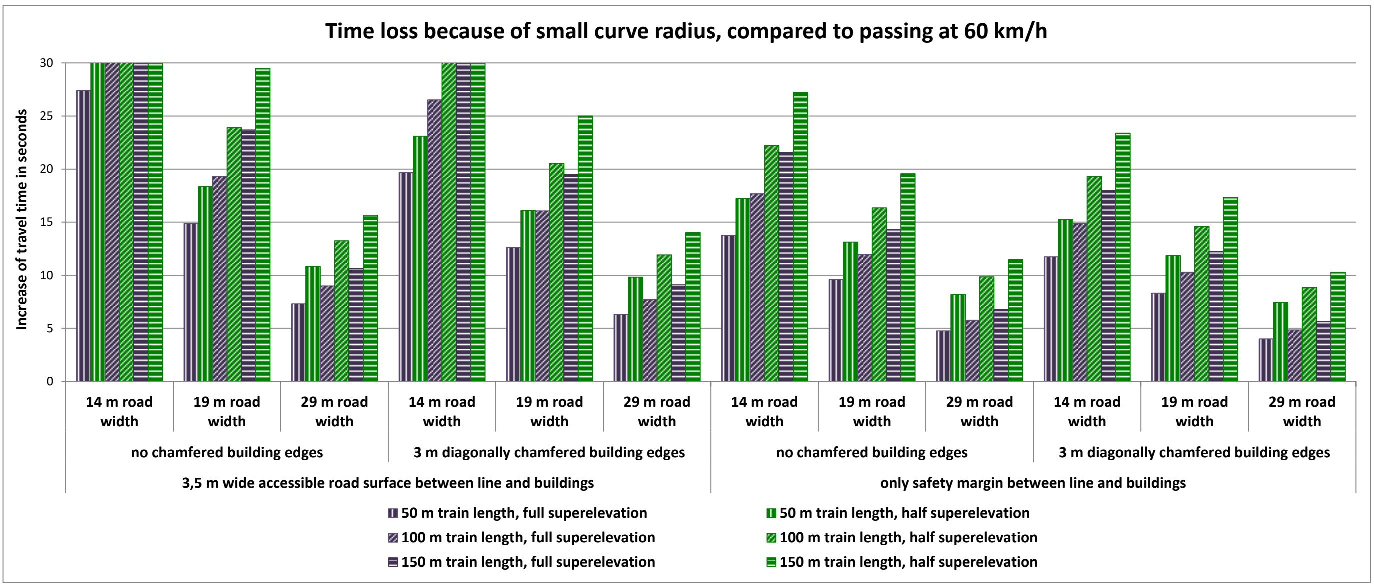

Figure 16: Calculated travel time increase due to curves at various framing conditions, compared to travel time at a constant speed of 60 km/h. Calculation assumptions: 0,8 m/s² acceleration & deceleration, curve angle 90°, inner track of a double-track line at 2,4 m vehicle width and 0,7 m safety margin between and outside the tracks.

The calculation results shown in Figure 16 concerning time losses because of curves are interpreted as follows:

- Curves on street level with parallel traffic lanes on both sides of the track are feasible only from 20 m road width up, with a train length as usual for metros the minimum road width is 25-30 m. In case of more narrow streets, the whole road width has to be used to accommodate the curved track. Probably this will be only possible with the LCRT track below street level, lowered by nearly the whole crossing height difference of 2,8 m (see 2.5.4).
- The effect of chamfered building edges has low relevance (at least to the extent of chamfering, assumed for the calculation).
- As a rough guide value over all debatable combinations of input values, 15 seconds of travel time increase per 90° direction change is assumed.

Time losses because auf speed restrictions in curves can be slightly reduced by placing curves as close as possible before or after a station: Although the acceleration resp. deceleration process must be interrupted in order to pass the curve at admissible speed, there is no time loss caused by deceleration before and acceleration after the curve. In the probably quite frequent combination of curve and underpass, the speed reduction facilitates even smaller vertical radii for the underpass ramps, particularly in the hollow.

2.2.3.1 Excursus: Relevance of top speed and speed restrictions for total travel time

In order to evaluate the relevance of different track alignment characteristics for achievable travel times, the average speed was calculated for the following variants and their combinations:

- Station distance:
  - 1000 m
  - 750 m
  - 500 m
- Speed restrictions because of curves:
  - No speed restrictions (straight line or sufficient curve radius thanks to suitable urban structures or bored tunnel sections)
  - One speed restricted 90° turn per km line
- Top speed:
  - 60 km/h
  - 50 km/h
  - 40 km/h

A top speed of 50 km/h or 40 km/h represents a compromise solution for sensitive public spaces resp. unimpeded possibilities for pedestrians to cross the LCRT line (see 2.8.1). The travel time increase caused by speed restrictions in curves, calculated for a top speed of 50 km/h and 40 km/h are shown in Figure 17 and Figure 18:

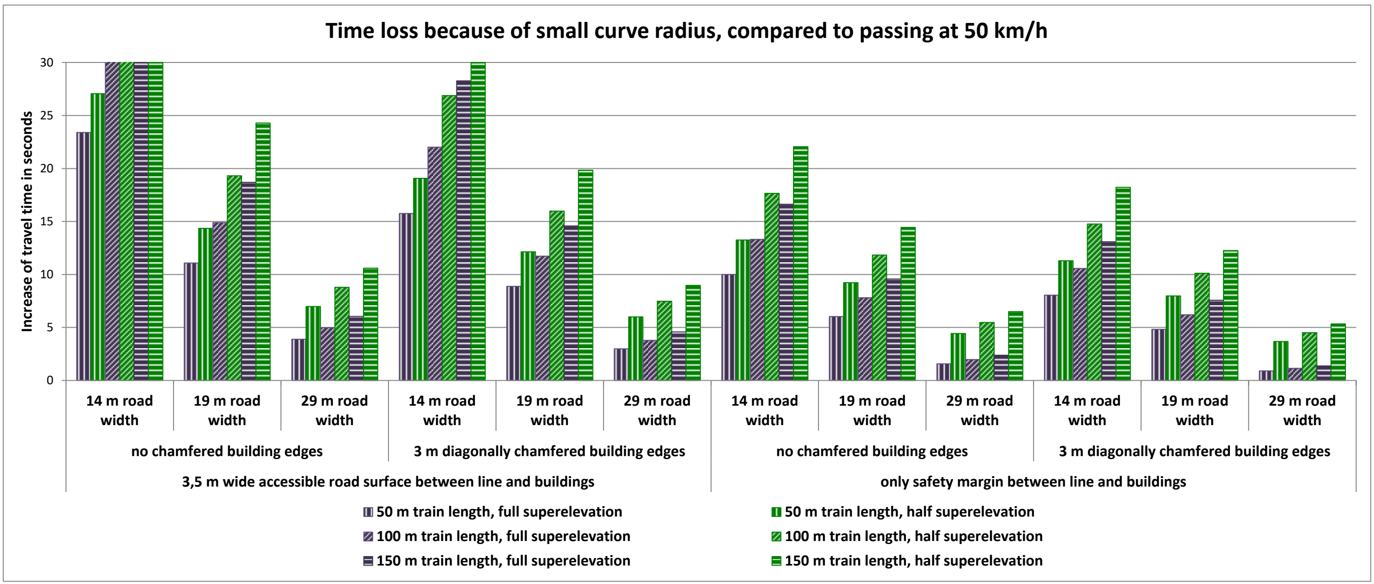

Figure 17: Calculated travel time increase due to curves at various framing conditions, compared to travel time at a constant speed of 50 km/h. Calculation assumptions: 0,8 m/s² acceleration & deceleration, curve angle 90°, inner track of a double-track line at 2,4 m vehicle width and 0,7 m safety margin between and outside the tracks.

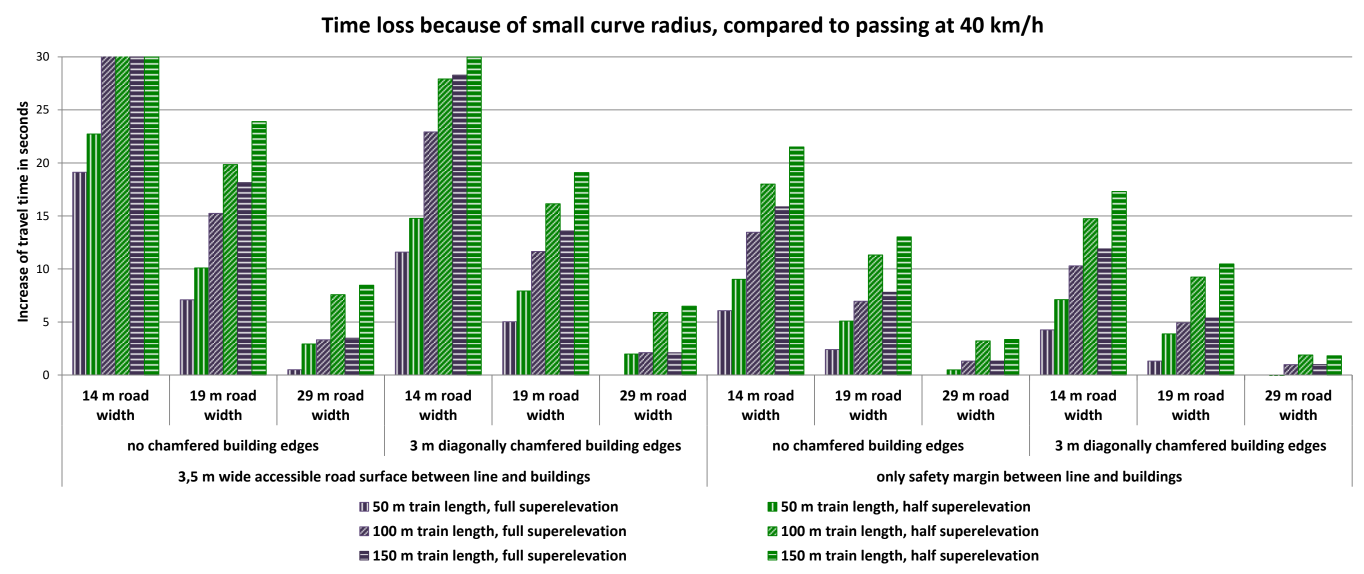

Figure 18: Calculated travel time increase due to curves at various framing conditions, compared to travel time at a constant speed of 60 km/h. Calculation assumptions: 0,8 m/s² acceleration & deceleration, curve angle 90°, inner track of a double-track line at 2,4 m vehicle width and 0,7 m safety margin between and outside the tracks.

As rough guide values, the travel time increase caused by speed restrictions in curves was assumed as 12 seconds at a top speed of 50 km/h and 10 seconds at a top speed of 40 km/h.

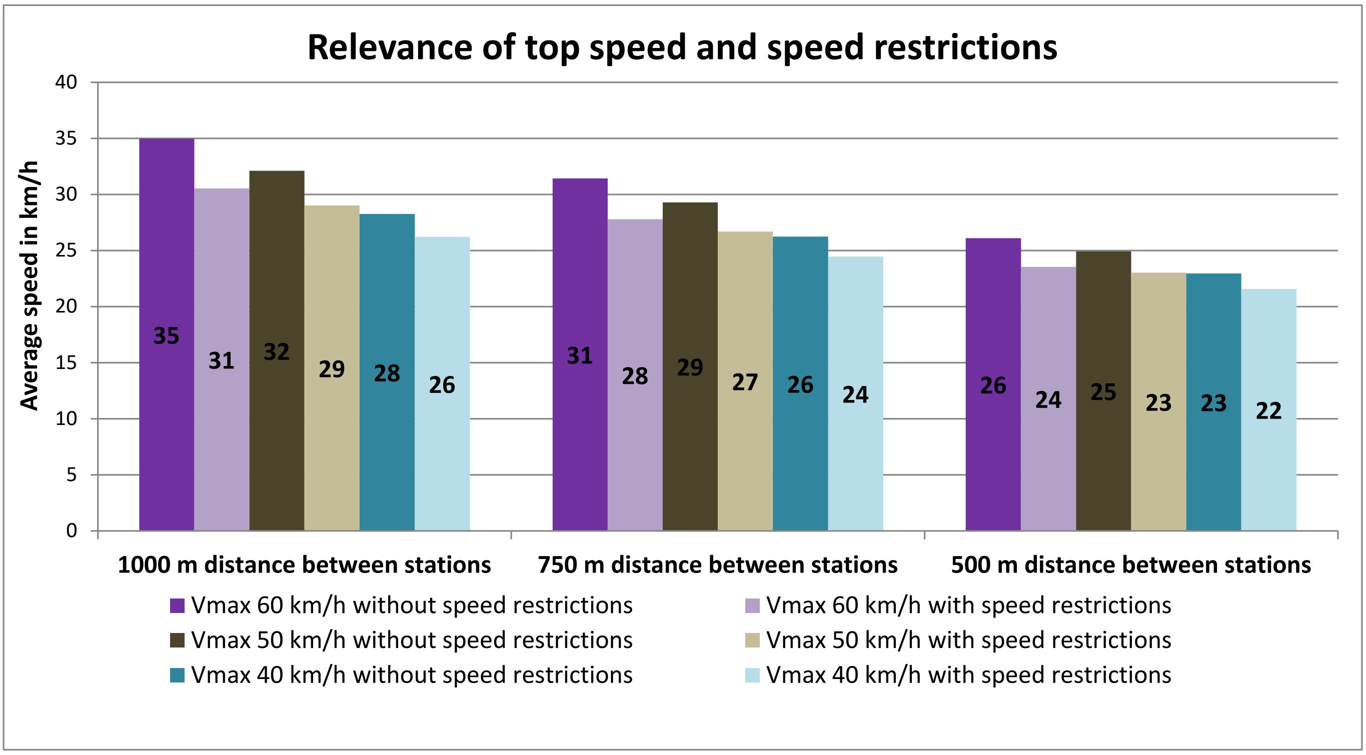

Figure 19: Influence of the station distance, the top speed to be reached between stops and the presence of speed restrictions in curves on the average speed of LCRT

As shown in Figure 19, the observed factors have relevant influence on the average speed, in the worst case travel times are about 60% longer, than in the best case. One curve with speed reduction per kilometre reduces the average speed by 6-13% and the higher the standard speed outside stations and curves, the more delay is caused by the speed restriction. Even in case of 40 km/h top speed combined with the consideration of speed restrictions, LCRT achieves average speed values approximately in the middle between conventional metros and conventional trams.

More detailed considerations about achievable average speed depending on the surrounding urban structures are subject of chapter 4.

2.3. Geometry parameters for crossing roads

In contrary to the previous section, the following considerations are not related to the LCRT line itself, but to those traffic lanes or sidewalks, which either cross the LCRT line grade-free, or run parallel to the LCRT line and must be elevated as well as far as they are connected to the elevated crossing road.

2.3.1 Longitudinal and cross slopes

2.3.1.1 Wheelchair accessibility

Usually, 6% is a guide value for slopes to be overcome by wheelchair users over a relevant distance[35]. Although this is as a limit value legally binding only for buildings[36], it is de-facto of high importance for public acceptability[37]. In order to avoid costs and space demand for additional elevators or detours for wheelchair users, at least for wheelchairs a maximum longitudinal slope of 6% is intended.

For wheelchair accessibility, the cross slope is relevant as well: Slopes of 2% and more (this means even less than the value of 2,5% recommended for proper drainage) makes it difficult for wheelchair or walking frame users to keep the direction of movement straight along the sidewalk[38,39,40]. For short distanced, e.g. house or property entries, 6% cross slope is permitted anyway, on case of LCRT-overpasses this would apply e.g. at the intersection of the sidewalks of the crossing road and that one, running parallel to the LCRT line.

2.3.1.2 Current regulation for road geometry

Existing regulations concerning road geometry allow similar or higher longitudinal slopes, than the wheelchair-oriented value of 6%. The Czech standard for design of urban roads[41] states 6% as a standard value for collector roads, only for arterial roads the regular value is 5%, but in justified cases, 7% may be applied too. In Austria, out of town up to 11% are admissible at a top speed of 50 km/h[42].

Concerning cross slope, the Czech standard mentioned above allows a maximum total incline of 9%, this means in case of 6% longitudinal slope also 6% cross slope. In Switzerland, for urban roads a limit value of 5% cross slope is applied[43], for Austrian rural roads, rather higher cross slopes are realized[44].

2.3.1.3 Considerations about safe and smooth traffic flow

For the specification of a practicable longitudinal slope, there should be considered, that the LCRT line is crossed basically only by collector roads and arterial roads, because minor streets are cut, enabling only turning to or from the lane, running parallel to the LCRT line, but not crossing it. With this in mind, it seems not appropriate always to apply limit values, but there should be paid some attention to safe and smooth traffic flow too. Also the necessity of frequent stop-and-go-situations on the slope should be kept in mind, particularly, if there is an intersection at the end of the slope.

2.3.1.4 Comparative measurements

As an example for an arterial road in Vienna, the longitudinal slope of Gumpendorfer Straße road at the intersection with Kaunitzgasse was measured as 4,9%. The maximum longitudinal slope of the neighbouring minor road Joanelligasse is 6,1%, that of the Berggasse, another minor road, is up to 11%.

Measurements of exemplary cross slopes in Vienna were 6,5% on the Mariahilfer Straße next to Otto-Bauer-Gasse or 4,2% on the Wasagasse at it's intersection with the Bergasse.

2.3.1.5 Slope parameters for the LCRT concept

For further dimensioning, a limit of **6%** for both longitudinal slope and cross slope is applied: This value guarantees passability for wheelchairs and represents a compromise between rather higher values out of road geometry standards and rather lower values from design practice concerning arterial roads.

2.3.2 Vertical radii on crests and in hollows

2.3.2.1 Visibility on the crest

The Czech standard for design of urban roads[45] defines minimum crest radii depending on design speed and justifies them with the necessary sight distance, depending on the speed as well.

For the calculation of an acceptable crest radius, the basic logic of the mentioned standard was applied, however using the following calculation assumptions:

- Height of the driver's eye above pavement: 1,2 m (originally this value had been used in the standard, later it was reduced to 1,0 m[46])[c]
- Not only the crest radius hat been taken into account, but also the slope of the ramps: If the ramps are not so steep, the vertical circle segment from the beginning to the end of the crest is rather short, shorter than the stopping distance. In this case, the required sight distance contains not only the crest (as the vertical circle segment), but also parts of the ramps with constant slope, so the sight distance is not predominately determined by the crest radius.
- Reaction time: 1 second
- Worst assumed friction coefficient between tyre and pavement: 0,5 (corresponding to wet pavement[47,48,d])

For the crossing of the LCRT line, a design speed of 30 km/h is proposed: This speed allows much more economical design of the overpasses and is anyway reasonable as a short speed restriction on arterial roads too: As an example, the Hörlgasse in Vienna has a 30 km/h speed limit although it is a three-lane road and also the Burggasse, Neustiftgasse and Gumpendorfer Straße have this speed limit over their whole length, still being main roads without doubt. Also on single-lane roundabouts of rather big radius, which represent a popular alternative to signal-controlled crossings on arterial roads, vehicles usually run at about 30 km/h[49,50].

At the mentioned calculation assumptions and 6% slope of both ramps, the resulting crest radius is **120 m**.

2.3.2.2 Vertical acceleration

At 120 m radius and 30 km/h driving speed, the centrifugal acceleration is 0,57 m/s^2. This is by far less than vertical accelerations, which had been measured in real car traffic[51].

[c] Extraordinary low vehicles with a lower height of the driver's eye can pass the crest anyway, they just have to pass it at slightly lower speed in order to enable stopping within sight distance.
[d] Even worse driving conditions (e.g. snow, ice) also require less speed

2.3.2.3 Ground clearance on the crest

At 120 m vertical radius on the crest, the necessary ground clearance height is 0,9 cm at 3 m wheelbase (passenger car) and 3,8 cm at 6 m wheelbase (low-floor bus), thus obviously unproblematic.

2.3.2.4 Comparative measurements

Attempts were made to measure vertical radii of real road crests. For this purpose, over a length of about 5-15 m along the crest, every 0,5 m the pavement slope was measured[e] in order to calculate the crest radius out of slope difference and arc length. Unfortunately, particularly on the more relevant collector and arterial roads, no useful measuring results could be achieved:

- Because of minor unevenness of the pavement, measured slope values did not continuously increase or decrease, but measured values fluctuated in both directions, so the calculated crest radii also varied enormously (often even between positive and negative values) between adjacent measurements.

- For safety reasons, the measurements could not be carried out directly on the driving lane, but only on the parallel sidewalk, so the measurements were influenced by lowering of the sidewalk next to the crossroad (for wheelchair accessibility).

In total, 9 crests were measured (thereof 7 minor roads), the vertical radii, calculated as an average over 2 m length, were between 30 and 65 m.

2.3.2.5 Vertical radius in the hollow

The vertical radius in the hollow, at the beginning and the end of the overpass, is of less importance than that on the crest: On one hand, there are no visibility problems in the hollow, on the other hand, there is little effect on the construction effort, because a big radius would enlarge only the lowest parts of the overpass. Therefore, the same radius as for the crest, **120 m**, is applied.

2.3.3 Elevation of traffic areas against the surrounding level

2.3.3.1 Possible effect on cityscape and neighbouring buildings

The elevation of traffic areas as crossing streets, but partially also driving lanes running parallel to the LCRT track in the area of grade-free crossings requires not only slopes and crests resp. hollows. It must be considered, how such elevated traffic areas in the middle of the street affect their surroundings:

- Elevated transport infrastructure itself, but also the vehicles circulating on it can impair the light conditions in neighbouring buildings
- At same noise emission, immission can increase, when the source of noise is elevated, getting e.g. closer to windows.
- In many buildings, rooms on the ground floor have sight protection thanks to moderate elevation of the ground floor by sufficient building’s base below. If the sidewalk is elevated to that extent, that pedestrians get direct, horizontal view into the windows, this sight protection gets lost.

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[e] As a measuring device, a measuring tape for the spacing between measurements and a Bosch PLR 50 C Digital Laser Measure for the inclination were used

- Corners of poor illumination and visibility may facilitate criminal activities and vandalism or cause at least fear[f]
- The aesthetic quality of public space can be affected (although hard to measure)

2.3.3.2 Real examples of height and width in public space

As an orientation, which building heights are usual and acceptable depending on their distance to the property line resp. house front, first of all examples were taken from the Viennese development plan (see Table 4). It turned out, that within high-density urban structures, elevation angles of more than 45° are admissible in neighbourhoods built up in the 19th century as well as in contemporary urban expansion areas.

Furthermore, within Vienna were found and measured[g] 25 exemplary situations of either really elevated roads or railroad resp. metro lines running very close to the house front, or a sidewalk or a lane lowered against the rest of the street surface (see Table 5).

As shown in Figure 20, elevated transport infrastructure is, apart from some outliers, at the same horizontal distance situated lower than ordinary buildings on the opposite side of the street: typical elevation angles for elevated road or rail lines are in a range of 20-30°. This seems realistic, because elevated transport infrastructure does not only affect light conditions and privacy, but also emits noise.

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[f] From the passenger's point of view, LCRT is in terms of perceived security anyway better, than a metro with large underground station buildings

[g] As a measuring device, a Bosch PLR 50 C Digital Laser Measure for distance and inclination was used, the expected accuracy is about +/- 10 cm. If the elevated road or railroad was equipped with a noise barrier, only the height up to the base of the noise barrier had been measured.

Exemplary street or district in Vienna	Width (m)	Height (m)	Angle (°)	Remarks
Narrow streets in Favoriten district: Keplergasse, Raaberbahngasse, Ordensgasse; with building height stated in the development plan	11	18	59	
Narrow streets in Favoriten district: Keplergasse, Raaberbahngasse, Ordensgasse; with construction class stated in the development plan	11	14	52	
District Margareten: Gießaufgasse, Diehlgasse	15,17	19,17	52	
Aspern expansion area: Agnes-Primocic-Gasse, Schenz-Danzinger-Gasse	12	15	51	
Aspern expansion area: Ilse-Arlt-Straße	14	17	51	
Rather wide streets in Favoriten district: Humboldtgasse, Scheugasse	15	18	50	
Nordbahnhof expansion area: new road (yet unnamed)	30	30	45	Business quarter, rather no housing
District Ottakring: Crossroads of Hasnerstraße (Fröbelgasse, Liebhartsgasse, Habichergasse, Haberlgasse)	15,1	14	43	
District Ottakring: Hasnerstraße	19	16	40	
Sonnwendviertel expansion area: Alfred-Adler-Straße	30	21	35	
Aspern expansion area: Sonnenallee	32	21	33	

Table 4: Examples of admissible building height in relation to the road with according to the Viennese development plan

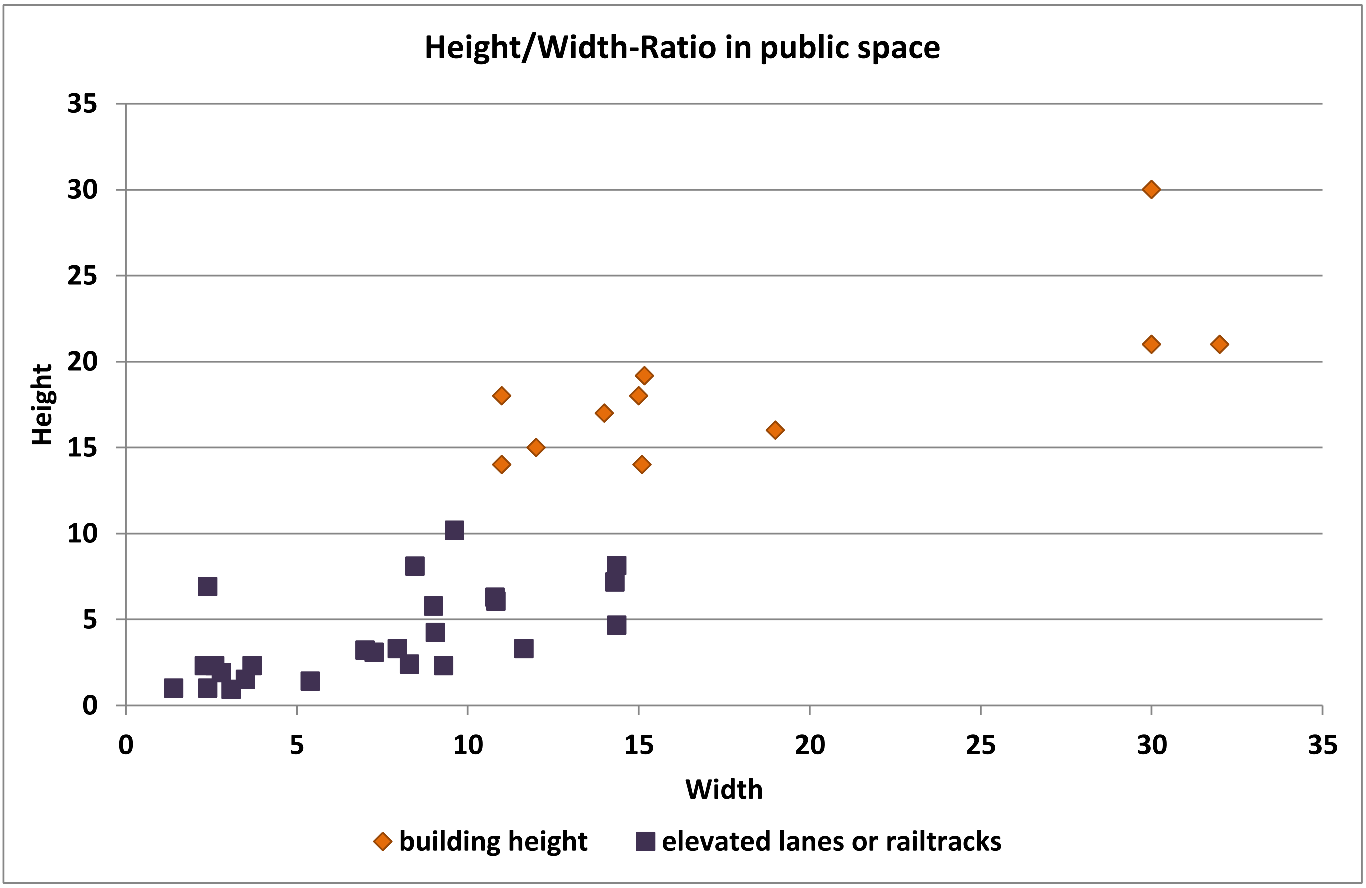


Figure 20: Height and width of typical public spaces and spacing between buildings and elevated transport infrastructure in Vienna

Location	Width (m)	Height (m)	Angle (°)	Remarks	Picture
Stiegengasse	2,4	6,9	71	Extreme case in the corner of the stairs, unknown building use in the corner, next to the corner shops	
Holzgasse / elevated B14 highway	9,6	10,2	47	Business building, no residential use	
Marokkanergasse at Zaunergasse	2,3	2,3	45	Maximum value at the corner, unknown building use	
Bahndammweg 24 / U6	8,5	8,1	44	Allotment garden, intense traffic	
Marokkanergasse at Heumarkt	2,6	2,3	41	Maximum value at the corner, restaurant; intense traffic	
Joanelligasse next to Luftbadgasse	1,4	1,0	36		
Salvatorgasse, minimum width	2,8	1,9	34		
Southern part of Durchlaufstraße / Metro U6 – Building edge next to Handelskai	9,0	5,8	33	Municipality-owned pure residential building, intense traffic	

Location	Width (m)	Height (m)	Angle (°)	Remarks	Picture
Salvatorgasse, maximum height difference	3,7	2,3	32		
untere Viaduktgasse at Adamsgasse	10,8	6,3	30	Intense traffic, rather loud vehicles	
Suburban line „Vorortelinie“ / Weinheimergasse, east side	14,4	8,1	30		
obere Viaduktgasse opposite to Adamsgasse	10,8	6,0	29	Intense traffic, rather loud vehicles	
Suburban line „Vorortelinie“ / Weinheimergasse, west side	14,3	7,2	27		
untere Viaduktgasse at Kolonitzgasse	9,1	4,2	25	intensiver Verkehr, eher laute Fahrzeuge	
Nordbahnhofareal/S-Bahn-Trasse next to Lasallestraße	7,0	3,2	25	Business district, rather no residential use; intense traffic, rather loud vehicles; only indirect measurement of poor accuracy because of construction site	
Mattiellistraße	3,5	1,5	23		
Baumanngasse	7,3	3,1	23	Business building, rather no residential use	

Location	Width (m)	Height (m)	Angle (°)	Remarks	Picture
Zaunergasse at Salesianergasse	2,4	1,0	23	Very short section, storage or similar use	
Southern part of Durchlaufstraße / Metro U6 – Building edge next to Vorgartenstraße	7,9	3,3	23	Municipality-owned pure residential building, intense traffic	
Luntzgasse / Handelskai	14,4	4,7	18	Municipality-owned pure residential building, intense traffic with loud vehicles	
Luftbadgasse next to Joanelligasse	3,1	0,9	17		
Salesianergasse at Ölzeltgasse	8,3	2,4	16		
Jägerstraße / Forsthausgasse /Nordwestbahn	11,6	3,3	16	Few traffic but loud vehicles, early closure of the railway was known when houses were built	
Technikerstraße	5,4	1,4	15		
Heumarkt	9,3	2,3	14		

Table 5: Exemplary situations of elevated roads or railtracks, or traffic areas lowered against the rest of the street surface

2.3.3.3 Limit values of elevation angle for the LCRT concept

For further dimensioning of the LCRT concept, a standard elevation angle of **20°** measured from the base of the house front up to the edge of the elevated traffic area (lane and evtl. Sidewalk) is intended. In exceptional cases, **up to 30°** are acceptable, if additional costs for the adaptations of the building, compensation for the owner or purchase and resale at lower price are calculated (see 3.2.1.6 too). Furthermore, the sensitivity of the use of the building shall be considered individually, e.g. if there are apartments on the ground floor or just storage facilities and garbage rooms.

It was considered to evaluate the appropriateness of elevated traffic areas not only proportionally to the elevation angle, but also by the use of other criteria, e.g. whether the building is placed on a higher base. These considerations were discarded, because although in these cases a slight elevation does not yet cause any problems concerning the lighting situation, an adverse effect on sight protection is possible just in case if the distance to the house front as well as the amount of elevation is very small.

2.3.3.4 Feasible elevation depending on available public space

The elevation angle, measured from the base of the house front up to the edge of the elevated traffic area, which is affecting a building, depends on the following factors:

- Height difference between LCRT line and crossing road (assumption of 2,8 according to 2.1)
- Vertical radius on the crest and maximum slope of the elevated traffic areas – see specifications in 2.3.1 and 2.3.2
- Crown height of the crossing road's pavement on the overpass (share of the height difference, that is achieved by elevation of the crossroad, the remaining height difference has to be covered by lowering the LCRT line).
- Width of the road along the LCRT line: The wider the road, the lower is the pavement of the crossing road at the beginning of the buildings next to the crossing
- Distance from the house corner: The most affected buildings resp. rooms are those situated immediately at the corner of the intersection between the road with the LCRT line and the crossroad. With increasing distance from this corner, the level of the traffic areas converges to the level of the surrounding area resp. the previous state
- Horizontal distance between the building and the elevated traffic area.

In Table 6, the height difference and the elevation angle are listed for various combinations of the influencing factors mentioned above. In those parts of the table, which show elevation angles, according to the limit values defined before, values up to 20° are highlighted **green**, those between 20°and 30° yellow and values over 30° **red**.

The most significant factor is the horizontal distance between the house front and the elevated parts of the road: If it consists only out of a 2 m wide sidewalk, an elevation of more than 1 m is hardly possible, so the LCRT line must be lowered at least 1,8 m. If the distance is 4 m, e.g. a driving lane and a narrow sidewalk or a calmed traffic zone without division in driving lane and sidewalk (shared space), the LRCT line must be lowered only 0,5 – 0,8 m. In spacious conditions, which allow 6 m distance of the elevated traffic area to the house front, the whole required height difference can be achieved by elevation of the crossroad.

Height difference from the base of the house front to the elevated traffic area

Elevation of traffic areas depending on the position relative to the intersection (height difference in m)	Values apply at: 15 m road width along the LCRT line					Values apply at: 20 m road width along the LCRT line					Values apply at: 25 m road width along the LCRT line					Values apply at: 30 m road width along the LCRT line				
Crown height (m)	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3
resulting lowering of the LCRT line (m)	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5
Distance from the house corner (m)																				
0	0,3	0,8	1,3	1,8	2,1	0,1	0,6	1,1	1,6	1,9	0,0	0,5	1,0	1,5	1,8	0,0	0,3	0,8	1,3	1,6
5	0,0	0,5	1,0	1,5	1,8	0,0	0,3	0,8	1,3	1,6	0,0	0,2	0,7	1,2	1,5	0,0	0,1	0,5	1,0	1,3
10	0,0	0,2	0,7	1,2	1,5	0,0	0,1	0,5	1,0	1,3	0,0	0,0	0,4	0,9	1,2	0,0	0,0	0,2	0,7	1,0
15	0,0	0,0	0,4	0,9	1,2	0,0	0,0	0,2	0,7	1,0	0,0	0,0	0,1	0,6	0,9	0,0	0,0	0,0	0,4	0,7
20	0,0	0,0	0,1	0,6	0,9	0,0	0,0	0,0	0,4	0,7	0,0	0,0	0,0	0,3	0,6	0,0	0,0	0,0	0,1	0,4
25	0,0	0,0	0,0	0,3	0,6	0,0	0,0	0,0	0,1	0,4	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,1
30	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
35	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
40	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
45	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Elevation angle (degree) at 2 m distance between house front and elevated traffic area

Elevation of traffic areas depending on the position relative to the intersection (elevation angle in degree)	Values apply at: 15 m road width along the LCRT line					Values apply at: 20 m road width along the LCRT line					Values apply at: 25 m road width along the LCRT line					Values apply at: 30 m road width along the LCRT line				
Crown height (m)	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3
resulting lowering of the LCRT line (m)	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5
Distance from the house corner (m)																				
0	7,6	21,0	32,3	41,4	45,9	3,6	17,1	29,2	38,9	43,8	1,1	13,1	25,8	36,2	41,4	0,0	9,0	22,2	33,3	38,9
5	1,1	13,1	25,8	36,2	41,4	0,0	9,0	22,2	33,3	38,9	0,0	4,8	18,4	30,2	36,2	0,0	1,8	14,5	26,9	33,3
10	0,0	4,8	18,4	30,2	36,2	0,0	1,8	14,5	26,9	33,3	0,0	0,2	10,4	23,4	30,2	0,0	0,0	6,2	19,7	26,9
15	0,0	0,2	10,4	23,4	30,2	0,0	0,0	6,2	19,7	26,9	0,0	0,0	2,6	15,8	23,4	0,0	0,0	0,6	11,7	19,7
20	0,0	0,0	2,6	15,8	23,4	0,0	0,0	0,6	11,7	19,7	0,0	0,0	0,0	7,6	15,8	0,0	0,0	0,0	3,6	11,7
25	0,0	0,0	0,0	7,6	15,8	0,0	0,0	0,0	3,6	11,7	0,0	0,0	0,0	1,1	7,6	0,0	0,0	0,0	0,0	3,6
30	0,0	0,0	0,0	1,1	7,6	0,0	0,0	0,0	0,0	3,6	0,0	0,0	0,0	0,0	1,1	0,0	0,0	0,0	0,0	0,0
35	0,0	0,0	0,0	0,0	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
40	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
45	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Elevation angle (degree) at 4 m distance between house front and elevated traffic area

Elevation of traffic areas depending on the position relative to the intersection (elevation angle in degree)	Values apply at: 15 m road width along the LCRT line					Values apply at: 20 m road width along the LCRT line					Values apply at: 25 m road width along the LCRT line					Values apply at: 30 m road width along the LCRT line				
Crown height (m)	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3
resulting lowering of the LCRT line (m)	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5
Distance from the house corner (m)																				
0	3,8	10,8	17,6	23,8	27,3	1,8	8,8	15,6	22,0	25,6	0,5	6,6	13,6	20,1	23,8	0,0	4,5	11,5	18,2	22,0
5	0,5	6,6	13,6	20,1	23,8	0,0	4,5	11,5	18,2	22,0	0,0	2,4	9,5	16,2	20,1	0,0	0,9	7,3	14,2	18,2
10	0,0	2,4	9,5	16,2	20,1	0,0	0,9	7,3	14,2	18,2	0,0	0,1	5,2	12,2	16,2	0,0	0,0	3,1	10,1	14,2
15	0,0	0,1	5,2	12,2	16,2	0,0	0,0	3,1	10,1	14,2	0,0	0,0	1,3	8,1	12,2	0,0	0,0	0,3	5,9	10,1
20	0,0	0,0	1,3	8,1	12,2	0,0	0,0	0,3	5,9	10,1	0,0	0,0	0,0	3,8	8,1	0,0	0,0	0,0	1,8	5,9
25	0,0	0,0	0,0	3,8	8,1	0,0	0,0	0,0	1,8	5,9	0,0	0,0	0,0	0,5	3,8	0,0	0,0	0,0	0,0	1,8
30	0,0	0,0	0,0	0,5	3,8	0,0	0,0	0,0	0,0	1,8	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0	0,0	0,0
35	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
40	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
45	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Elevation angle (degree) at 6 m distance between house front and elevated traffic area

Elevation of traffic areas depending on the position relative to the intersection (elevation angle in degree)	Values apply at: 15 m road width along the LCRT line					Values apply at: 20 m road width along the LCRT line					Values apply at: 25 m road width along the LCRT line					Values apply at: 30 m road width along the LCRT line				
Crown height (m)	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3	0,5	1	1,5	2	2,3
resulting lowering of the LCRT line (m)	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5	2,3	1,8	1,3	0,8	0,5
Distance from the house corner (m) / Entfernung von der Hausecke (m)																				
0	2,5	7,3	11,9	16,4	19,0	1,2	5,9	10,5	15,1	17,7	0,4	4,4	9,1	13,7	16,4	0,0	3,0	7,7	12,4	15,1
5	0,4	4,4	9,1	13,7	16,4	0,0	3,0	7,7	12,4	15,1	0,0	1,6	6,3	11,0	13,7	0,0	0,6	4,9	9,6	12,4
10	0,0	1,6	6,3	11,0	13,7	0,0	0,6	4,9	9,6	12,4	0,0	0,1	3,5	8,2	11,0	0,0	0,0	2,1	6,8	9,6
15	0,0	0,1	3,5	8,2	11,0	0,0	0,0	2,1	6,8	9,6	0,0	0,0	0,9	5,4	8,2	0,0	0,0	0,2	4,0	6,8
20	0,0	0,0	0,9	5,4	8,2	0,0	0,0	0,2	4,0	6,8	0,0	0,0	0,0	2,5	5,4	0,0	0,0	0,0	1,2	4,0
25	0,0	0,0	0,0	2,5	5,4	0,0	0,0	0,0	1,2	4,0	0,0	0,0	0,0	0,4	2,5	0,0	0,0	0,0	0,0	1,2
30	0,0	0,0	0,0	0,4	2,5	0,0	0,0	0,0	0,0	1,2	0,0	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,0
35	0,0	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
40	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
45	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
50	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Table 6: Height difference to surrounding level and elevation angle depending on the elevation of traffic areas, the road width (along the LCRT line) and the distance between house front and the elevated traffic area as well as the distance to the house corner at the underpass intersection. Legend see next page.

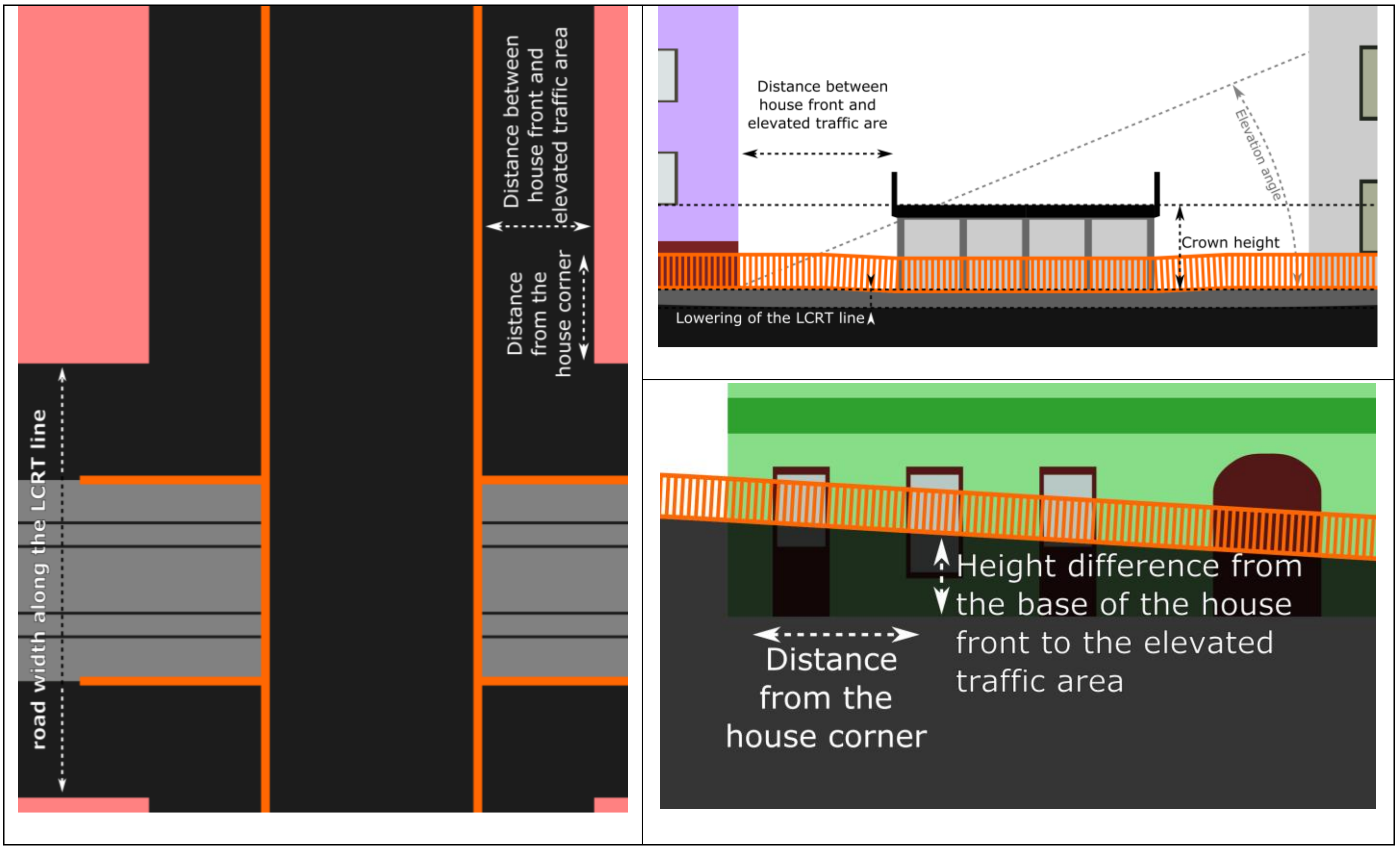


Figure 21: Legend for the table on the previous page

In extraordinary cases, it is also conceivable to realize no distance between house front and elevated traffic areas at all, but to elevate the road over its whole width. This might be possible, if all affected buildings have a sufficient base below their ground floor, so because of the elevation, it is not necessary to make new steps to the entrance, but in contrary, existing steps can be removed.

2.4. Trench depth of pipes and cables below the road surface[52]

A significant potential cost factor for the construction of LCRT lines is the relocation of various cables and pipelines. This concerns first of all water and sewer pipes, which are usually installed in the middle of the road or in the middle of a lane and partly also district heating pipes, which are rather installed next to the kerb. Usually, these installations are relocated when a tram line is constructed, in order to keep them accessible without dismantling of the tram track[53]. A possibility to avoid costly removal of lines and cables is the allocation of the LCRT track along the root area of avenue trees using root bridges (see 2.10.2), another option is the rubber-tyred version with minimized pavement stress (see 5.1.1). If a rail-wheel-system is chosen, smaller gauge means better accessibility to pipes and cables below the pavement, because there remains a wider area between the tracks in the middle of the road. Regardless to the decision between a rail-wheel-solution and the rubber-tyred alternative, the depth of the lowered LCRT line in the underpass area is of critical importance, because in this area, conflicts arise not only with the lines and cables running below the driving lanes parallel to the LCRT tracks, but also with those lines, running through the crossroad below the pavement.

In Vienna, for the most types of cables and pipelines, minimum depths of 0,7 – 1 m are applied, only water and sewer pipes are installed deeper. Because of the space requirements of the track construction and the necessity to protect the cables and pipes against mechanical stress (in case of water supply and sewer also against frost), it seems not realistic to lower the road level more than 0,5 m. Even this value is rather optimistic and supposes that either the lines are in fact installed a little deeper, or there will be found innovative solutions for extraordinary shallow crossing of the pipes or conduits below the track, e.g. some kind of utility corridor integrated into the track construction.

For a cost-benefit optimized dimensioning of the LCRT line and its crossings it seems to be practically, either to save costs for relocation of pipes and cables by lowering the LCRT tracks by maximally 0,5 m, or to accept these costs and cover most of the height difference by the LCRT depth while avoiding complications on the road surface and damage to the cityscape.

2.5. Standard dimensions of LCRT underpasses

Depending on detailed local conditions, there is a big variety of underpass shapes, which differ not only concerning the height levels of LCRT line and crossing road, but also in terms of horizontal arrangement of public space, traffic management etc. As a first approximation, four standard types are defined and subsequently used for cost estimation (see chapter 2.10.2) as well.

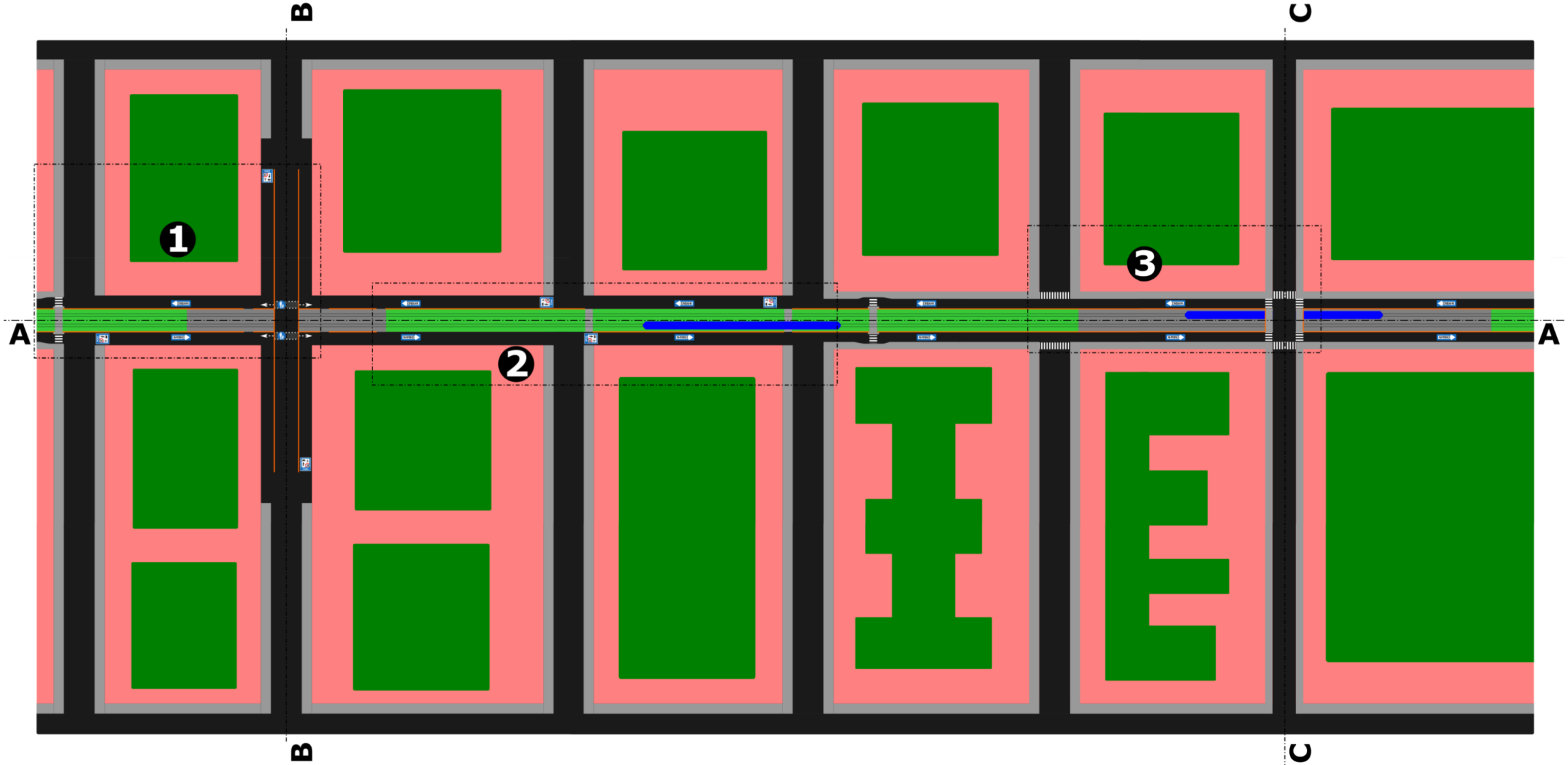


Figure 22: Ground plan of a section of an LCRT line with a shallow underpass (see also detail ❶, section B-B as well as the left part of section A-A), station area (see also detail ❷) and a deep underpass (see also detail ❸, section C-C and the right part of section A-A)

Figure 23: Longitudinal section of an LCRT-Line with a shallow underpass (left part), station area (center) and a deep underpass (right part)

2.5.1 Shallow underpass

The shallow underpass is dimensioned for minimum construction effort concerning the LCRT line: A track level only 0,5 m below the surroundings means hopefully no relocation of pipes and cables, no need for trench shoring but also no sight restrictions for the LCRT driver, making pedestrian level crossings (see also 2.7) possible in the underpass area as well. In order to reduce the effort for elevating traffic areas and to preserve cityscape, only the driving lanes of the crossing road are elevated. The lanes and sidewalks running parallel to the LCRT line remain on their original level and in the crossing road there are also established sidewalks and additional lanes on the unchanged surrounding level parallel to the elevated ramp. Thus, all entrances are accessible for pedestrians and vehicles and thanks to more distance between house front and overpass ramp, a smaller angle results from the same height difference. For pedestrians and cyclists, a passage through the overpass ramp is realized parallel to the LCRT tracks, but motor vehicles cannot continue straight along the LCRT line. When driving to resp. from an address in the street used for the LCRT line, motor vehicles have to turn from resp. into the crossing road when coming to an underpass.

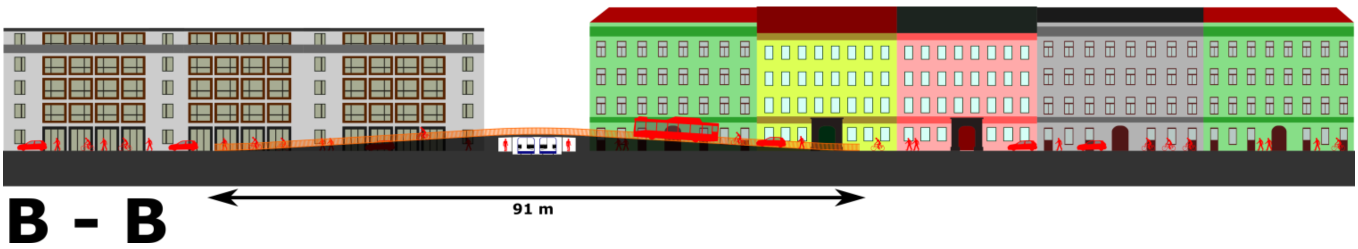


Figure 24: Longitudinal section through a road, crossing the LCRT line with a shallow underpass

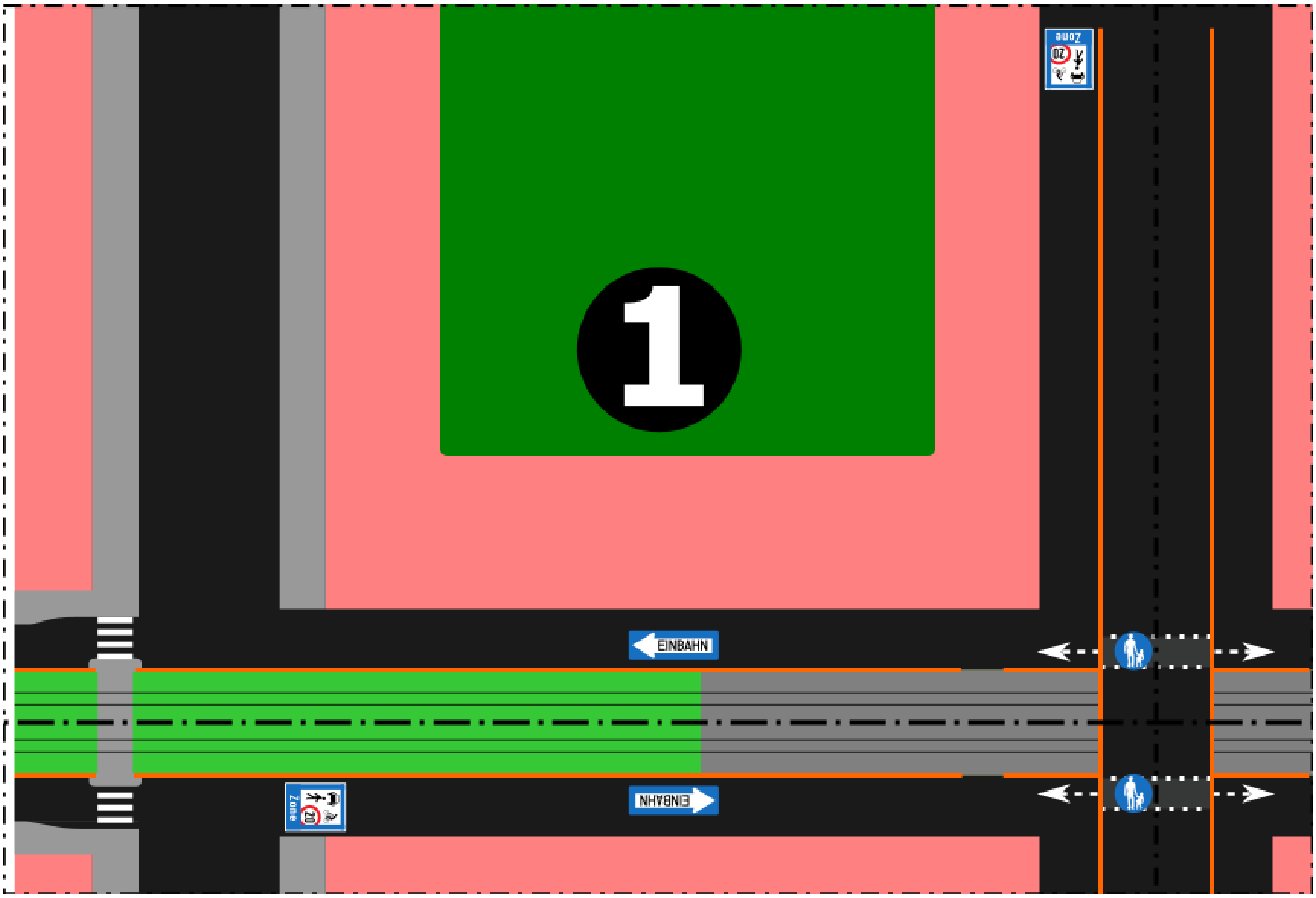


Figure 25: Detailed ground plan of an LCRT line with a shallow underpass

Figure 26: Detailed view of a longitudinal section of an LCRT line in the area of shallow underpass.

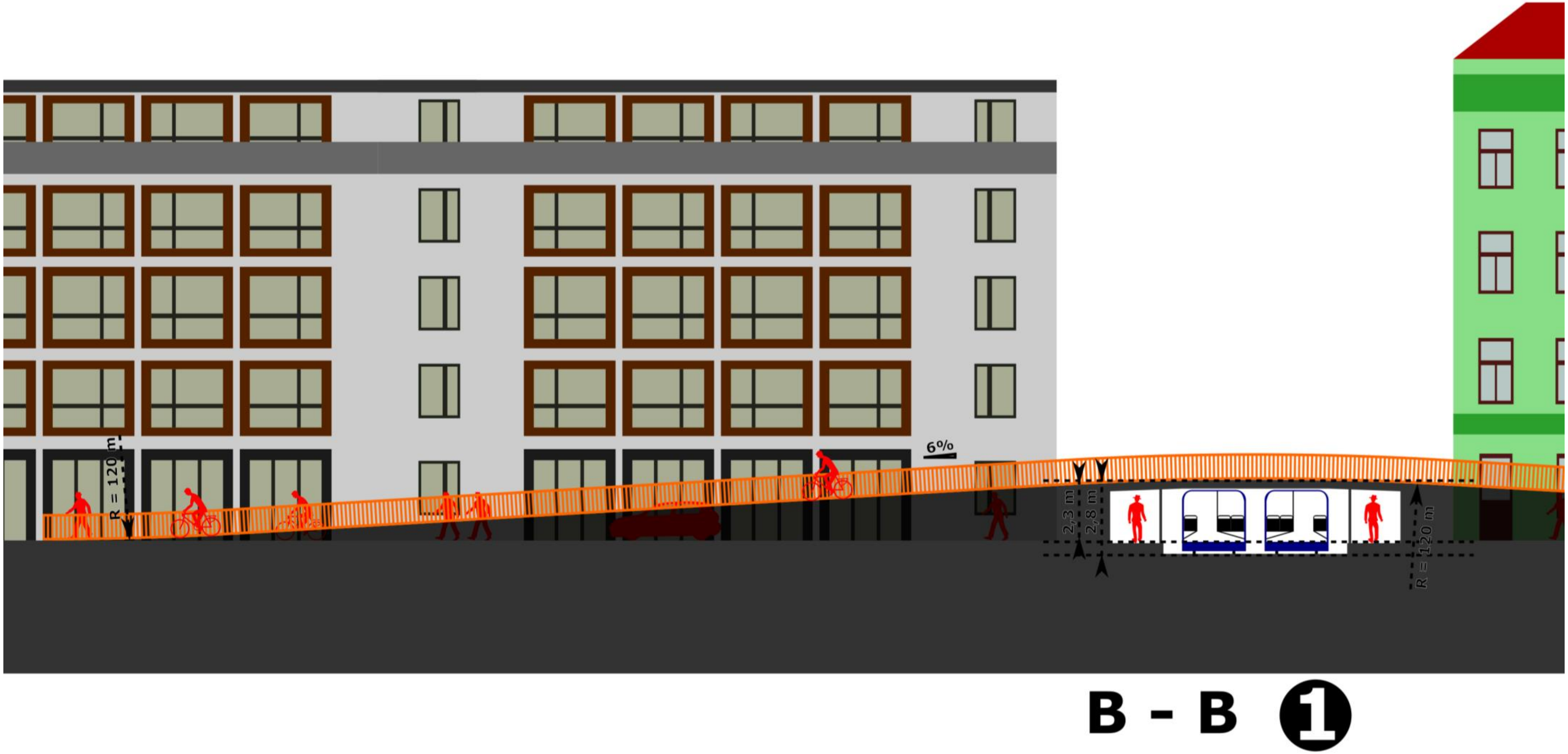


Figure 27: Detailed view of a longitudinal section of a road, crossing the LCRT line with a shallow underpass

In the example shown in Figure 24 until Figure 27, the traffic areas which on their original level (in the crossing road as well as along the LCRT tracks) are arranged as calmed traffic zones without division into driving lane and sidewalk (shared space) in order to reduce the overall road width to a minimum while still ensuring accessibility for waste collection, fire brigade or delivery vehicles. In this case, an overall width of the crossing road of about 15 m would be sufficient. The overall length of the underpass including the ramps is 53 m in the direction of the LCRT line and 91 m in the direction of the crossing road. This value seems realistic compared to a mobile temporary construction called "Fly-Over"[54,55], used by the Austrian motorway corporation ASFINAG for the repair of expansion joints, with a length of 106 m. The working height below it is 1,6-1,9, thus only a little less, than the LCRT clearance height of 2,45 m minus 0,5 m lowering of the LCRT tracks, but the "Fly-Over" is designed for urban motorways with a design speed of 80 km/h instead of intra-urban arterial or collector roads with speed limited to 30 km/h locally in the area of the overpass.

Shallow underpasses are particularly suitable, if the LCRT line does not follow an arterial road, but such a road, which is wide enough to accommodate the LCRT tracks, but anyway does not fulfil the function of a main road. In this case, the necessity of detours and loops for the access of the street sections between the underpasses is acceptable and comparable to usual traffic calming by the implementation of one-way streets.

2.5.2 Deep underpass

For a deep underpass, the relocation of pipes and cables below the pavement is necessary without doubt, because the LCRT line is lowered against the original road level by 2,3 m. In contrary, the highest point of the crossing road is elevated by only 0,5 m, so it becomes possible to elevate the sidewalks and the driving lanes running parallel to the LCRT line as well. The upper side of the underpass represents a rather conventional road intersection that can be passed parallel or transversely to the LCRT line and turning is possible too.

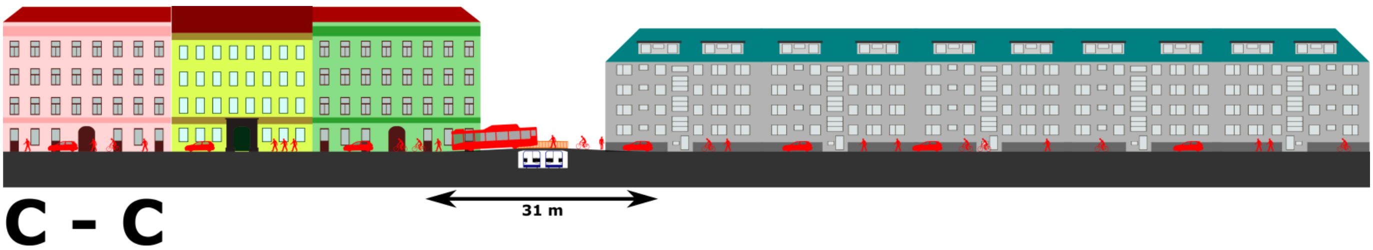


Figure 28: Longitudinal section of a road, crossing the LCRT line with a deep underpass

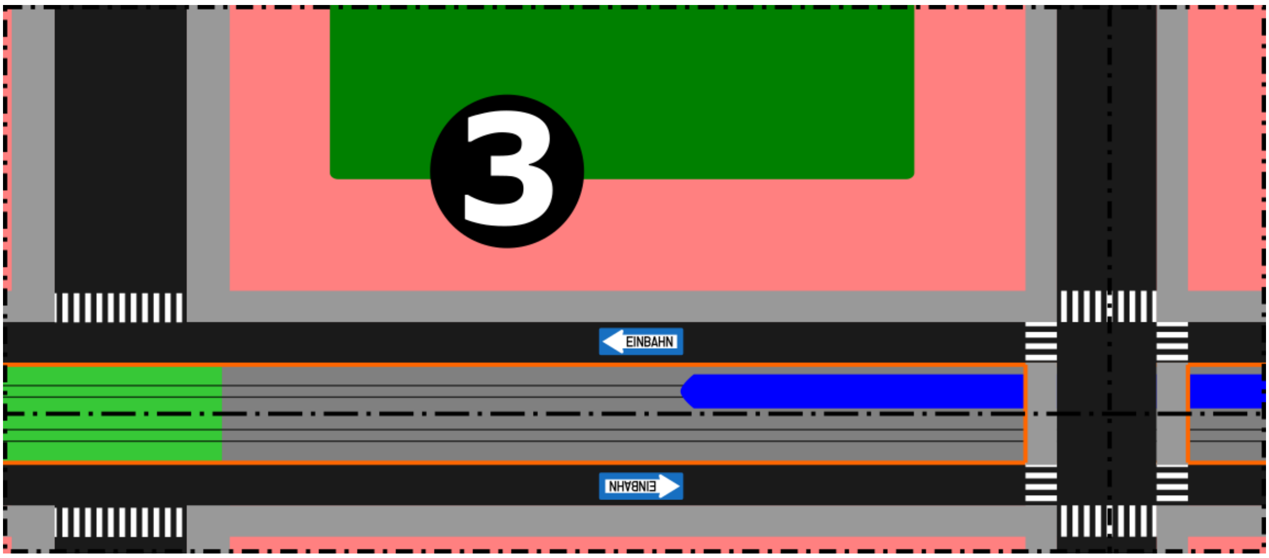
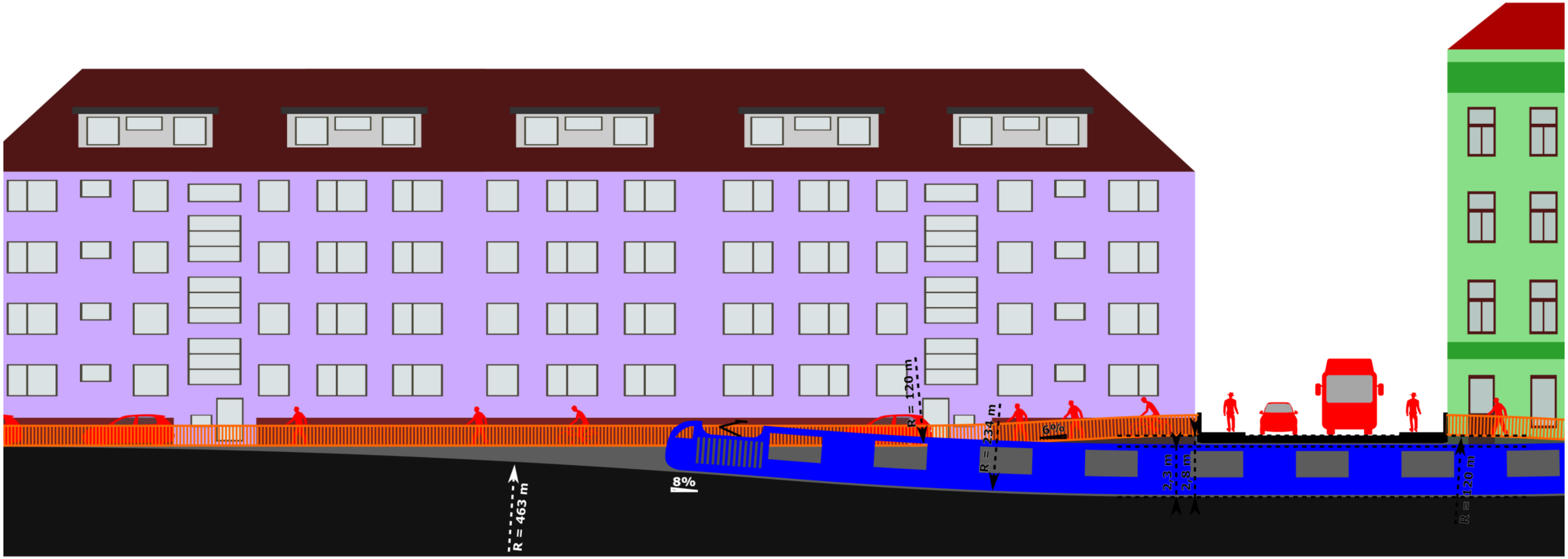
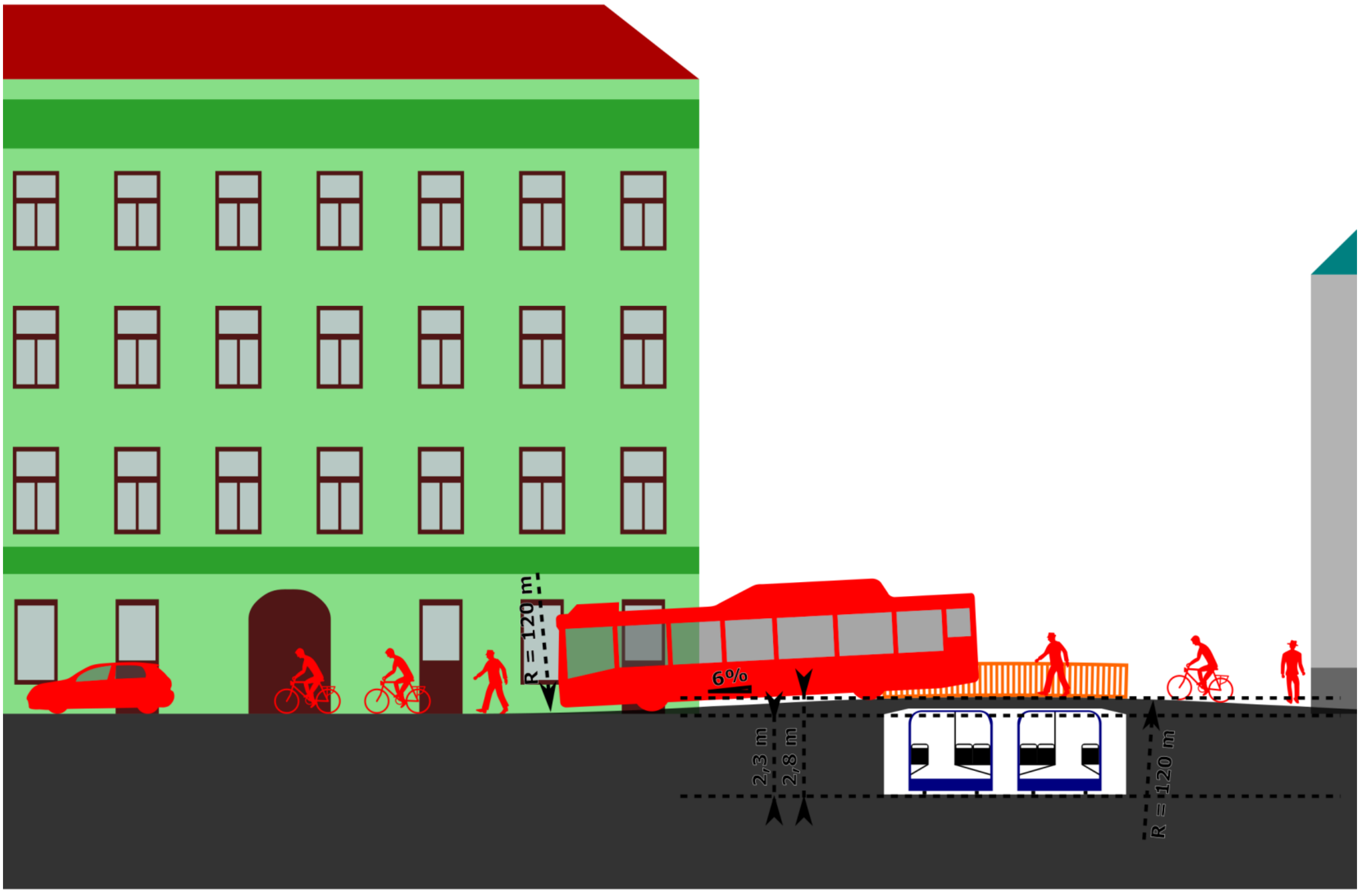


Figure 29: Detailed ground plan of an LCRT line with a deep underpass



A - A ❸

Figure 30: Detailed view of a longitudinal section of an LCRT line in the area of a deep underpass



C - C ❸

Figure 31: Detailed view of a longitudinal section of a road, crossing the LCRT line with a deep underpass

The proportions of a deep underpass are shown in Figure 28 until Figure 31. In this case, the length of an underpass including the ramps spreads over 113 m along the LCRT line, but only over 31 m along the crossing road. On the LCRT tracks, the crests cause sight restrictions below stopping distance, so without highly reliable protecting devices, no pedestrian level crossings (see 2.7) can be established within 120 m on both sides of the underpass. Preceding LCRT vehicles are always visible because of their height, so visibility conditions in the underpass area do not require a train control system (which might be anyway useful for other reasons).

Deep underpasses are a particularly practical solution if the LCRT line follows a road of high traffic importance, requiring continuous passability and freedom of turning into or out of that road. Furthermore, deep underpasses are to be deployed, if the crossing roads are too narrow to accommodate the main driving lanes and at least 4 m wide calmed-traffic areas on both sides as required for the shallow underpass.

2.5.3 Underpass with hairpin curve

If a shallow underpass is infeasible because continuous driving lanes along the LCRT line are required or the crossing roads are too narrow, underpasses with hairpin curve are another option to avoid the construction effort for deep underpasses: Instead of a direct crossing, the driving lane along the LCRT line splits up in to a lane running straight ahead on ground level, and another lane, ascending on a ramp up about 2,3 m, then crossing the LCRT line in a 180° turn and descending again down to ground level. Such a solution of course requires sufficient road width in order to accommodate on both sides of the LCRT tracks two driving lanes and a sidewalk.

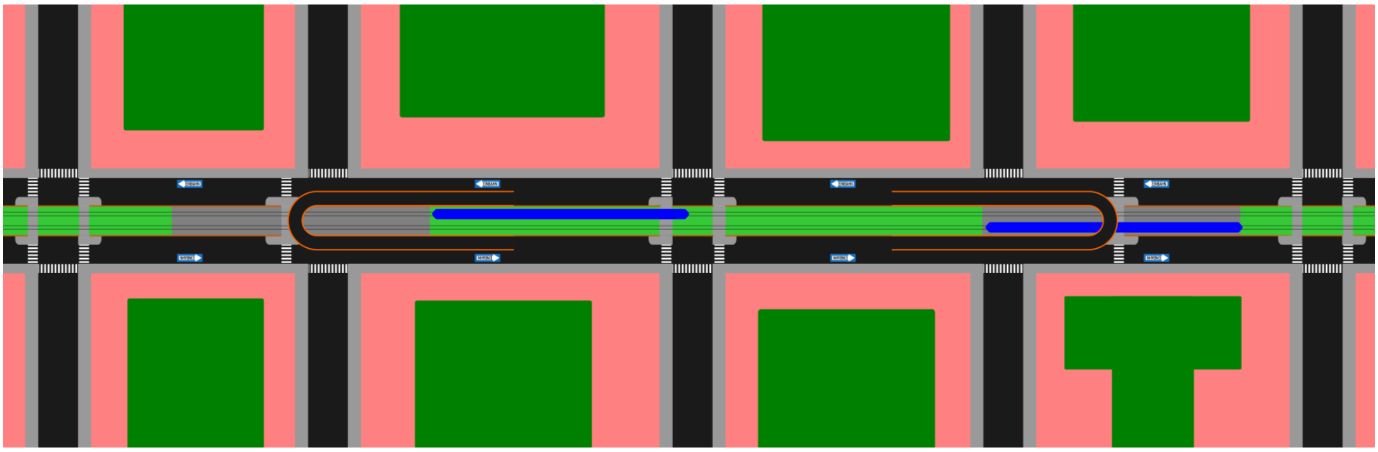


Figure 32: LCRT underpass with hairpin arrangement of the crossing route.

2.5.4 Completely sunken underpass

If it is completely impossible to elevate the surrounding traffic areas, the LCRT tracks must be lowered by 2,8 m as the whole height difference necessary for the grade-free crossing. In this case, LCRT runs similarly to a conventional cut-&-cover metro or underground tram, though at less tunnel depth thanks to less vehicle height. The most probable case of these deepest underpasses are curves which require the use of the whole road width in order to realize a maximum curve radius, so there wouldn't remain any space between the LCRT line and the buildings. With consideration of the counter-curves at the ends of the curve circle segment, the catenary-free section of such a sunken curve would be about twice the curve radius. Depending on curve radius and vehicles length, a solution with two pantographs might be still possible or another solution could be required (see also 2.1.3.2 and 2.2.3).

2.6. Detailed considerations about traffic routing

2.6.1 Bidirectional traffic on both sides of the LCRT line

If the LRCT line follows the middle of wide main road, with two driving lanes on both sides of the LCRT tracks, on each side of the LCRT line could be established one driving lane for each direction. Compared to a two-lane one-way-road on each side of the LCRT tracks, such an arrangement would reduce average speed and avoid some detours as it is possible to turn into the road accommodating the LCRT tracks to the right or to the left from any side road without using an overpass to get to the lanes on the opposite side of the LCRT line.

2.6.2 Traffic signal cycle in case of missing turning lanes

Despite the much higher capacity of rapid transit compared to individual traffic, the realization of an LCRT line could affect smooth traffic flow because the opportunity for crossing and turning left is restricted to a lower number of intersections and there might be no space available for designated turning lanes. So turning vehicles that have to stop because of pedestrians or oncoming traffic would block other vehicles too. In this case, a traffic signal cycle with an exclusive pedestrian phase and one green phase per direction could solve the problem:

Conventional traffic sign cycle of a four-way intersection:	Optimized traffic signal for a four-way intersection without turning lanes:
1. Green phase in north-south direction for vehicles and pedestrians 2. Green phase in west-east direction for vehicles and pedestrians (in between eventually special turn phases with additional clearance periods)	1. Exclusive pedestrian phase (green for pedestrians in any direction, red for all vehicles) 2. Green phase for vehicles from the north, red for all other road users 3. Green phase for vehicles from the east, red for all other road users 4. Green phase for vehicles from the south, red for all other road users 5. Green phase for vehicles from the west, red for all other road users

Despite the new traffic control cycle has more phases and thus less time for each of them, each of the phases can be used more efficiently, because all vehicles from the respective direction can move freely and even for turning vehicles there is no need to give priority neither to pedestrians, nor to vehicles coming from the opposite direction. Short, but well used green phases for the vehicles are in this case feasible, because they do not include a pedestrian clearance interval.

2.6.3 Application of roundabouts

Along the LCRT line there could also be applied roundabouts. Roundabouts obviously do not require turning lanes, nevertheless a roundabout is no solution in case of insufficient road width anyway, because an adequate roundabout size for arterial roads (from 26-30 m outer diameter[56]) requires same or more space, than turning lanes. Roundabouts seem to be most suitable in case of bidirectional driving lines on both sides of the LCRT line (see 2.6.1) which inevitable lead to a multi-leg intersection, which can be handled better as a roundabout, than as an ordinary intersection.

2.7. Level crossings for pedestrians and cyclists

The fact, that the LCRT line can be crossed only by main roads doesn't represent a significant disadvantage for motorized traffic: For reasons of traffic calming many destinations in the minor street network can be reached only via roundabout ways and one-way streets anyway. For reasons of safety and capacity, turn restrictions are also very common on intersections between main and minor roads.

In contrary to the situation in motorized traffic, cutting connections for pedestrians would make foot trips significantly longer and less comfortable and would be a real step back in terms of sustainable transportation. Because of this, for pedestrians there are established level crossings in addition to the overpasses. The achievable speed and reliability of LCRT is not affected by these level crossings because pedestrians, thanks to much less space requirement and better manoeuvrability do not cause those unintended congestions and obstructions, which occur regularly where the routes of cars and tram intersect.

There are two different types of level crossings planned:

- Level crossings without active protection devices are established only next to a station. In this case, the platforms for the two tracks are aligned diagonally in that way, that there is a cross-section, which is passed by the vehicles of both directions only with very low speed, immediately after starting from the stop.

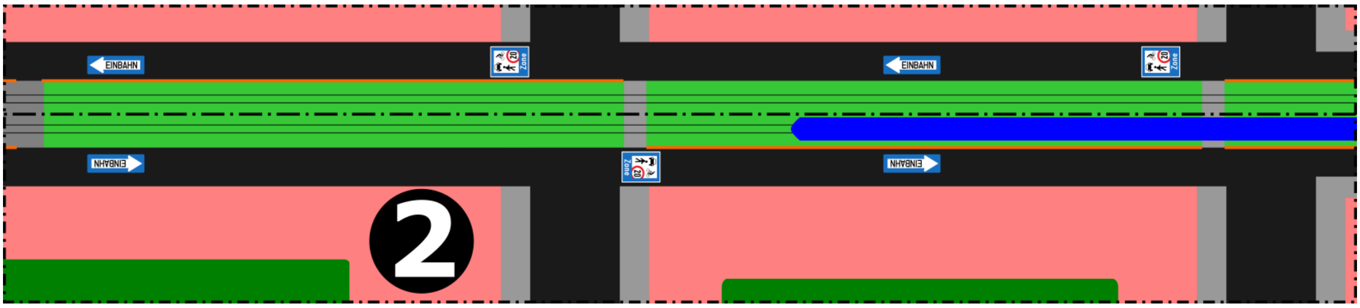


Figure 33: Ground plan detail of an LCRT line in the station area (diagonally offset interruption of the fences, unprotected level crossing immediately in front of the stopping position of the vehicles)

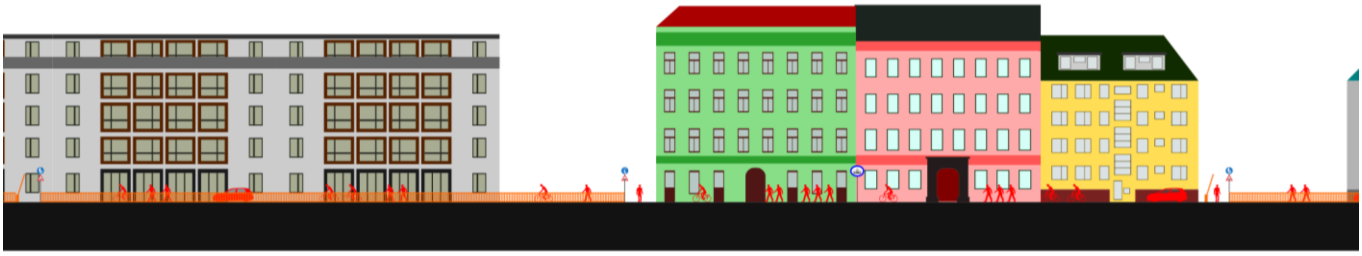


Figure 34: Detailed view of the longitudinal section of an LCRT line in the station area

- Other level crossings are protected similarly to optimally equipped railway level crossings with boom barriers, representing a physical barrier effective also in case of maximum inattention or irrationality. Depending on visibility conditions, two different solutions can be applied:
  a) If local visibility conditions allow stopping within sight distance before reaching the level crossing, there are low requirements concerning safety and reliability of the protecting device, because the driver has the possibility to react and stop the train if the level crossing remains open or if there is somebody on the track. Such level crossings require a minimum visibility of 100 m[h], the optimum distance to the next station should be at least 190 m[i], if the dwell time at the station and the closing time of the level crossing shall not influence each other.
  In order to reduce the risk of inattention of the driver, a track-side element of the train control system can evoke a warning sound in the drivers cabin, indicating that the train approaches a pedestrian level crossing. If the driver doesn't confirm within an admissible reaction time that the level crossing is closed and the track is free, the train is stopped automatically.
  b) If a level crossing shall be established close to a deep or completely sunken underpass or next to a curve, it has to be protected by a protection device which guarantees (at a reliability level as usual in the railway sector) that no rail vehicle passes the level crossing if it isn't closed. Ideally, such a protection device includes an obstacle

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[h] Assumptions:
- Initial speed 60 km/h
- Braking deceleration 2,73 m/s² (Minimum value according to Austrian tram regulation)
- Average acceleration of 1,0 m/s² from 0 to 60 km/h
- 3 seconds reaction time from visibility of the level crossing to the begin of deceleration
- 7 m line width
- 1,8 km/h (50 cm per second) walking speed for leaving the level crossing
- 50 m train length

[i] Level crossings, which are closer to a station, are feasible too, but in this case closure has to be started during the stop in the station. If the duration of the stop lasts shorter, than expected, the vehicle has to wait (under supervision of the train control system) before departure, until sufficient clearance and reaction time has been provided. In the opposite case, an unexpected long duration of the stop in the station, the waiting time for pedestrians is extended accordingly.

detection device, detecting people who remained on the closed level crossing. Although all these protection devices represent additional expenses, the following reasons lead to lower costs compared to heavy rail level crossings:

- The incomparably shorter braking distance shortens the cabling lengths accordingly
- As LCRT is an isolated System apart from interoperability requirements of heavy rail, solutions based on specific vehicle equipment can be applied
- In urban areas, it is much easier to provide electricity supply, than along conventional railroads
- In contrary to the retrofit of existing lines, many works, necessary for the implementation of state-of-the-art level crossing protection devices have to be done anyway, in particular the cabling along the track

Additional safety is achieved by a safety margin between the vehicle and the barrier boom, wide enough to allow a person to stay there safely while the vehicle passes by. Instead of usual boom barriers as used for conventional level crossings, the LCRT pedestrian level crossings could be equipped with doors or turnstiles which can be pushed open from the track side at any time, allowing pedestrians to leave the tracks if the level crossing is already closed.
The maximum closure time is 22,5 seconds per track, in case of the most unfavourable sequence of two trains in double-track operation pedestrians have to wait 45 seconds. The waiting time for crossing pedestrians can be reduced if a waiting area of sufficient width is placed between the tracks and each track is protected individually with an own protection device. If waiting times shall be avoided or if a level crossing would be unfeasible or too expensive because of bad visibility conditions, pedestrian overpasses with stairs can be established additionally.

Whether the use of level crossings should also be allowed for cyclists, which represent a space requirement between those of pedestrians and cars, should be decided individually depending on spatial conditions (possible width of a waiting area between driving lane and track) or the traffic intensity of car traffic parallel to the line. Basically, unprotected crossings next to stops seem to be more suitable for the use with bicycles, than those with barrier booms.

2.8. Barrier effects on pedestrian flow and possible special solutions to overcome them

2.8.1 Barrier effect of the standard solution

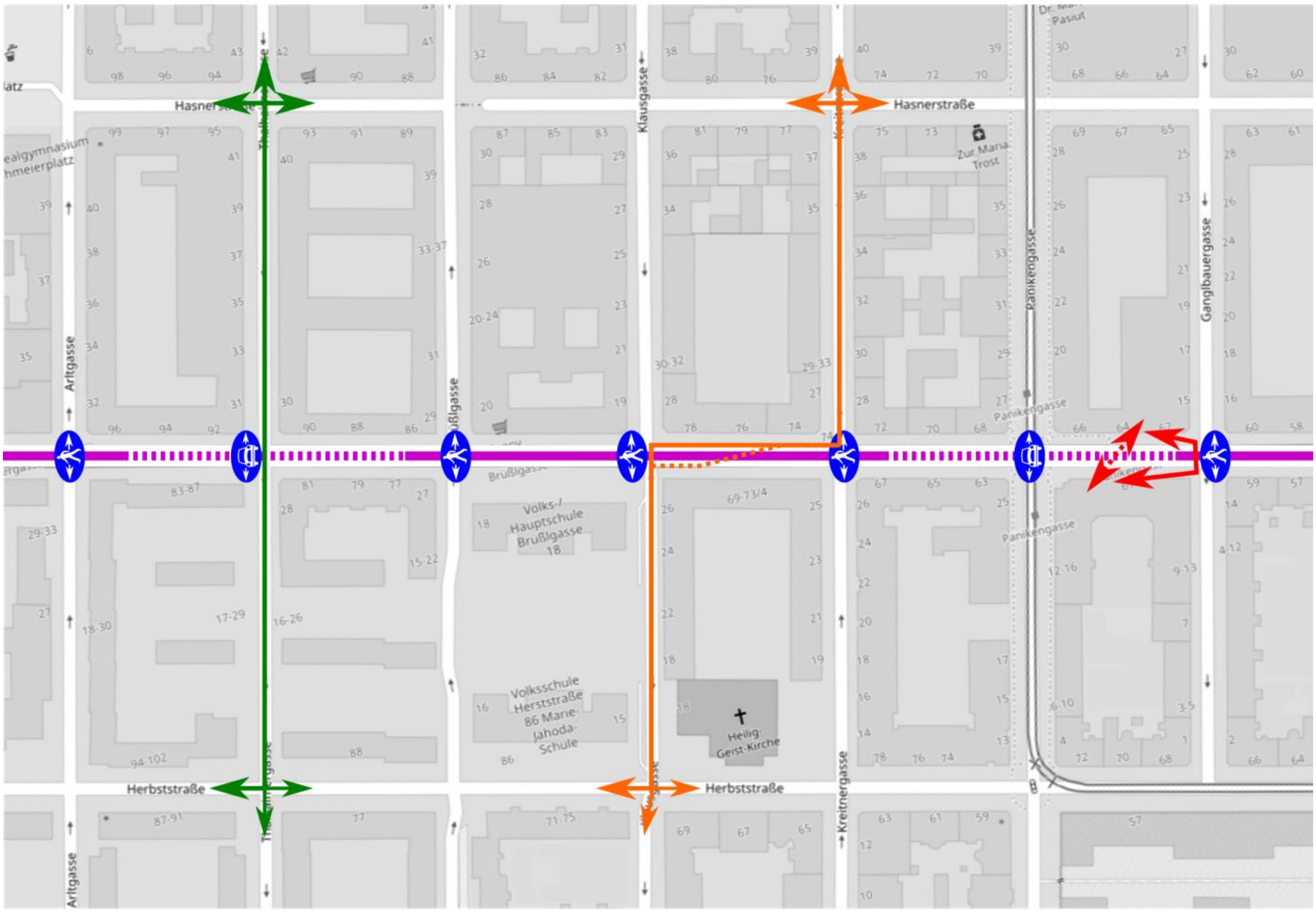


Figure 35: LCRT line (violet, lowered sections dotted) with unchained pedestrian routs (green), moderately impaired pedestrian routes (orange) and significantly impaired pedestrian routes (red).

If underpass ramps and fences restrict the possibility to cross the LCRT tracks to dedicated, protected pedestrian level crossings or LCRT underpasses, this means reduced freedom of movement for pedestrians in the road space. If resp. to which extent pedestrians have are affected by longer walking distance depends on the specific route:

a) Pedestrians who approach the LCRT track at a right angle following a crossroad can cross the track directly at a level crossing without any diversion (see Figure 35, left)

b) If the route of the pedestrian turns from a crossroad into the main road with the LCRT line, follows this road for some length and turns then again into another crossroad, without the obstruction of the LCRT line, pedestrians could cross the main road diagonally, so the restriction to the orthogonal level crossing makes the route a bit longer (see Figure 35, middle) . More relevant than the longer distance might be the perceived time loss, as pedestrians have to choose one of the level crossings and wait there for a gap in the car traffic (or the green traffic light) to cross instead of walking along the main road during the waiting time for a gap.

c) A significant time loss and longer walking distance occurs, if somebody wants just to cross from one side of the road to the other between two pedestrian level crossings (see Figure 35, right): Instead of the shortest route across the road, it is necessary to walk until the next crossroad and back.

A relevant barrier effect on pedestrian flow arises only in case c) and this case occurs more or less frequently only if first intensity and speed level of the car traffic on the respective road would allow free pedestrian crossing between traffic lights or a zebra crossing and second there would be enough shops, bars or other institutions in the road to generate relevant pedestrian flow between both sides of the road. Both preconditions apply for shopping streets in central districts, in such streets LCRT can be only realized if one of the special solutions described in 2.8.1 to 2.8.1 is applied.

For the comparison of LCRT and conventional urban public transport systems it should be considered, that conventional metro lines often represent a mix of tunnelled and elevated sections in order to reduce the expensive tunnelling to those sections, which are not suitable for elevated tracks. In these cases, ramps of 300-400 m length are necessary between tunnelled and elevated sections. These ramps are a significant more relevant obstruction against pedestrian flow, because they are longer than usual building blocks, thus even along some crossroads the metro line cannot be crossed at all or only by overcoming of height differences through over- or underpasses.

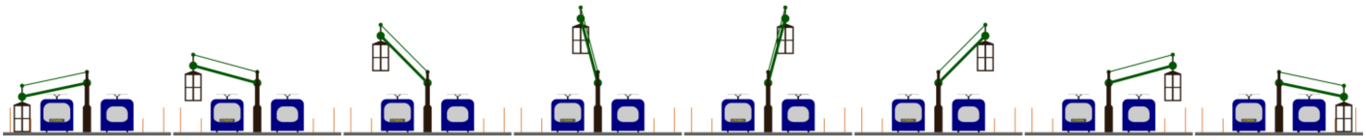
In order to maximize the cost advantage of LCRT it is desirable to realize LCRT lines in roads with such low demand for crossings, that can be satisfied by the combination of underpasses as described in 2.5 and pedestrian level crossings according to 2.7. If the desired connection or coverage of important origin and destination areas can be realized only by a route alignment through a road with high pedestrian frequency and high quality of stay, the following special solutions come into consideration:

2.8.1 LCRT line without fences (in at-grade sections)

The easiest option how to reduce the barrier effect of the LCRT line is to realize it without fences in the at-grade sections between the underpasses, so similar to a conventional tram, the tracks can be crossed freely everywhere. This seems realistic only in case of lower top speed (e.g. 40 or 50 instead of 60 km/h) resp. with additional travel time reserve for more defensive driving and running on sight. (For the effect on average speed see 2.2.3.1). Such a solution is only considerable for rather short sections and in particular if a solution with fences would not comply with regulations concerning guaranteed access for emergency vehicles (see 2.10.1).

2.8.2 Mechanical crossing aid (special design elevator)

Instead of pedestrian level crossings, secured with lights and boom barriers, crossings can be facilitated by mechanical crossing aids that move a passenger cab, similar to that of an elevator, from one side of the road to the other side within a single move:



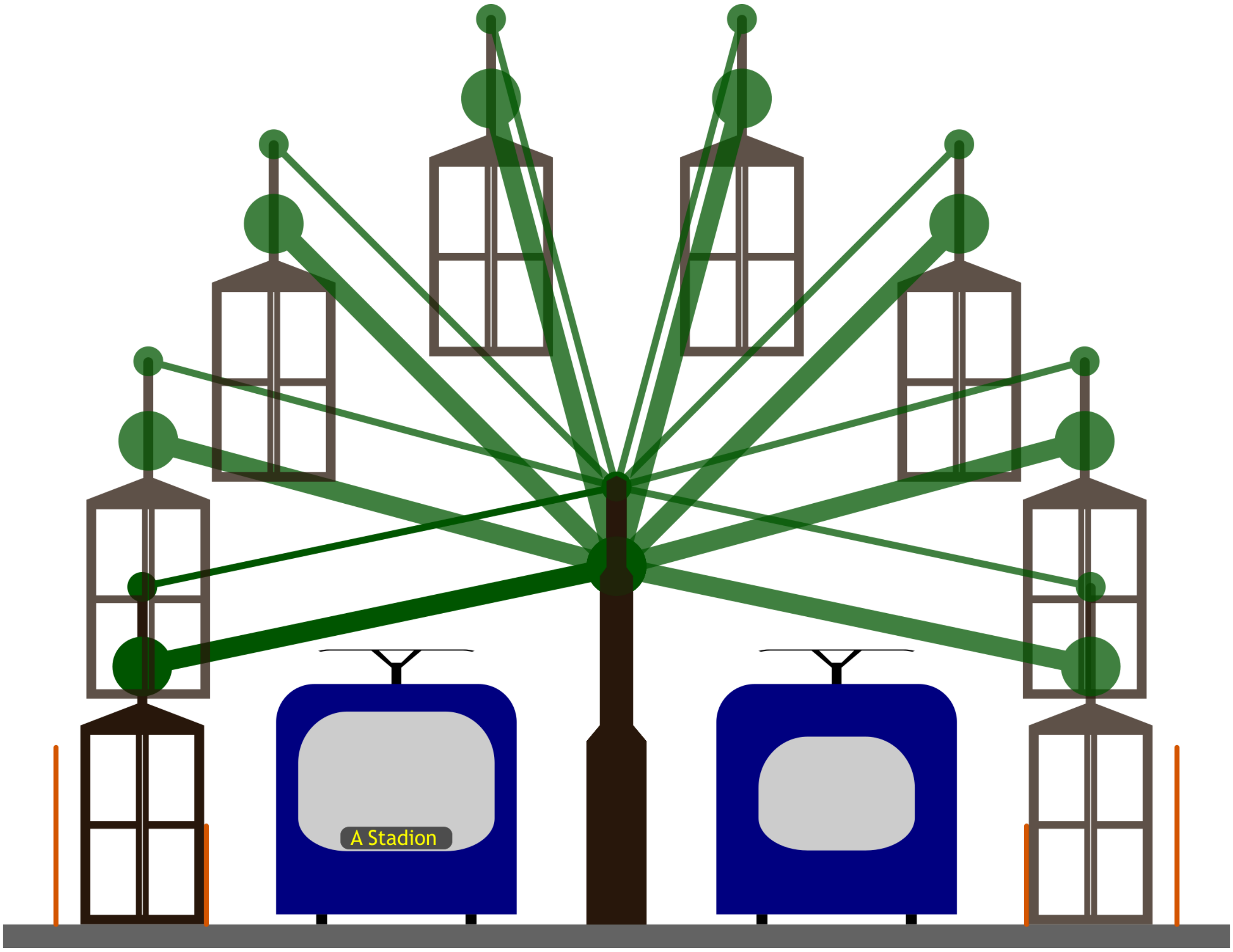


Figure 36: Mechanical LCRT crossing aid in various positions.

Using such a crossing aid, the LCRT line can be crossed while a train is passing and it can also be allocated at positions where a level crossing would be infeasible, e.g. at underpass ramps or in case of poor visibility. Within their capacity, such crossing aids can be used by cyclists too. Concerning the time requirement for crossing, there are no more waiting times caused by crossing trains, but the movement takes some time, including time for closing and opening the doors and possibly for calling the cab from the other side of the street. The chance to have a cab on the right side of the track can be increased, if there are several crossing aids arranged side by side similar to two or three elevators next each to other in highly frequented metro stations.

Compared to a pedestrian overpass with elevators in both sides, such a crossing aid means less optical impact to the streetscape. Time requirement for crossing is significantly reduced as calling the cab, opening and closing the doors as well as accelerating and decelerating must happen only once instead of twice. Specific cost factors of such a crossing aid might be higher mechanical load and torque, on the other hand, the number of cabs, doors, sensors, switches etc. is only the half and the number of moving parts is reduced significantly.

2.8.3 Retractable fences

The barrier effect of an LCRT line can be reduced to the minimum time requirement for the passage of the train by a continuous overpass in the form of a fence, that hides retracted below the street surface apart from the necessary time before and during the passage. This solution is suitable only if the two tracks for the two directions are located in two parallel streets in order to avoid an overlap of the closure times caused by two trains of opposite directions. At any position along the line, the following cycle repeats continuously (see Figure 37):

1. As long as there is no train approaching, the whole width of the street can be walked on as a continuous pedestrian area. Only motorized vehicles should stay left or right to the LCRT track.
2. As a prior warning announcing an approaching train, LEDs embedded into the street surface start blinking, e.g. arrow-shaped leading outside the track area.
3. After four seconds of prior warning, the fence starts moving upwards. It takes three seconds until it reaches its maximum height.
4. After three further seconds (reaction time and safety margin) there is the last chance for the driver to activate the emergency brake in order to stop before reaching a person that remained between the fences.
5. After three further seconds the front of the train reaches the regarded point.
6. The passage of the trains takes between 3 seconds (50m train length) and 9 seconds (150m). Meanwhile, the fence is being retracted again.

The mentioned numbers refer to a speed of 60 km/h, a pedestrian speed of 1,8 resp. 3,6 km/h for leaving the track (from the middle to a side resp. for complete crossing) and a deceleration of 2,73 m/s^2. The duration of the whole process is 16 to 22 seconds depending on the train length, thus in case of a 3 minute interval between the trains, 90% of the time the street can be crossed freely. If the speed is reduced from 60 to 40 km/h, the time requirement is nearly the same as it takes more time for passing the braking distance, but less time for the passage of the train itself.
The whole distance from the warning lights until the end of the train is 270-370 m depending on the train length, the necessary visibility is 100 m.

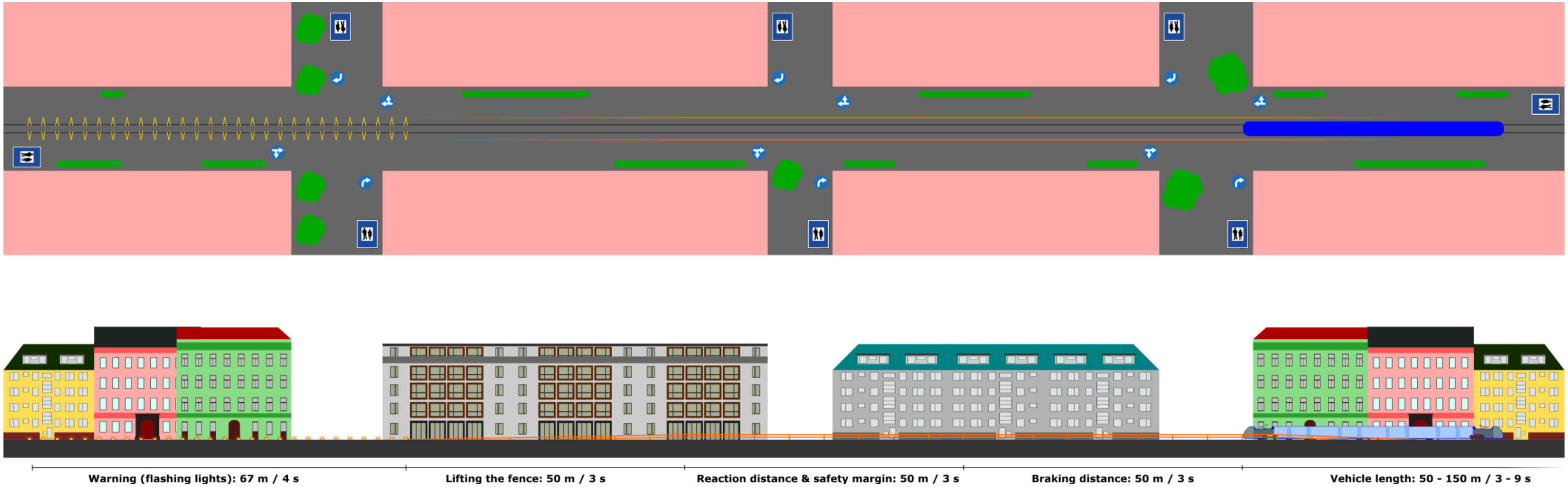


Figure 37: Single-Track LCRT line in a pedestrian zone, protected by retractable fences

A retractable fence can be realized without a continuous slot along the entire length of the fence: Single holes for the individual posts similar to retractable parking bollards and a shallow groove in the street surface accommodating the longitudinal parts of the retracted fence are sufficient (see the functional principle shown in Figure 38).

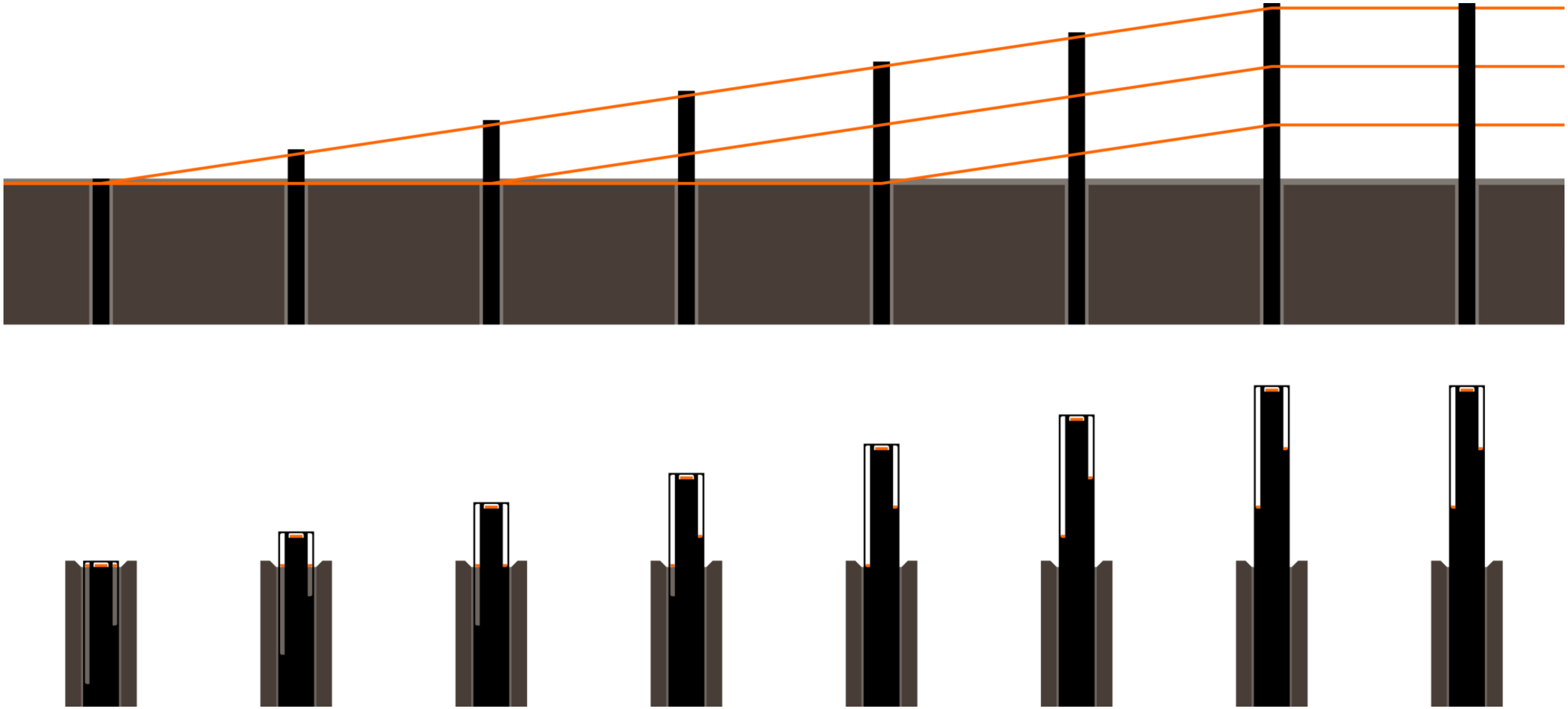


Figure 38: functional principle of a retractable fence without continuous slot between the fence posts. Upper image: longitudinal section (schematic representation with shortened distance between the posts); Lower image: Cross-section through an individual fence post

2.8.4 Shallow cut-&-cover construction with direct platform access

Even if a significant section of the LCRT line is realized as underground tracks in order not to compromise the quality of public space on the surface, the required depth is less than the half of a conventional metro: The oldest metro lines were located directly under the street with stairs leading from the platform to the middle of the street. During the automobile oriented period of urban and transportation planning in the 1960s and 1970s, it was common to place an intermediate level between the street surface and the platform level in order to provide at each end of the platform two entrances, one on each side of the driving lanes in the middle of the street, usually heavily frequented by cars. In case of pedestrian zones or traffic-calmed areas with an entirely walkable street surface, there is no more need for such an intermediate level:

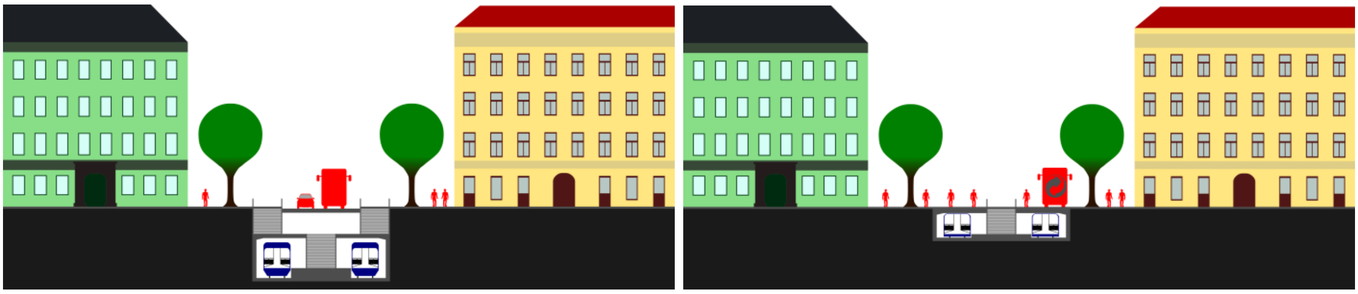


Figure 39: Left: conventional metro station with intermediate level, right: LCRT station in a cut & cover section with direct station access in the middle of the street

Relocation of cables, pipes and sewers will be inevitable in case of such a shallow cut & cover construction too, but there might be a synergy in the construction of LCRT and a parallel utility tunnel.

2.9. Effects of LCRT underpasses on the cityscape

Whether or to which extent the cityscape is adversely affected by an LCRT line and its underpasses cannot be measured in an objective way similar to the question of barrier effects, but rather depends on subjective perception. The following images are intended to support the imagination, how the view of public space would change after the implementation of LCRT.

Figure 40 shows perspective views of a deep underpass, simulated in a 3D model:

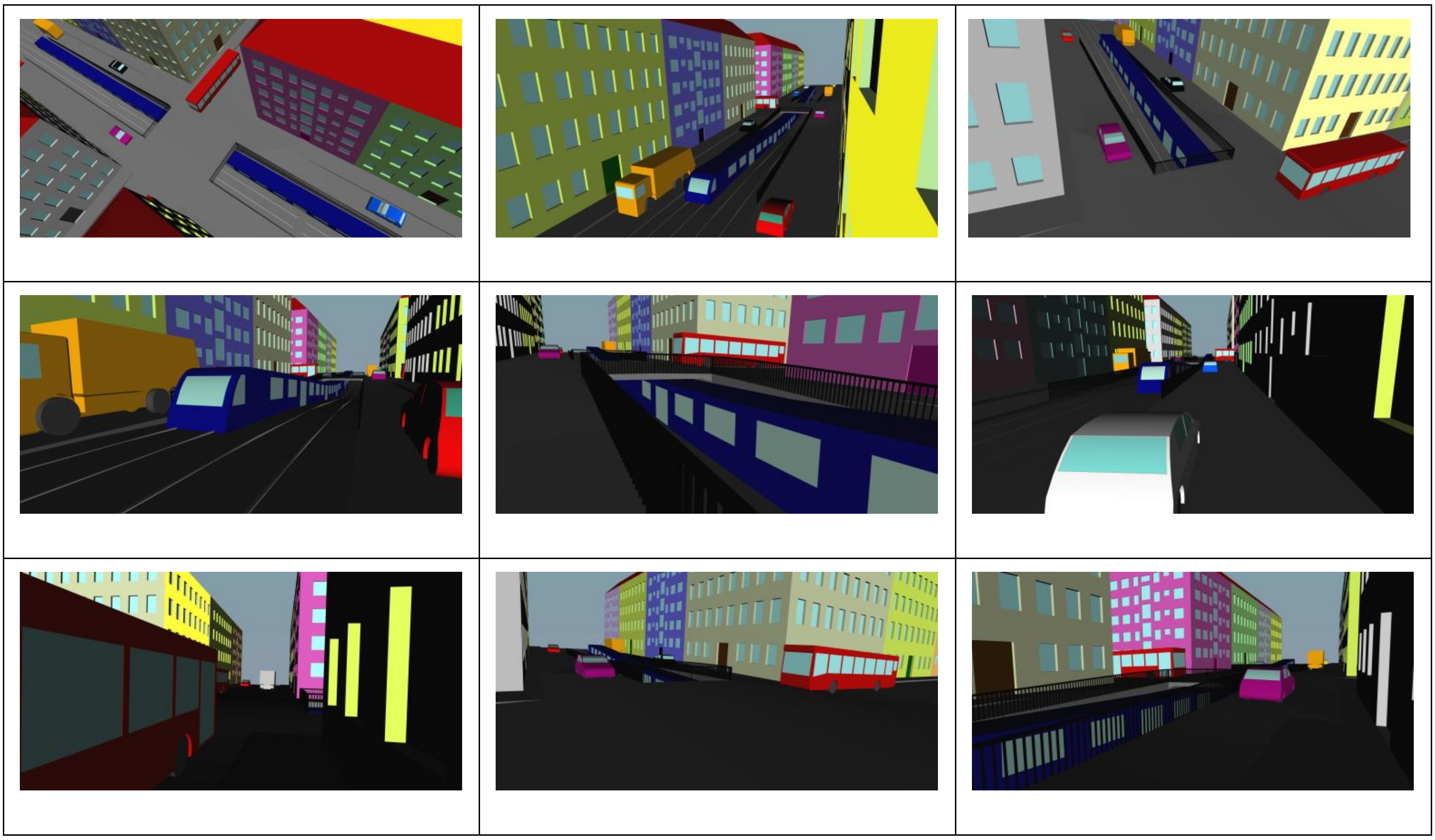


Figure 40: Perspective views out of a 3D model of a deep underpass

Existing shallow underpasses for pedestrians and cyclists give a certain imagination of the optical effect of the lower underpass depth of LCRT underpasses compared to conventional road or tram underpasses. Figure 41 shows photos of three pure pedestrian and/or bicycle underpasses with similar clearance height as LCRT underpasses compared to a photo of main road underpass with conventional clearance height:

Figure 41: Examples of underpasses in Vienna: Upper left: Pedestrian and bicycle underpass at Oswaldgasse /Donauländebahn, Upper right: Pedestrian underpass in the Vienna Zoo (Connection between Orangerie and the rest of the zoo area), lower left: Pedestrian and bicycle underpass between Prater Hauptallee and Praterstern (Station area in the middle oft he big roundabout), lowr right: Underpass of the straight driving lanes of Wiedner Gürtel below the Matzleinsdorfer Platz

2.10. Possible division of the street cross-section depending on its width

2.10.1 Street cross-sections for maximum use of the road width as traffic area

The calculation of the necessary cross-section width of a road for realizing an LCRT line is based on the following assumptions and dimensioning rules:

- Width of the LCRT Line: 7 m incl. 3 x 0,7 m safety margin (see also Figure 10) and fences, if provided
- Maximum width of road vehicles without or with retracted rear-view mirrors: 2,5 m (trucks, fire brigade, waste collection vehicle)
- Maximum width of road vehicles with rear-view mirrors: 3,5 m, rear-view mirrors may be above the sidewalk, a parking lane and also the safety margin[j]
- Standard sidewalk width 2,2 m
- In the area of level crossings (limited length): 1 m wide waiting area between crossing and driving lane, sidewalk width: 1,5 m
- Parking lane width 2m (where it is intended to be used as for delivery, the adjacent driving lane or sidewalk is narrowed)
- If the residual parts of the street on both sides of the LCRT tracks are wide enough for fire brigade or crane operations, the tracks can be realized as grass tracks, which would be favourable not only because of their general advantages, but particularly in order to gain acceptability if trees need to be felled for LCRT.

A street with a double-track LCRT line, which plays also in car traffic the role of a major road, requires at least 29,4 m total width in order to accommodate a sidewalk, a parking lane and two driving lanes per direction.

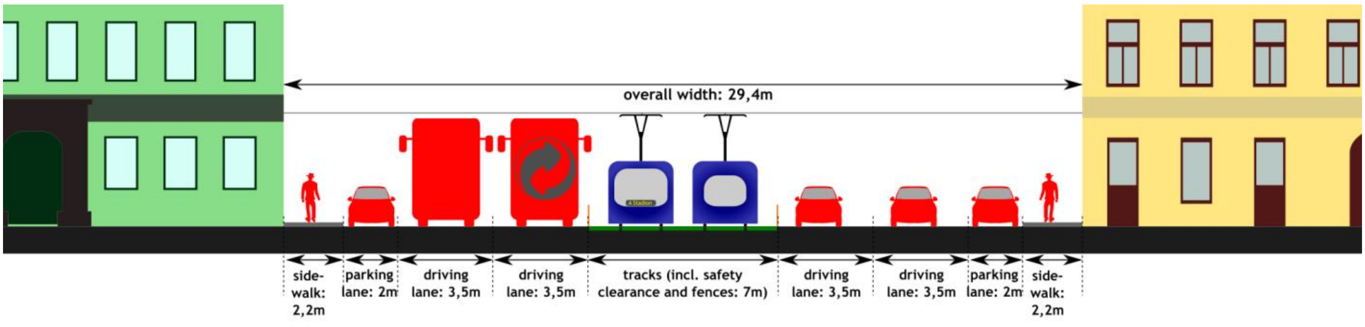


Figure 42: Minimum required street cross-section for a double-track LCRT line, two driving lanes, a parking lane or loading zone and a sidewalk on both sides

If in the street, where a double-track LCRT line should be built, parking or intense delivery should remain possible as well as significant through-traffic on one driving lane per direction, the minimum

[j] According to Austrian tram legislation, the safety margin may be part of road area.

required width of the street's cross-section is 22,4 m. In this case, the parking lane is interrupted near the level crossings, so there can be realized a wide safety island.

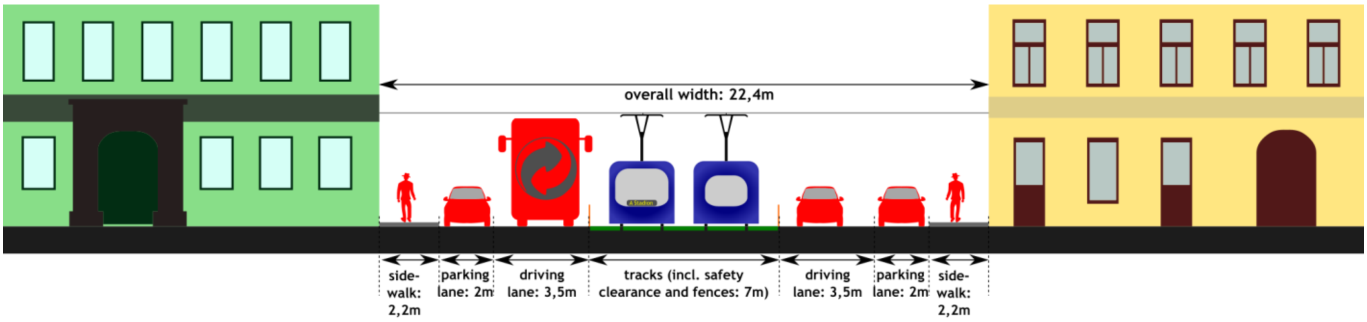


Figure 43: Minimum required street cross-section for a double-track LCRT line, a driving lane, a parking lane or loading zone and a sidewalk on both sides (situation apart from level crossings)

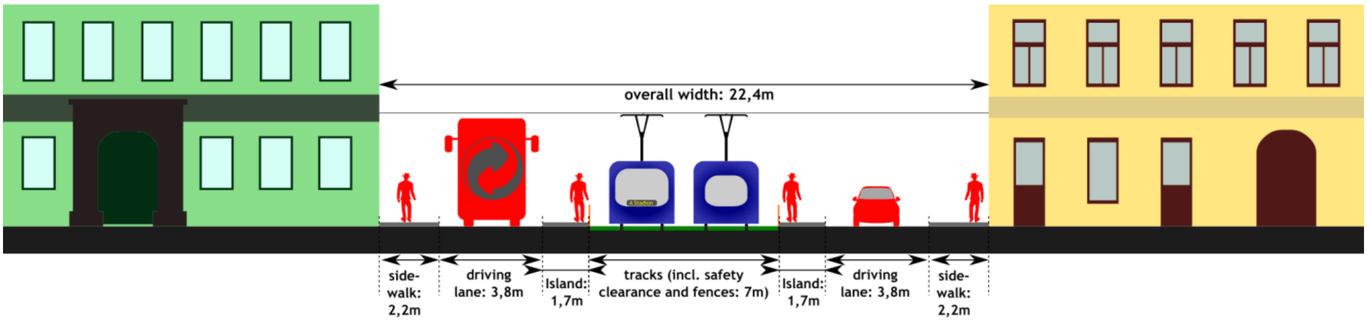


Figure 44: Minimum required street cross-section for a double-track LCRT line, a driving lane, a parking lane or loading zone and a sidewalk on both sides (situation at the level crossing with a safety island between LCRT line and driving lane)

In shopping streets, which might be of minor importance for through traffic, but where intense delivery takes place every day, it is possible to establish a calmed-traffic zone, intended for mix-use by vehicles and pedestrians, which is wide enough to allow a truck to pass by another, parked truck (at least with retracted rear-view mirrors). If both sides of the street are designed this way, a minimum width of 19 m is required.

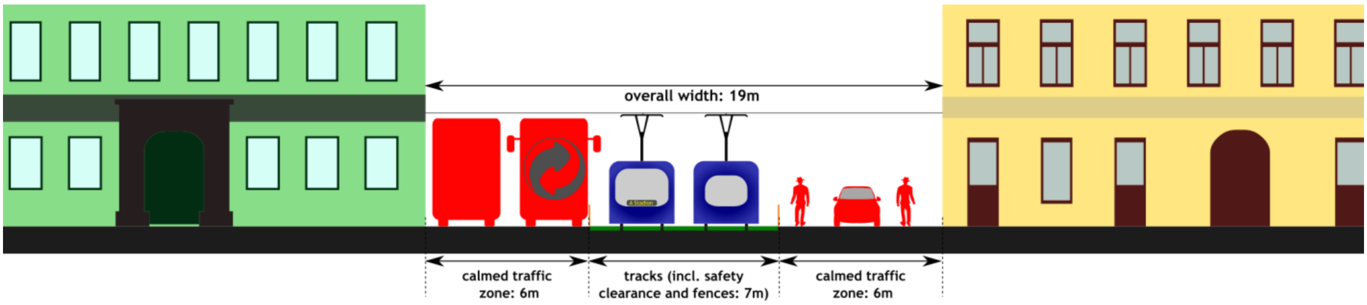


Figure 45: Minimum required street cross-section for a double-track LCRT line and calmed traffic zones on both sides, wide enough for delivery without blocking the passage.

If the street is at least 17,4 m wide, it is possible to establish a driving lane and a sidewalk on both sides of the double track line, although in the area of a level crossing, the driving lane as well as the sidewalk must be a little narrowed in order to make room for the safety island between the LCRT line and the driving lane. On such a street cross-section, significant car traffic is possible, however any delivery is representing a relevant obstruction for car or pedestrian flow.

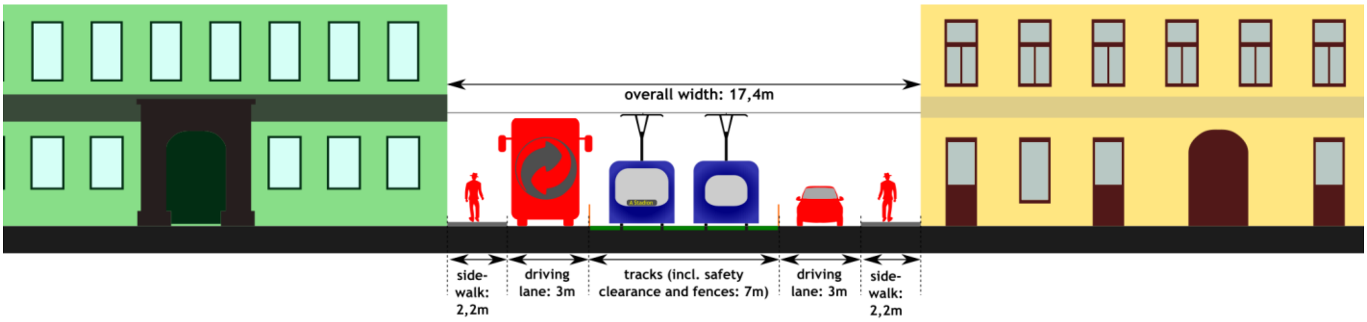


Figure 46: Minimum required street cross-section for a double-track LCRT line with driving lane and sidewalk in both sides (situation apart from level crossings)

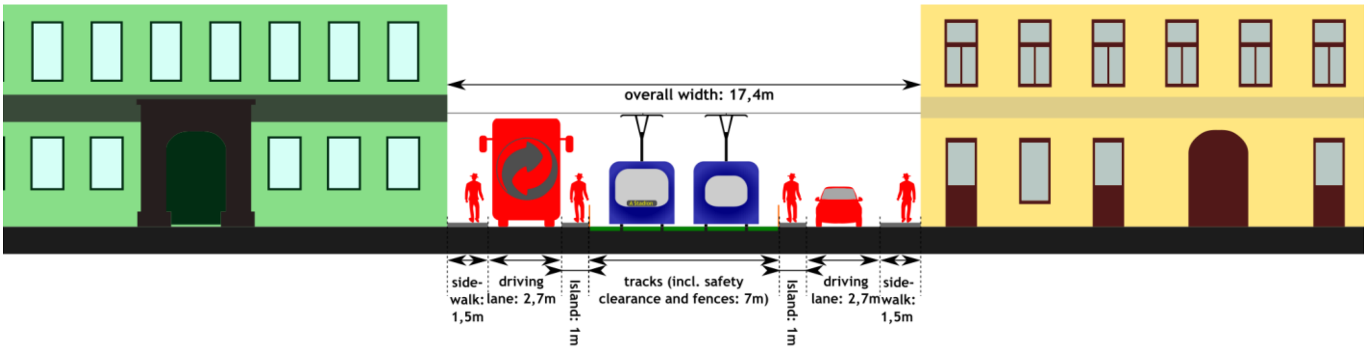


Figure 47: Minimum required street cross-section for a double-track LCRT line with driving lane, sidewalk and a waiting area (safety island) between driving lane and track

In urban environments with buildings immediately next to the street, the minimum required road width, which still allows the realization of a double track LCRT line and car access on both sides of the street is 14 m. In this case, on both side of the line, there can be established only a 3,5 m wide calmed traffic zone for mix-use by pedestrians and all kinds vehicles – if the space would be divided into a driving lane and sidewalk, the sidewalk would be unacceptable narrow. As far as such a street allows only low speeds and any standing vehicle (except bicycles and motorcycles) blocks the route completely for car traffic, this model is suitable only for roads with very low traffic volume. Regular delivery, e.g. for shops, is feasible only from side streets. Cranes for construction works on buildings in the respective street must either be placed in side streets as well, or on a portal, that can be passed under by vehicles. For mobile crane works during night hours or for fire brigade operations, it should be possible to remove the fences easily, the track should be suitable for tyre vehicles as well.

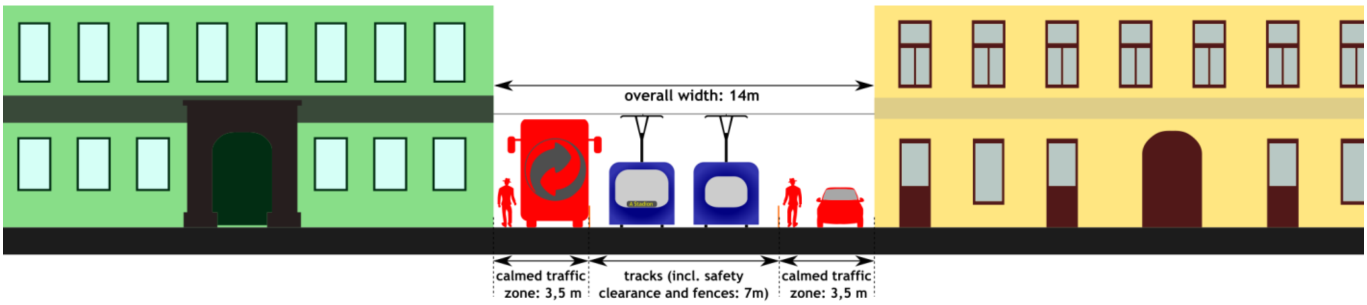


Figure 48: Street cross-section for a double-track LCRT line and calmed traffic zones on both sides, without a possibility to pass by stopping vehicles.

In some countries, at least for newly developed urban areas, such a minimum coherent pavement width is required that allows emergency vehicles to bypass a vehicle that broke down or is parked incorrectly. A compromise solution that provides such a bypass option could be achieved by reducing the fences to some low longitudinal barriers of a shape and height that can be crossed by a car safely, but still rather uncomfortably so the LCRT track will not be misused as an additional driving lane regularly.

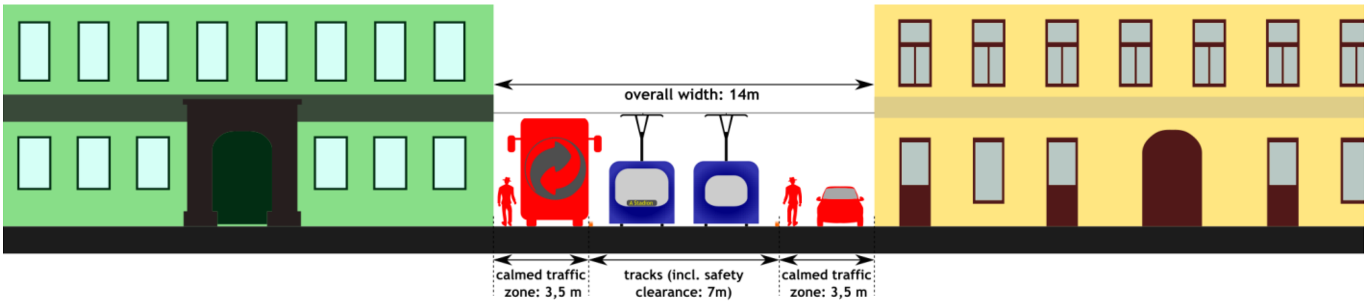


Figure 49: Street cross-section for a double-track LCRT line and calmed traffic zones on both sides, with low longitudinal barriers to pass by stopping vehicles.

If insufficient road width makes this solution necessary in the area of poor visibility close to an underpass, an interaction mechanism between the train control system and the emergency vehicle must be implemented: If the emergency vehicle driver or the emergency operation centre demands the permission to drive on the LCRT track, the train control system switches to a speed restriction according to visibility conditions and makes this restricted mode visible to both LCRT drivers and emergency vehicle drivers. An option for emergency vehicles to drive on the LCRT track if they could not reach their destination otherwise could be combined with retractable fences as described in 2.8.3. Anyway, the emergency vehicle drivers or their operation centre must be able to switch the LCRT system into a safe, slow mode on the section concerned.

If a solution without any barriers along the LCRT tracks is chosen in order to facilitate free pedestrian crossing and reduce the aesthetical impact, a lower top speed and generally more defensive driving must be accepted (see 2.2.3.1 and 2.8.1).

If there is an option, that in extraordinary, inevitable cases emergency vehicles can drive or even stop on the LCRT track, for some short bottlenecks of insufficient road width it would be acceptable to reduce the lane width on one side of the LCRT track to less than the width of a truck. In this case, there must not be any carparks in the buildings along the narrow lane in the bottleneck section and delivery as well as waste disposal must happen from the other side of the street, crossing the track by foot.

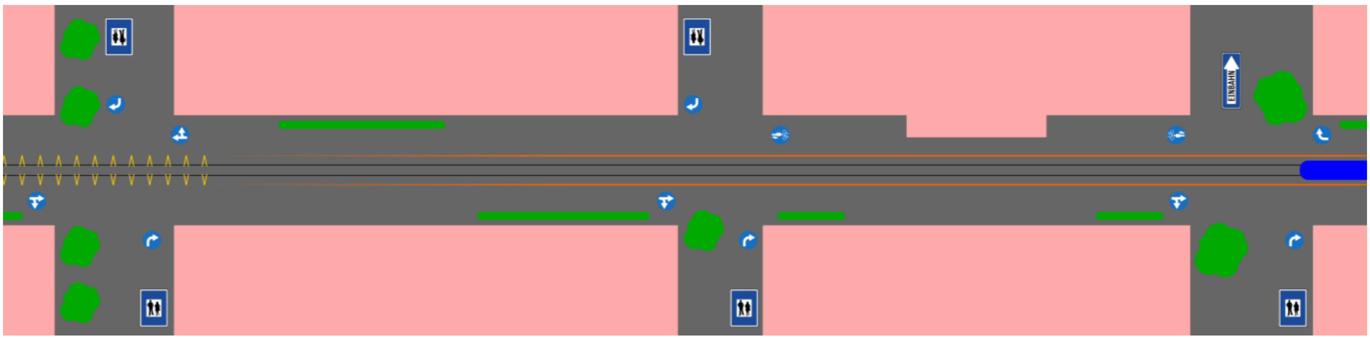


Figure 50: Narrow section with retractable fences and the possibility to pass the LCRT track with emergency vehicles.

There are urban areas where entrances to staircases and garages are not located to the main, public street but access is provided via the back side of the building and/or paths inside the housing complex. In these cases, the distance between the LCRT line and the building can be less than the width of a road vehicle. If there are no other regulations requiring more distance than the safety clearance (e.g. for noise protection), the minimum road width for a double-track LCRT line is 10,5 m.

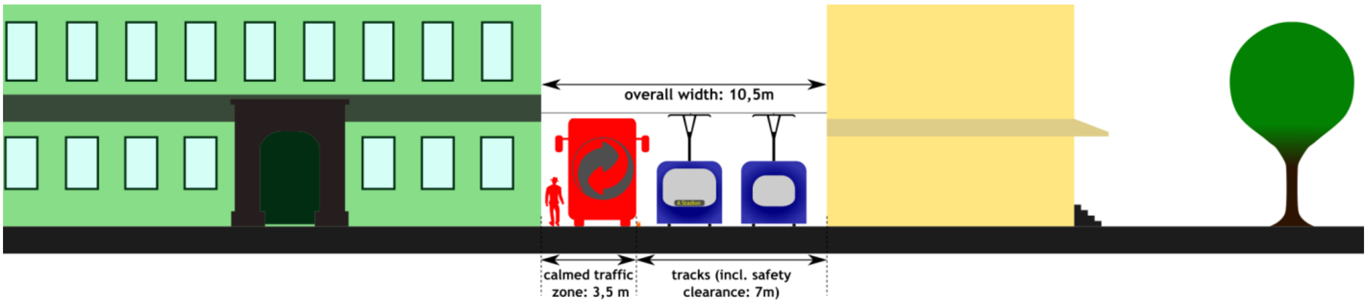


Figure 51: Street cross-section for a double-track LCRT line with buildings without road-side entrances.

If there is no alternative to the use of very narrow roads with detached houses in order to realize a desired LCRT route, it is considerable to compensate property owners for tolerating catenary masts in their garden (if possible directly on the border between two neighboring plots) and overlapping of rear-view mirrors of large road vehicles (e.g. waste collecting vehicles) above their fences. A disadvantage of such a solution is that wide vehicles and pedestrians can bypass each other only through the safety clearance of the LCRT line, so small delays due to speed reduction must be taken into account. If this solution is combined with a single-track line on suburban sections with moderately longer intervals (see 5.3), the absolute minimum road width for the realization of an LCRT line is 9,5 m.

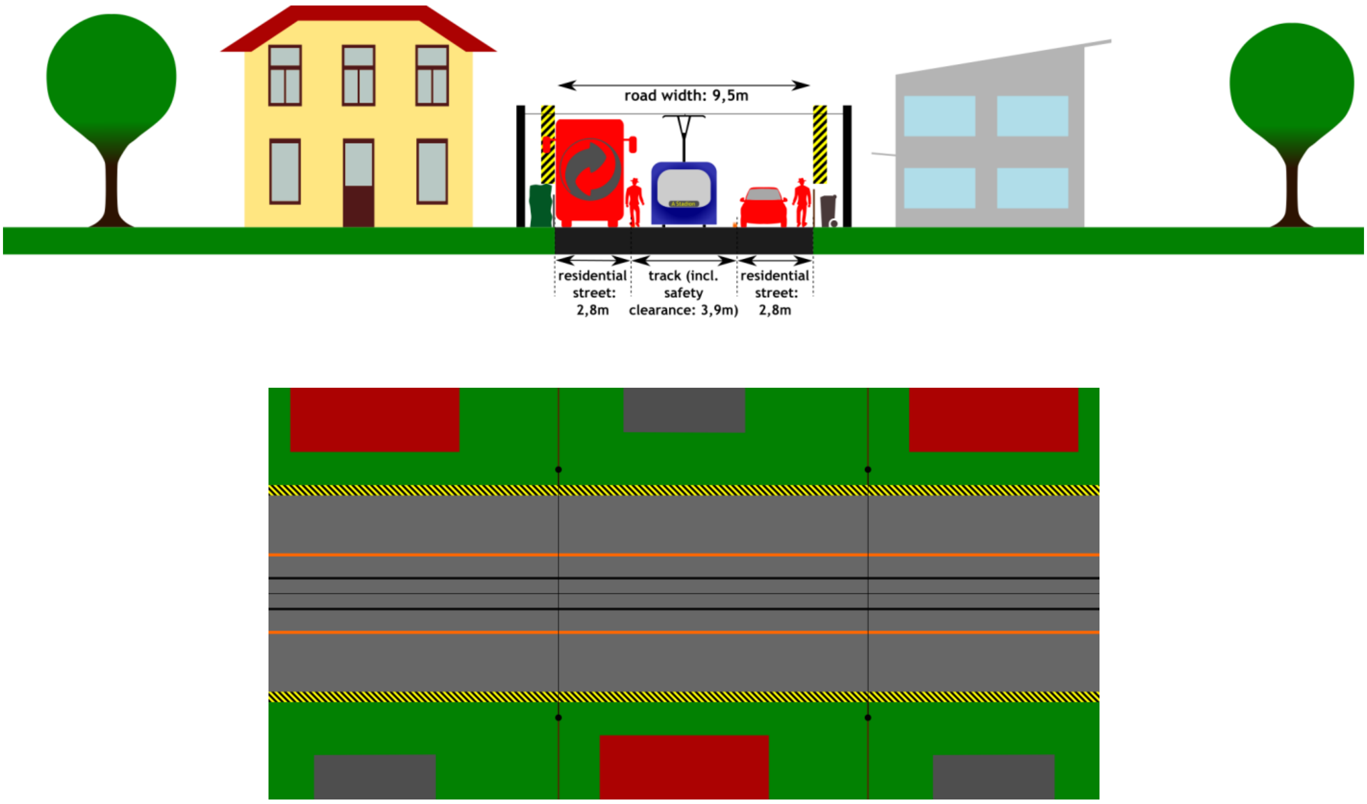


Figure 52: Street cross-section for a single-track LCRT line with involvement of neighboring property.

In Table 7, there are listed minimum width requirements for all possible layout combinations of either side of the street for double track as well as for single track lines (see also 5.2) under the condition of car access along both sides of the road:

Double track LCRT line							
		one side of the road					
		2 driving lanes + parking lane + sidewalk	1 driving lane + parking lane + sidewalk	Wide calmed-traffic zone	1 driving lane + sidewalk	Narrow calmed-traffic zone	Involvement of neighboring property
other side of the road	2 driving lanes + parking lane + sidewalk	29,4	25,9	24,2	23,4	21,7	21
	1 driving lane + parking lane + sidewalk	25,9	22,4	20,7	19,9	18,2	17,5
	Wide calmed-traffic zone	24,2	20,7	19	18,2	16,5	15,8
	1 driving lane + sidewalk	23,4	19,9	18,2	17,4	15,7	15
	Narrow calmed-traffic zone	21,7	18,2	16,5	15,7	14	13,3
	Involvement of neighboring property	21	17,5	15,8	15	13,3	12,6
	Buildings without direct street access	18,2	14,7	13	12,2	10,5	9,8
Single track LCRT line							
		one side of the road					
		2 driving lanes + parking lane + sidewalk	1 driving lane + parking lane + sidewalk	Wide calmed-traffic zone	1 driving lane + sidewalk	Narrow calmed-traffic zone	Involvement of neighboring property
other side of the road	2 driving lanes + parking lane + sidewalk	26,3	22,8	21,1	20,3	18,6	17,9
	1 driving lane + parking lane + sidewalk	22,8	19,3	17,6	16,8	15,1	14,4
	Wide calmed-traffic zone	21,1	17,6	15,9	15,1	13,4	12,7
	1 driving lane + sidewalk	20,3	16,8	15,1	14,3	12,6	11,9
	Narrow calmed-traffic zone	18,6	15,1	13,4	12,6	10,9	10,2
	Involvement of neighboring property	17,9	14,4	12,7	11,9	10,2	9,5
	Buildings without direct street access	15,1	11,6	9,9	9,1	7,4	6,7

Table 7: Minimal required street width depending on the layout of either sides for double-track or single-track LCRT lines.

2.10.2 Special aspects of LCRT lines in streets with vegetation

If the width of the street allows a grass strip, this can be used to facilitate the construction: In the area next to the underpasses, between the lowered LCRT line and the elevated driving lane, a green embankment can be realized instead of a vertical retaining wall.

If the implementation of a new LCRT line shall be reconciled with the conservation of existing trees in the concerned street, a special solution could be applied, delivering as a positive side effect the reduction of costs for the relocation of pipes or cables below the street surface: Because of the risk of damage by roots, pipes and cables are not laid too close to trees, e.g. DIN 18920 recommends a minimum distance of 2,5 m from the middle of the trunk[57]. For the LCRT track bed, root penetrated ground represents an obstacle which is not negligible, but still surmountable using root bridges:

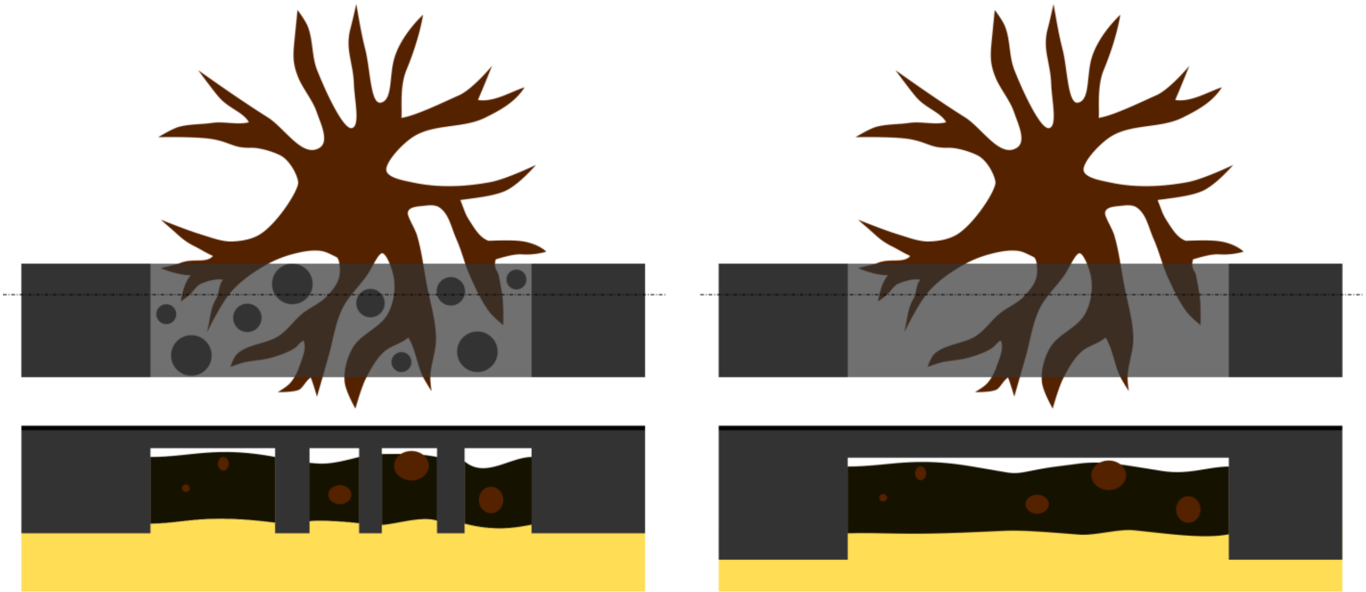


Figure 53: Ground plan (upper row) and longitudinal section (lower row) of a root bridge with spot and strip foundation (left column) resp. strip foundation only (right column)

Root bridges are implemented if a part of the area around the trunk must on one hand remain irrigated and uncompressed, but shall be passable by vehicles or a relevant number of pedestrians on the other hand. Root bridges can rest on strip foundations at the brides ends outside the root are only, or additional spot foundations can be added in larger gaps between the roots.

The approach of using the vicinity of existing trees for transport purposes is particularly promising if the LCRT track is extraordinary narrow-gauge, because the overhanging part of the vehicle does neither collide with roots, nor obstruct excavation works. The street cross-section shown in Figure 54 is based on a track gauge of 760 mm and a whole width of the ballastless track of one meter.

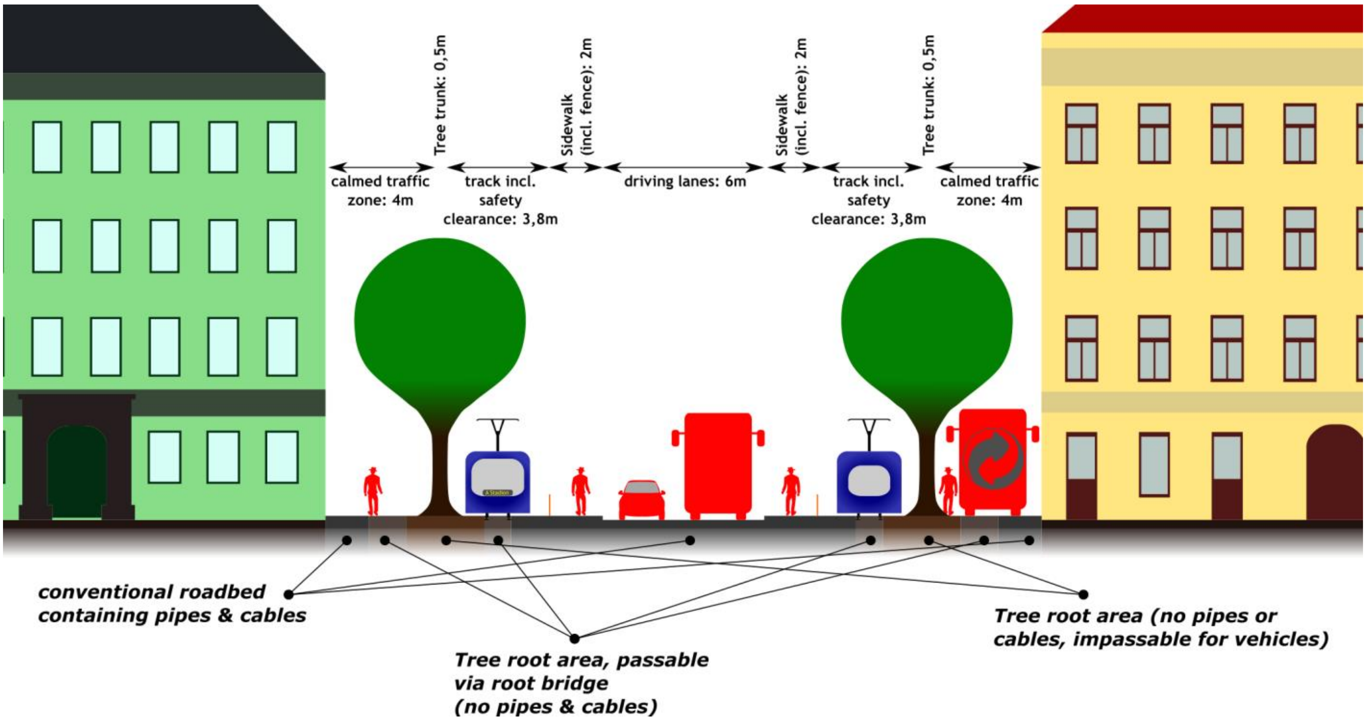


Figure 54: Cross-section of a street with pre-existing trees and LCRT tracks allocated next to them

Following this division of the street cross-section, between the trees and the buildings, at least a pedestrian zone or calmed traffic area of sufficient width and height for delivery, fire brigade or waste collection vehicles is required. In contrary to these areas which serve primarily for non-motorized traffic and can be passed by motorized vehicles only for shortest possible access, between the LCRT tracks there is space for two additional lanes which are connected with other streets only at main intersections with LCRT underpasses. Between the LCRT lines and these middle lanes, an additional sidewalk or at least a safety island is necessary as a safe place for pedestrians between the crossing of LCRT track and driving lanes. The street cross-section displayed in Figure 54 represents an overall road width of 26,6 m. If the street is not wide enough or due to an unfavourable position of the trees there is not enough width left for two middle lanes and sidewalks, a one-way driving lane or a bicycle highway can be accommodated there.

3. Cost estimation

3.1. Preamble

The quantification of the savings potential of LCRT compared to a conventional metro is probably the most important part of this feasibility study. Nevertheless, it is also the most difficult part because there rarely exist examples of comparable buildings and few data are publicly available about detailed cost components of infrastructures. Readers, who know more about various input data are therefore invited in case of possibly implausible assumptions not to doubt the whole study or the LCRT concept, but to contact me in a way of constructive criticism in order to give me the possibility to improve the quality of the calculations.

As the whole feasibility study, the cost estimations do not refer to a concrete line or city, but they are based on general assumptions. The focus of the cost estimates is on the construction costs of the infrastructure, consisting of the costs of the LCRT tracks including the underpasses and the necessary redesign of public space. The effects of the LCRT principle onto the vehicle costs are discussed rather superficially. Concerning the other relevant cost components, similarity to construction costs (infrastructure maintenance costs) resp. to costs of conventional tram operation (rolling stock maintenance and other operational costs) is assumed.

3.2. Infractructure construction costs

3.2.1 Methodology and input data

3.2.1.1 Calculation scenarios

In order to calculate a possible range of variation of results according to uncertain input data, the whole cost estimation was carried out in three scenarios: Apart from the standard scenario, an optimistic and a pessimistic calculation were performed. “Optimistic” means “in favour of LCRT”, including a higher cost estimate for conventional metro systems (elevated or in cut-&-cover tunnels) to be compared with, “pessimistic” in opposite lower costs for the conventional solutions. The calculation scenarios differ not only by unit rates, but also concerning the distance between the underpasses and the shares of the different standard types of underpasses (see Table 8)

	Optimistic	Standard	Pessimistic
Total number of underpasses per km	2,5	3	4
Thereof completeley lowered	0,25	0,5	1
Thereof deep underpasses	1,25	1,5	2
Thereof shallow underpasses or hairpins	1	1	1

Table 8: Underpasses per line-kilometre depending on calculation scenarios

3.2.1.2 Indexation and currency conversion

The cost examples used for the calculations refer to construction projects from several decades, so an indexation was necessary in order to ensure comparability: Figures in Euro resp. from European sources were indexed using the civil engineering cost index of the Statistics Austria[58], precisely the road construction cost index was used as it represents the longest available time series. Costs in U.S. Dollars were indexed using the price index of new family houses[59] published by the U.S. Census Bureau as the best fitting index found, finally these costs were converted in Euro using the actual conversion rate[60]. One value published in Swiss franc was used, it was converted in Euro using the historic conversion rate for 2011 (1.Juli 2011) and then indexed.

3.2.1.3 Costs for conventional tram and metro lines as cost base and for comparison

As a starting point for the construction costs of an LCRT line, construction costs for conventional tram projects were collected, but also costs for conventional metro lines: On one hand, they are used for the analogy calculation method (see 3.2.1.4), on the other hand they serve as a reference value for the calculation of the relative savings of LCRT compared to conventional mass transit. The following sources concerning rail transit construction costs were used:

- A professional paper about construction costs of new tram lines in Germany[61]
- A PhD thesis about tram projects in France including the comparison to metro costs[62]
- A publication about system costs of tram and busway[63]
- An report of the Vienna court of auditors concerning construction cost differences between the metro systems of Vienna and Munich[64]

- A world-wide comparative study of the ITA concerning construction costs of elevated and tunneled mass transit[65]

- A conference contribution about the potential of MRT systems in developing cities[66]

- A cost estimate report for various alternatives of the Los Angeles westside subway extension [67]

- For reference parameters and projections, further websites about the metro networks of Vienna[68] and Munich[69] as well as base maps[70,71] were used.

In the comparative study of the ITA[72], the following cost ratio between at-grade, elevated and underground lines are mentioned:

- Common „rule-of-thumb“: 1:3:6

- New conclusion of the ITA: 1:2:4,5

Based on the last mentioned ratio, attempts were made to extrapolate from the average cost of the metro networks in Vienna and Munich to the costs for at-grade, elevated and underground lines in these cities.

The ranges of costs per kilometer depending on the source and the category of mass rapid transit system are shown in Figure 55:

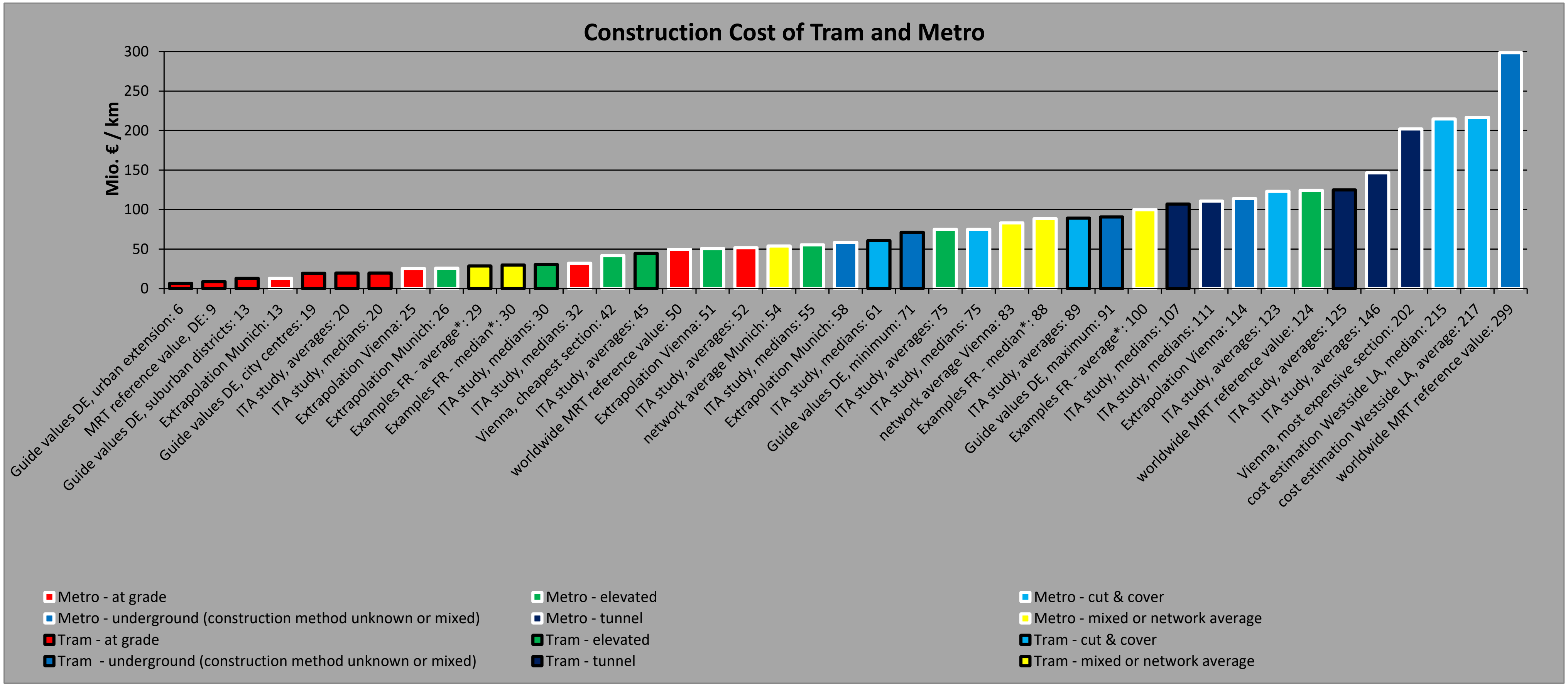


Figure 55: Construction costs of conventional tram and metro lines at grade, underground or elevated. Sources: Christoph Groneck (Guide Values DE) [73], Christoph Groneck (Examples FR) [74], FGSV (MRT reference values) [75], International Tunneling Association (ITA study)[76], Stadtrechnungshof Wien (Values for Vienna and Munich)[77], Parsons Brinckerhoff (cost estimation Westside LA) [78], Allport & Bamford (worldwide MRT reference values)[79] *: including vehicle costs. All values are indexed for 2016.

Based on the values displayed in Figure 55, the following assumptions were made for further calculations:

	Optimistic	Standard	Pessimistic
Tram at grade	20	24	28
Elevated metro	70	55	45
Cut-&-Cover metro	150	100	75

Table 9: Assumed construction costs of conventional tram and metro lines in Mio. € / km

3.2.1.4 Additional costs: Analogy calculation

For the first of two parallel applied calculation methods, LCRT underpasses are calculated as extraordinary short and shallow cut-&-cover sections and the overpasses of the crossing roads as extraordinary short and low elevated lines. For this calculation it was necessary to estimate the cost ratio between station and the line without stations:

- Among the sources used for the total costs of tram and metro lines, only the cost estimate report for various alternatives of the Los Angeles westside subway extension[80] differentiates explicitly between costs for stations and costs for the line without the station. Depending on the alternative a station building causes same costs as 0,96 – 1,33 km line length, the average is 1,22 km. All alternatives consist completely of cut-&-cover underground sections.
- When using a rough cost estimation model for heavy (rapid) rail projects[81], the result is a line length of about 2 km with same costs as one station. However, the model reports generally unrealistic high costs (more than twice the values shown in Figure 55)
- The Vienna court of auditors argues with regard to construction costs of the metro networks in Vienna and Munich, that the construction costs for the station buildings are about five times higher, than those for the line without stations. If the factor 5 is referred to the platform length of 115 m and the additional costs of the station, a metro station in Vienna has the same costs as 460m outside stations.

For further calculations it was assumed, that the costs of a station are equivalent to a pure line length of 1,5 km in the optimistic calculation, 1 km in the standard calculation and 0,75 km in the pessimistic calculation.

The extrapolation from the costs of a cut-&-cover or elevated section to the LCRT underpasses can basically be done proportionally to the excavation resp. filling volume or to the length of the under- resp. overpasses including their ramps. Reasons for the calculation according to the volume are not only the effort for excavation and disposal of the soil resp. supply and filling, but also that construction efforts increase by pit depth, e.g. because of more comprehensive excavation support, problems with ground water and similar. An argument for the calculation proportional to the length are depth-independent efforts as e.g. relocation of pipes and cables, or the longitudinal supporting structure of elevated lines, but on the other hand, the effort for the coverage of a cut-&-cover underground line is nearly completely obsolete in case of an LCRT underpass. As a conclusion of these considerations, the additional costs for underpasses were calculated as a mixed extrapolation using the following distribution keys per calculation scenario:

	Optimistic	Standard	Pessimistic
Extrapolation proportional to volume	100%	75%	50%
Extrapolation proportional to length	0%	25%	50%

Table 10: Distribution key of the extrapolation according to volume and according to length depending on the calculation scenario.

For the comparison of the excavation resp. filling volume, the following height resp. depth levels of conventional metro lines were assumed:

	Optimistic	Standard	Pessimistic
Elevated line: height above surrounding level (m)	8	7	6
Cut-&-Cover line: depth below surrounding level (m)	12	10	8

Table 11: Assumed height and depth levels of conventional elevated and cut-&-cover undergound metro lines.

3.2.1.5 Additional costs: compontents calculation

Parallel to the analogy calculation, costs were estimated in detail for those components resp. construction steps of the LCRT underpasses, which are necessary additionally to a conventional tram. For this calculation, the following components were taken into account:

- Bridges (supporting structures):
  - Found unit costs:
    - Bridge of a rural main road across a motorway[82]: 1584 € / m²
    - "Sulzbrücke" bridge in Mühlhausen (two-lane road, two openings of 12-15 m span each)[83]: 2746 € / m²
  - Assumptions for further calculations:
    - Optimistic calculation: 1500 €/ m²
    - Standard calculation: 2250 € / m²
    - Pessimistic calculation: 3000 € / m²
- Filling of overpass ramps including material supply:
  - Found unit costs[84]:
    - Concrete sand 0/16 washed: 31,2 € / m³
    - Filling gravel 4/12: 32 € / m³
    - Grit 4/8 (paver sand): 34 € / m³
  - Assumptions for further calculations:
    - Optimistic calculation: 30 € / m³
    - Standard calculation: 32,5 € / m³

        - Pessimistic calculation: 35 € / m³

- Excavation of the underpass including soil transport and disposal:
    - Found unit costs:
        - Disposal of excavation material[85]: 18,5 € / m³
        - Removal of upper soil, terrain ablation[86]: 8 €/ m³
        - Soil excavation[87]: 17,5 € / m³
        - Bulk material transport from and to Vienna exluding landfill fee[88]: 11,5 m³
        - Disposal fee for excavated soil (category 31411 29-32 / ÖN S 2100) [89]: 4,5 € / t
        - Disposal fee for excavated soil (category 31411 33-35 / ÖN S 2100) [90]: 14,4 € / t
        - Disposal fee for excavated soil of other contamination[91]: 22,2 € / t
    - Assumptions for further calculations:
        - Optimistic calculation: 30 € / m³
        - Standard calculation: 35 € / m³
        - Pessimistic calculation: 40 € / m³
- Retaining Walls along the ramps (overpass as well as underpass):
    - Found unit costs:
        - Retaining walls < 3m with traffic load[92]: 370 € / m²
    - Assumptions for further calculations:
        - Optimistic calculation: 300 € / m²
        - Standard calculation: 370 € / m²
        - Pessimistic calculation: 450 € / m²
- Soil compaction and sub-surface preparation of the overpass ramp along the crossing road[k]:
    - Found unit costs:
        - Sub-surface preparation, rolling[93]: 1,37 € / m²
        - Compaction[94]: 0,92 € / m²
        - Sub-surface preparation[95]: 1 € / m²
    - Assumptions for further calculations:
        - Optimistic calculation: 1,5 € / m²

[k] Along the LCRT line already included in the base costs of a conventional tram

        - Standard calculation: 2 € / m²
        - Pessimistic calculation: 2,5 € /m²

- Pavement of the crossing road:
    - Found unit costs:
        - Pavement of rural main roads[96]: 38 € / m²
    - Assumptions for further calculations:
        - Optimistic calculation: 34 € / m²
        - Standard calculation: 38 € / m²
        - Pessimistic calculation: 42 € / m²
- Railings along the ramps of the crossing road (along the LCRT line see 3.2.1.6):
    - Found unit costs:
        - Bridge railings[97]: 715 € / m
        - Railings for private homes[98]: 120 € / m
    - Assumptions for further calculations:
        - Optimistic calculation: 200 € / m
        - Standard calculation: 400 € / m
        - Pessimistic calculation 600 € / m
- Relocation of pipes below the crossing road[l]:
    - Found unit costs[99]:
        - District heating: 1000 € / m
        - Water supply: 500 € / m
        - Gas supply: 500 € / m
        - Mixed water sewer: 1000 € / m
    - Assumptions for further calculations (Sum of alle pipes per overpass length including the ramps):
        - Optimistic calculation: 1000 € / m
        - Standard calculation: 2000 € / m
        - Pessimistic calculation 3000 € / m
- Unforeseen costs (relative supplement to the sum of all component costs):

[l] Under the LCRT line already included in the base costs of a conventional tram

- Optimistic calculation: 10%
- Standard calculation: 15%
- Pessimistic calculation 20%

3.2.1.6 Additional costs: Pedestrian overpasses, fences & compensations

The analogy calculation as well as the component calculation was completed by cost estimations for the following specific components of an LCRT line:

- Pedestrian level crossings: For the costs of the protected level crossings a huge range results out of the question, which safety standard shall be applied: The cost of a tram-type pedestrian level crossing is about 10.000 € for surface construction plus 56.000 € for a traffic signal according to road-safety standards[100] and on top 4000 € per piece of barrier booms similar to those deployed at parking facilities[101]. A heavy-rail compliant railway level crossing costs 450.000 – 670.000 € per piece[102]. Following the considerations in 2.7, an optimistic value of 75.000 €, a standard value of 150.000 € and a pessimistic value of 300.000 € per crossing was assumed for further calculations.

- Fences resp. railings along the LCRT lines: For the separation between the LCRT tracks and the adjacent traffic area, the same unit costs were assumed, as for the railings of the overpass ramps (see 3.2.1.5).

- Compensations: It was assumed, that in case of shallow underpasses in some cases there will occur such disadvantages for neighbouring buildings (noise, lighting, sight protection), that their owners will claim compensations or the transport operator will have to purchase the concerned apartment or premise and resell it at lower price (see also 2.3.3.3). The estimation of real estate prices was based on a price report for Vienna[103], for depreciation, the following examples were found:

  - Depreciation caused by road traffic noise after changed traffic management, confirmed by court[104]: 13,5%
  - Depreciation caused by aircraft noise according to surveys among real estate brokers[105]: up to 20%
  - Depreciation caused by densely built-up surroundings[106]: 17%

  For further calculations, the following assumptions were made:

  - Optimistic calculation: One building per shallow underpass to be compensated, 50 m² affected floor area per building, 3000 € / m², 10% depreciation
  - Standard calculation: Two buildings per shallow underpass to be compensated, 75 m² affected floor area per building, 4500 € / m², 15% depreciation
  - Pessimistic calculation: Four buildings per shallow underpass to be compensated, 100 m² affected floor area per building, 6000 € / m², 20% depreciation

3.2.2 Results

The calculated total costs for the construction of a double-track LCRT line following the analogy method are in the standard calculation 36 Mio. € / km, in the optimistic scenario 28 Mio. € / km and in the pessimistic scenario 45 Mio. € / km. The component calculation leads to significant lower costs: 28 Mio. € / km in the standard case, 22 Mio. € / km in the optimistic and 36 Mio € / km in the pessimistic scenario.

As displayed in Table 12, the construction costs of an LCRT line according to the standard calculation represent only a quarter to a third of the costs of a cut-&-cover underground metro. Compared to a conventional tram, the additional costs of LCRT are 15-50%.

		Optimistic	Standard	Pessimistic
Compared to cut-&-cover metro	Analogy calculation	-81%	-64%	-40%
	Components calculation	-86%	-72%	-52%
Compared to elevated metro	Analogy calculation	-59%	-34%	-1%
	Components calculation	-69%	-50%	-21%
Compared to conventional tram	Analogy calculation	+42%	+50%	+60%
	Components calculation	+8%	+15%	+28%

Table 12: Construction costs of an LCRT line compared to conventional urban rail transit systems

As expected, the combination of the ranges of input data according to the three calculation scenarios leads to an even wider range in the final result. As shown in Figure 56 and Figure 57, only a part of the variation of the relative savings potential is caused by uncertainties about specific costs of the LCRT concept: To significant extent, the reasons are also different assumptions concerning the base costs of a conventional tram and the also quite hardly estimable costs of a conventional metro.

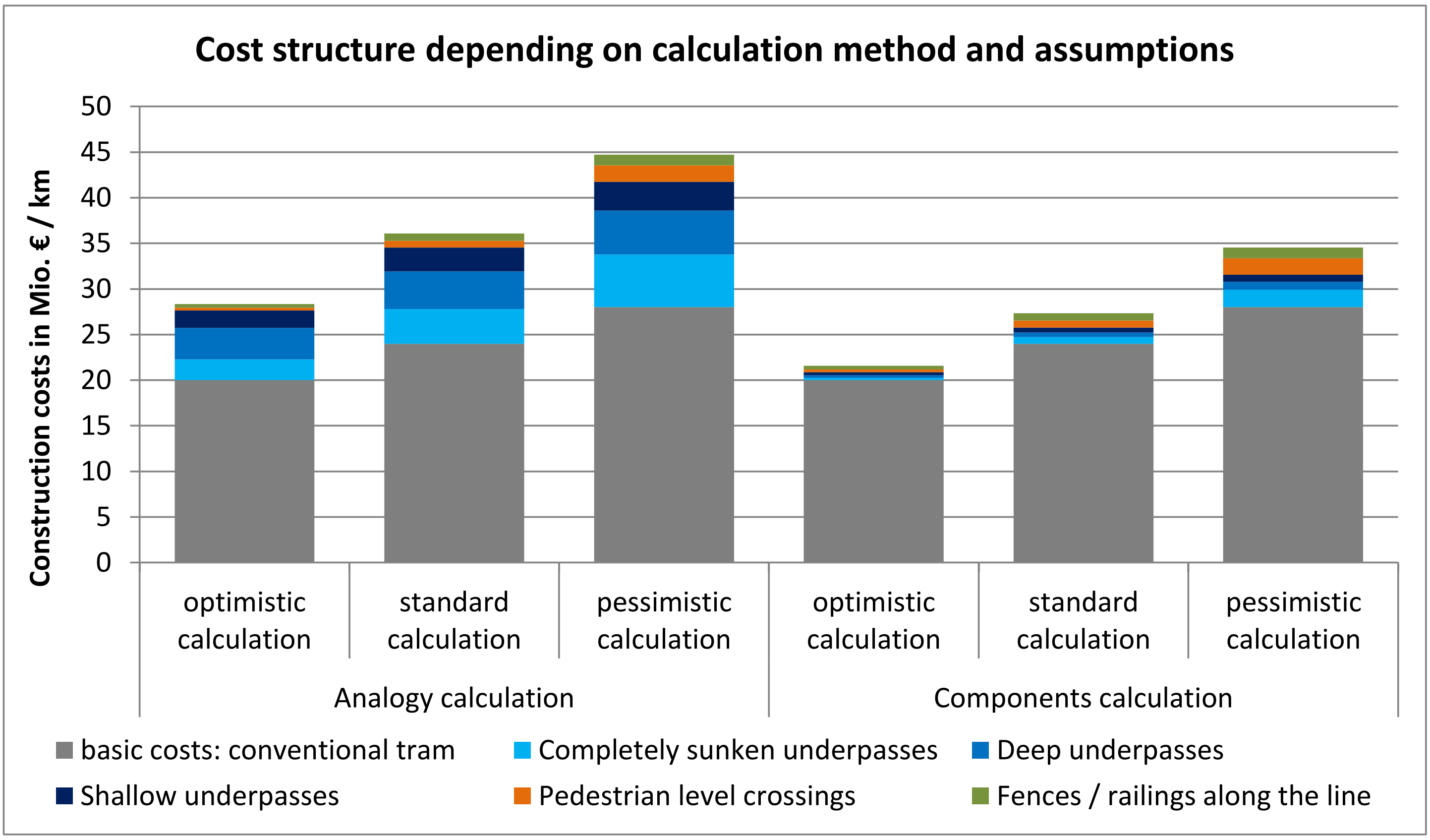


Figure 56: Construction cost structure of an LCRT line depending on calculation method and scenario.

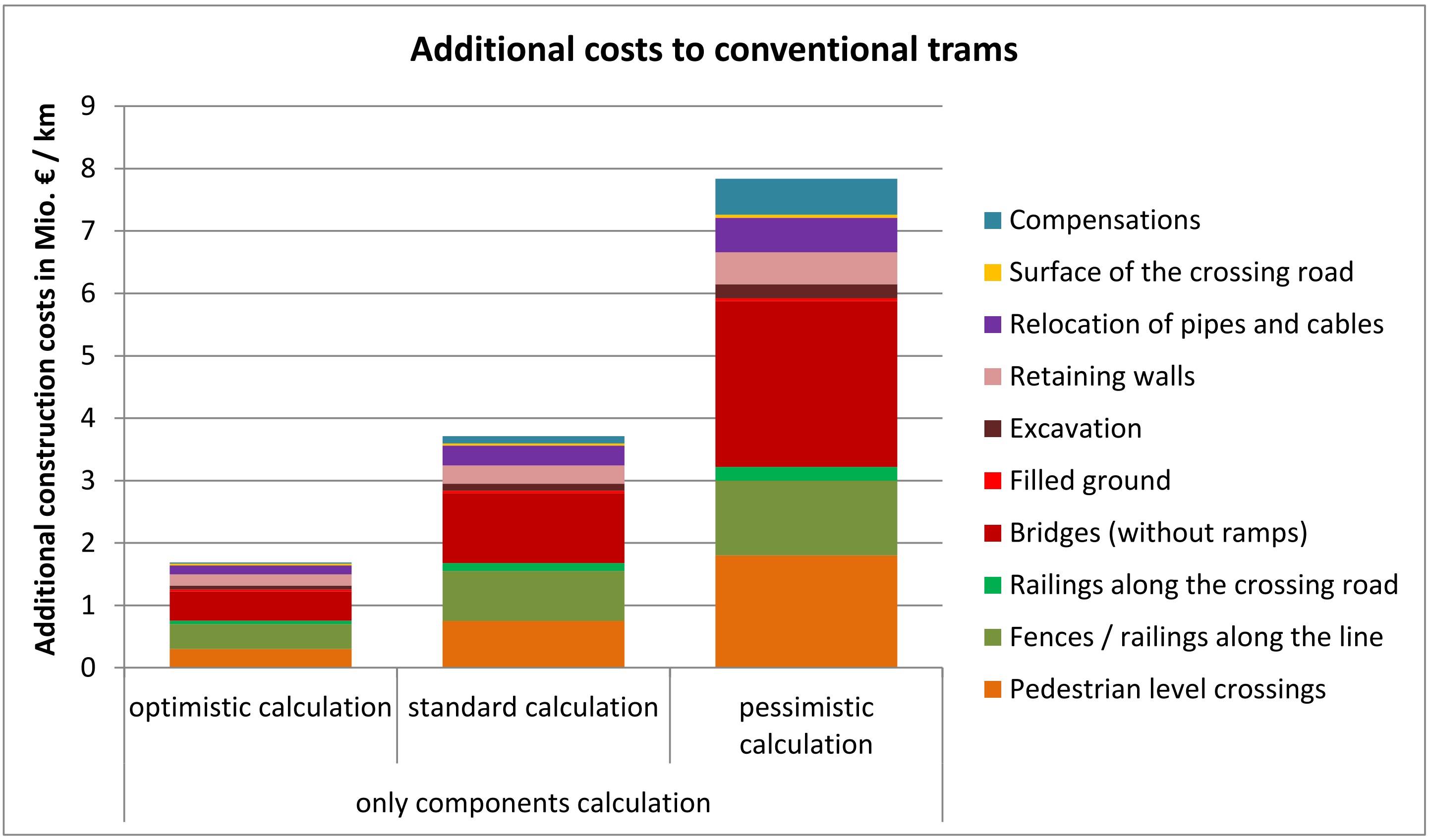


Figure 57: Detailed structure of the additional costs according to the components calculation depending on the calculation scenario

Nevertheless it seems likely, that generally favourable or adverse cost factors as e.g. the local salary level or the intensity of competition have the same effect on the cost of an LCRT line as on the cost of a conventional metro, so the extreme values appear rather unrealistic and with a fair degree of certainty the savings potential will be in a range of 2/3 to 3/4 of the costs of conventional cut-&-cover underground metro lines. Similar considerations apply to the comparison with elevated metro lines: On one hand, the lower compared costs lead automatically to a lower savings potential, but on the other hand, an elevated line requires so much space, that for an LCRT line of similar route alignment there is no need for deep or completely sunken underpasses and also compensations for depreciation of neighbouring buildings do not seem appropriate.

3.3. Vehicle costs

A possible, specific cost factor of the LCRT concept stem from the fact, that for the same seating capacity, longer vehicles are required because various technical devices (powertrain electrics, air condition etc.) cannot be accommodated as rooftop equipment. In order to assess this effect, the volume of these rooftop components was quantified using the example of a Bombardier Flexity low floor tram (the version for Linz Linien): with the aid of a cross section drawing[107], width and height of the rooftop elements could be measured as 450 x 1450 mm, the share of the vehicle length covered by rooftop equipment was estimated as 75% according to various photographs[108,109,110]. In the result, the volume demand is 0,49 m^3 per m vehicle length or about 10% of the passengers compartment. The length of a completely lowered pantograph was estimated as 2,5 m, thus already the two systemically necessary pantographs lead to a total length of the utility segments at the vehicles ends of 5 m. Following the assumption of a useful utility compartment height of 1,5 m (between high-floor driven running gear and lowered roof below the pantograph) and 2,4 m vehicle width this means useful volume of 18 m^3. In case of a vehicle length of 50 m, this covers about ¾ of the volume demand mentioned above. It was assumed, that the residual quarter can be distributed over the vehicle length, e.g. under seats, so the additional vehicle length compared to a conventional low floor tram is again exactly 10%. Even if this would proportionally lead to a 10% higher vehicle price, this would still not mean additional costs because LCRT makes travel time savings of much more than 10% possible (see 1.2 and 2.2.3.1), thus the vehicle demand decreases as well by more than 10% at same intervals. At an early stage of first LCRT applications the vehicle price would of course be higher in order to cover one-time development costs, but during a wider market penetration of LCRT systems, this cost handicap would disappear gradually.

4. Costs and achievable speed depending on the surrounding urban structure

For a more meaningful comparison of LCRT and conventional public transport, the cost estimation as well as the calculation of achievable average speed had been calculated separately for different urban structures. Four exemplary types of urban structures had been defined:

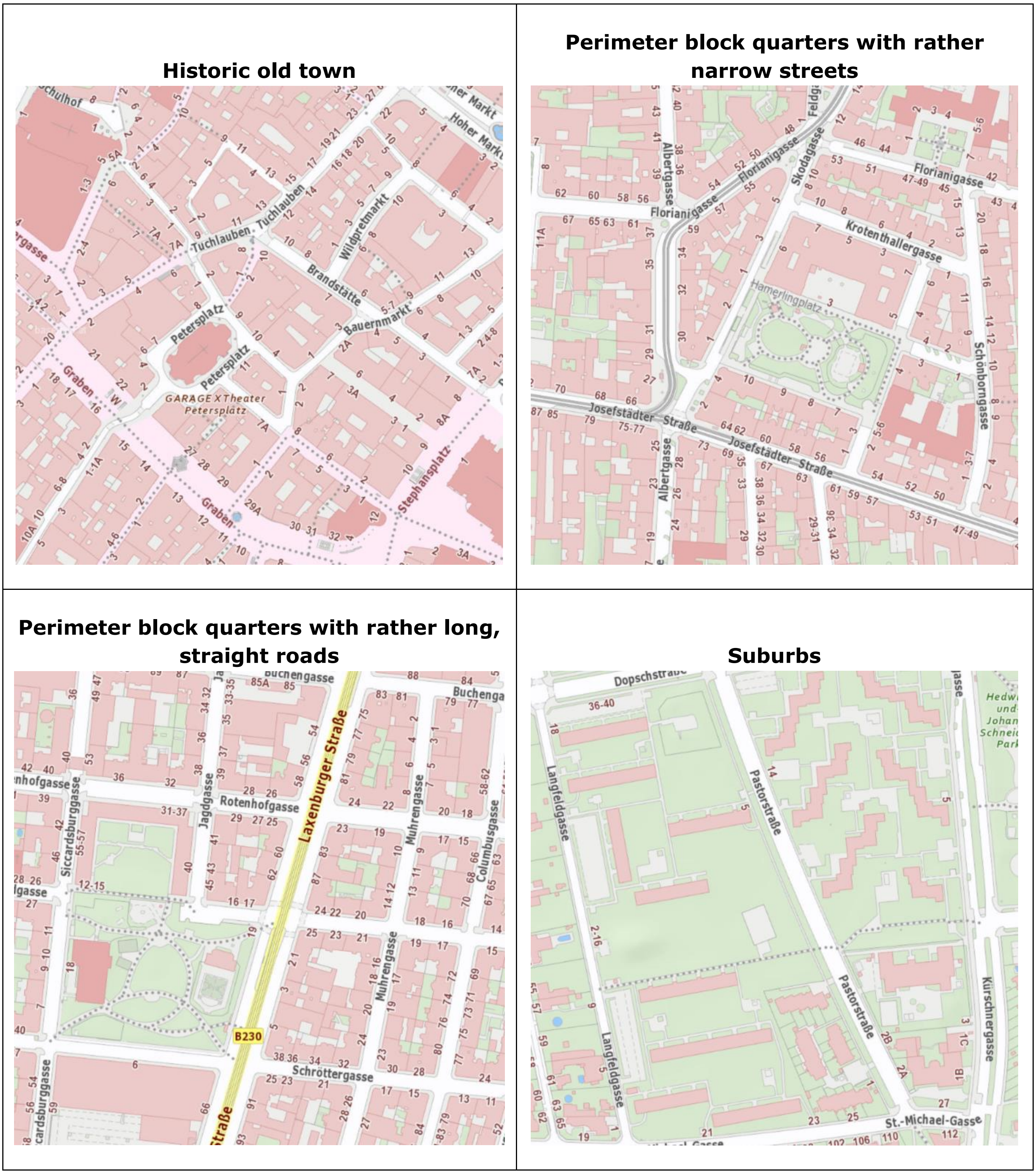


Figure 58: Exemplary urban structures for the comparison of LCRT and conventional urban rail transport

In the urban environment of a historic old town, the construction of at-grade tracks according to the LCRT line is assumed to be infeasible, such areas can be only passed by a bored tunnel at similar cost and speed as a tunnelled metro line.

Concerning the other urban structure types, for the following parameters different input values had been assumed, than in the general cost estimation as described in chapter 3:

		Perimeter block quarters with rather narrow streets	Perimeter block quarters with rather long, straight roads	Suburbs
Number of pedestrian level crossings per kilometer	optimist	No level crossings, reduced speed	4	3
	standard		5	4
	pessimist		6	5
Number of properties to be compensated per shallow underpass	optimist	2	0	Kein Entschädigungs-bedarf
	standard	3	1	
	pessimist	4	2	
Real estate prices per floor area	optimist	4.000	3.000	
	standard	5.000	4.000	
	pessimist	6.000	5.000	
Depreciation to be compensated resp. lost at resale	optimist	15%	10%	
	standard	18%	13%	
	pessimist	20%	15%	
Total number of underpasses per km	optimist	2,5	2,5	2,5
	standard	3	2,75	2,75
	pessimist	4	3	3
Thereof completely sunken underpasses	optimist	0,5	0	0
	standard	1	0,25	0
	pessimist	1,5	0,25	0
Thereof deep underpasses	optimist	1	1	0,5
	standard	1	1	1
	pessimist	1,5	1,25	1,5
Thereof shallow underpasses or such with hairpin curve	optimist	1	1,5	2
	standard	1	1,5	1,75
	pessimist	1	1,5	1,5
Conventional metro: share of tunneled sections	optimist	50%	25%	0%
	standard	67%	33%	0%
	pessimist	75%	50%	10%
Conventional metro: share of cut-&-cover sections	optimist	50%	50%	20%
	standard	33%	50%	40%
	pessimist	25%	50%	50%
Conventional metro: share of elevated sections	optimist	0%	25%	80%
	standard	0%	17%	60%
	pessimist	0%	0%	40%

Table 13: Assumptions for the cost estimation for different urban structures if differing from the general cost estimation

Corresponding to the examples shown in Figure 55, the construction costs for conventional metro lines were estimated as follows:

Mio. EUR / km	optimist	standard	pessimist
Bored tunnel	110	140	200
Cut-&-Cover	75	100	150
Elevated tracks	45	55	70

Table 14: Estimated construction costs for conventional metro lines depending on the construction method

For the calculation of the achievable average speed, a station spacing of 750 m was applied in all cases, the other input variables were assumed as follows:

- Conventional Metro: Same average speed of 31 km/h for all urban structures, originating from the examples in section 1.2 and Figure 3, standardized for a homogenous station spacing of 750 m.
- LCRT (calculation according to section 2.2.3)
  - Historic old town: Similar to a metro, because LCRT can be realised in these areas only tunnelled, similar to a metro.
  - Perimeter block quartes with rather narrow streets:
    - Optimist: 40 km/h maximum speed, one speed restricted cross-section per kilometre, causing 10 seconds time loss
    - Pessimist: 40 km/h maximum speed, two speed restricted cross-sections per kilometre, causing 10 seconds time loss each
  - Perimeter block quarters with rather long, straight roads:
    - Optimist: 60 km/h maximum speed without speed restrictions
    - Pessimist: 60 km/h maximum speed, one speed restricted cross-section per kilometre, causing 10 seconds time loss
  - Suburbs: Same as a metro (consistent separation from car traffic by fences, no small curve radii)
- Conventional tram (calculation according to section 1.2 and Figure 3):
  - Historic old town: not feasible
  - Perimeter block quarters with rather narrow streets:
    - Optimist: 75% like a tram on an own, segregated track, 25% like a tram in mixed traffic
    - Pessimist: 25% like a tram on an own, segregated track, 75% like a tram in mixed traffic
  - Perimeter block quarters with rather long, straight roads:
    - Optimist: continuously like a tram on an own, segregated track
    - Pessimist: 75% like a tram on an own, segregated track, 25% like a tram in mixed traffic
  - Suburbs: Same as a metro (consistent separation from car traffic by fences, no small curve radii)
    - Optimist: Like a fully grade-separated rapid tram
    - Pessimist: Like a tram on an own, segregate track

The results of the refined calculation for different urban structures is shown in the following charts:

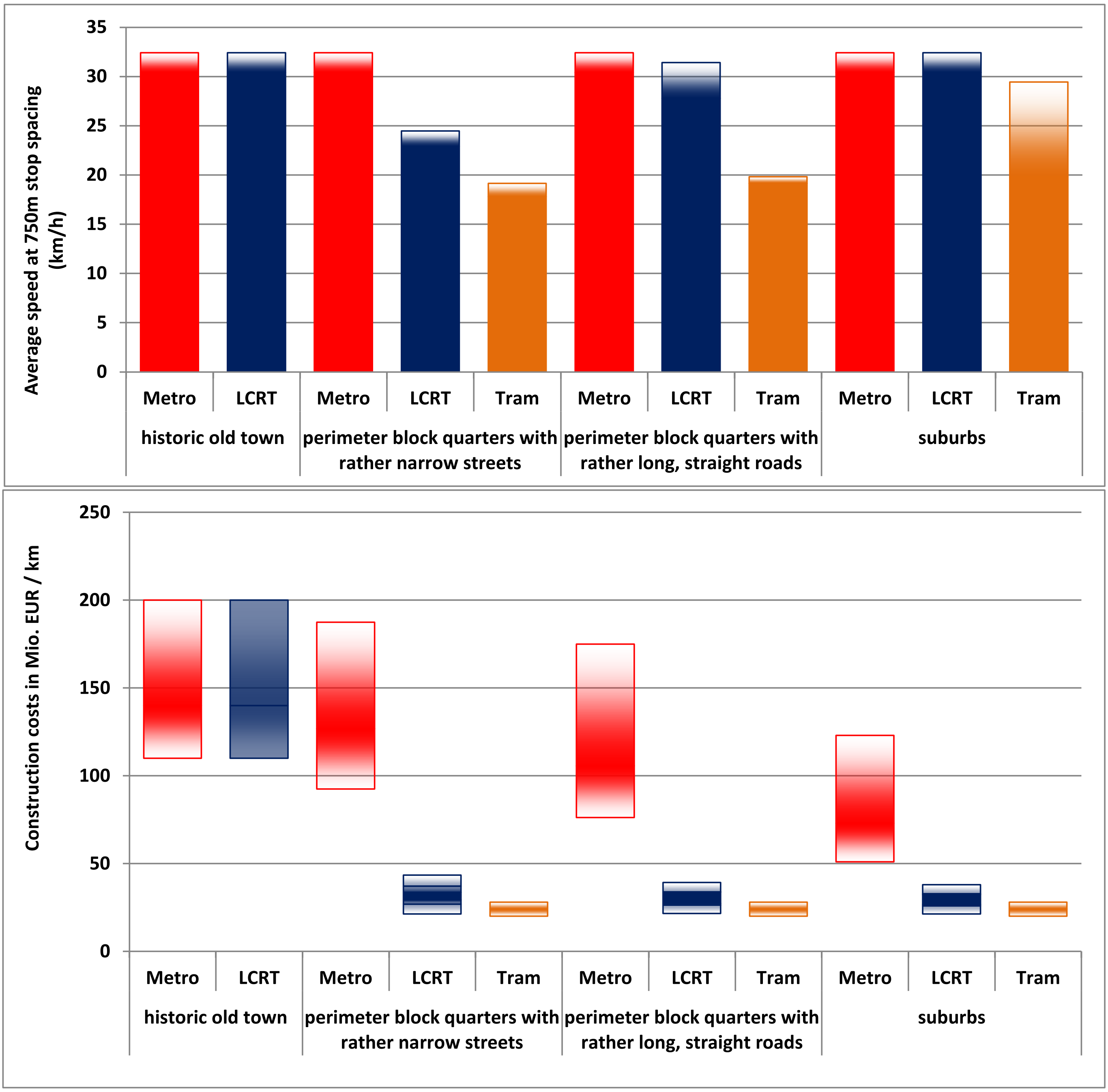


Figure 59: Comparison of speed and costs between LCRT and conventional metro resp. tram. Colour gradients and frames represent band widths according to different assumptions (optimist/standard/pessimist) and calculation methods.

The biggest improvement of the ratio between investment costs and travel time savings can be achieved in districts with perimeter block quarters and rather long, straight roads, dominating big parts of European cities. In the districts closer to city centre the travel time advantage over the conventional tram decreases moderately, in historic old town districts costs and travel times of LCRT are the same as those of a metro. On the other hand, in the suburbs, a conventional tram represents an adequate alternative to LCRT, if the planners make use of the opportunities of spacious building structures.

In addition to the comparison of travel speed in various urban structures, it must be taken into consideration, that LCRT can be operated with similar long trains as a metro regardless to the surrounding structure of buildings and road network. Thus, LCRT can be operated in the suburbs like a rapid tram, in the most central parts of the city as a metro and in the districts in between as an optimized solution with elements of both systems.

5. Further alternatives and design considerations

5.1. Rubber-tyred version

Vehicles, that are guided by metal rails, but equipped with rubber tyres bearing the load of the vehicle, as they are already sporadically used in modern tram networks, are particularly interesting for LCRT. Generally, the Translohr system[111] is regarded as the most suitable, however the adaptations described in the following paragraphs are considered:

5.1.1 Minimization of pavement stress

Whilst existing Translohr vehicles have similar load per wheel as conventional wheel-rail-trams, the rubber tyred LCRT vehicle could be optimized for as low pavement stress as possible:

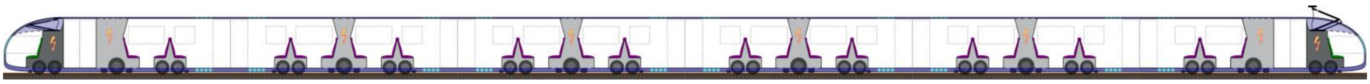


Figure 60: longitudinal section of a rubber-tyred LCRT vehicle

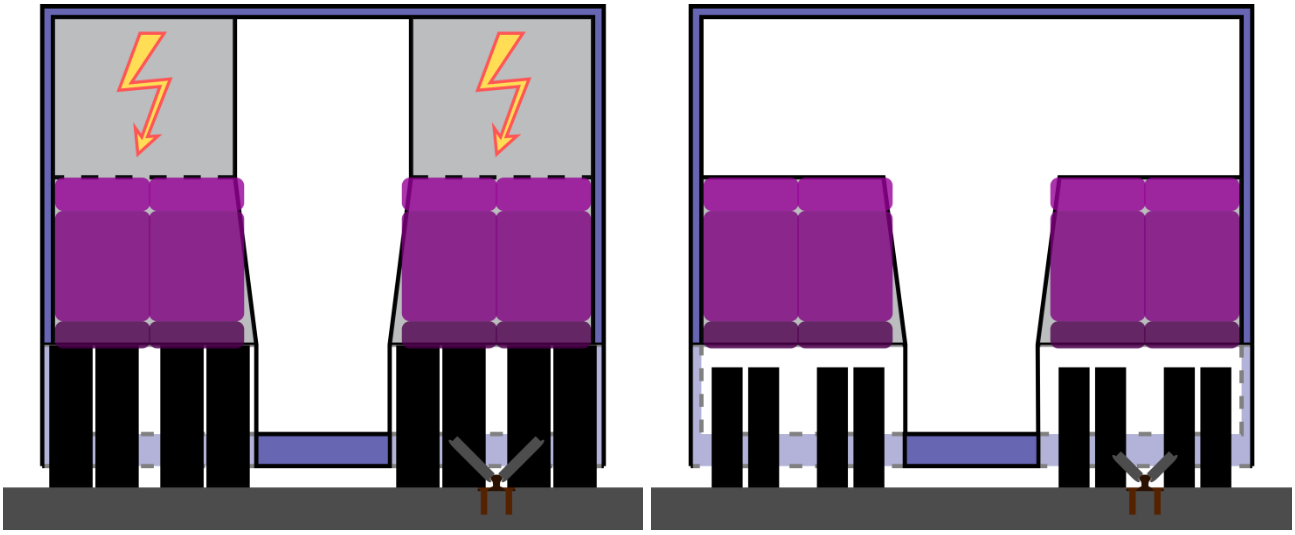


Figure 61: Cross-section of a rubber-tyred LCRT vehicle in the area of driven wheels (left) and non-driven wheels (right).

The car body section length of the proposed LCRT vehicle is approximately the same as that of existing Translohr vehicles, but instead of one wheelset per section, there shall be five wheelsets which consist each out of four twin tyres[m] instead of two big single tyres. In total this means eight tyres per wheelset or 40 tyres per section. In Detail, the wheelsets are arranged in the following way (see also Figure 60 and Figure 61):

- In the middle of each section there are the driven wheels, above them up to the ceiling of the passengers compartment there is a cabinet for the powertrain, air condition and other technical devices on both sides of the central aisle. Thanks to their position in the middle of the section, the driven wheels can always run exactly tangential to the guiding rail, they are not steerable, but rigidly fixed to the car body.

[m] The twin wheels are fixed each to another concerning rotation speed as well as steering angle, but each pair is driven and steered separately.

- The non-driven wheels are arranged under back-to-back positioned benches. Because of their eccentrical position within the section, they have to be steerable in the meaning of changing their orientation against the car body depending on the curve radius (see also 5.1.2)

Because of the symmetric arrangement of masses and wheels within the car body section, the weight can be distributed evenly over all wheels by adjusting the suspension system. This would be optimal in terms of pavement preservation, but the share of weight, resting on driven wheels decreases to 20%. In case of bad weather conditions, steep inclines or high expected acceleration, this could be insufficient. In order to prevent these problems, an adaptive pneumatic or hydro-pneumatic suspension system is proposed: Similar to the kneeling function of low-floor-buses[112], air can be moved between the individual air springs for achieving more load on driven wheels when needed (even if this means momentary higher pavement stress):

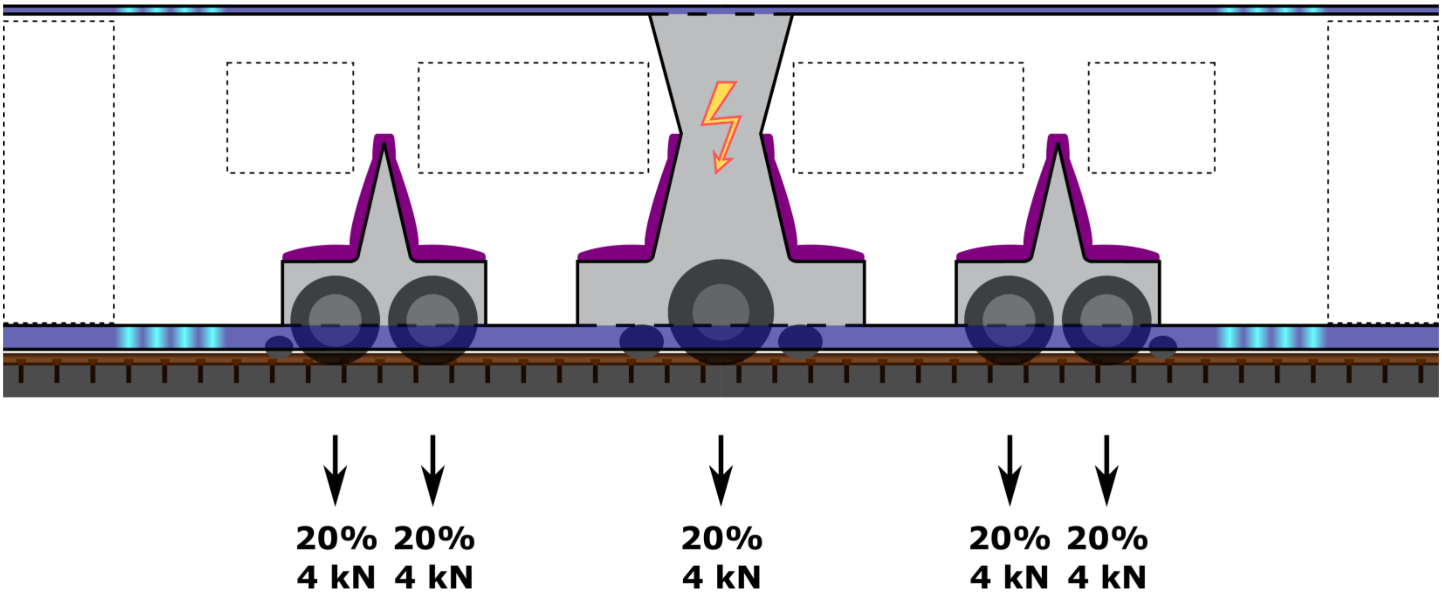


Figure 62: Weight distribution, controlled by air suspension: Even load on all wheels (usual case)

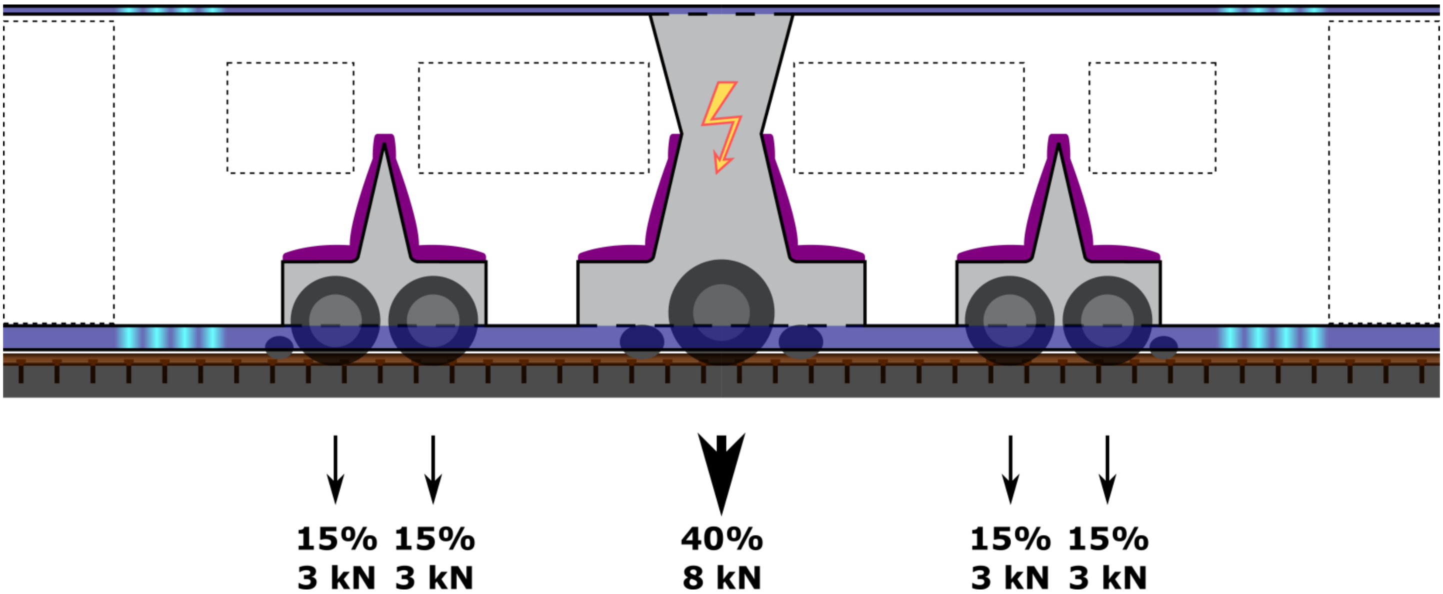


Figure 63: Weight distribution, controlled by air suspension: disproportionally high load on driven wheels (bad weather conditions or high tractive force required)

Because of the possibility to put more load onto the driven wheels than on the non-driven ones, these have to be dimensioned for higher load. Therefore, they are wider and have a bigger diameter than the non-driven wheels. Because of this, next to the non-driven wheels there remains space for steering movements and thanks to the smaller diameter, the non-driven wheels can be placed completely below the seats.

Examples for the estimation of the vehicles's weight-length-ratio			
Type	Length (m)	Empty weight (kg)	weight per length (empty)
Siemens ULF A[113]	24,2	30000	1240
Siemens ULF B[114]	35,3	43000	1218
ČKD RT6N1[115]	27,6	32850	1190
Škoda Anitra[116]	20,09	24200	1205
TWT VARIO LF2R.E[117]	23,7	30000	1266
Škoda 13T5[118]	31,06	41485	1336
Stadler Variobahn[119]	33,94	39000	1149
Bombardier Cityrunner[120]	40,6	48500	1195
Translohr STE 3[121]	25	36000	1440
Translohr STE 6	46	63000	1370
Calculation of the required tyre load capacity			
Assumed weight per length (empty)		1200	kg/m
Vehicle width		2,65	m
Share of passenger compartment area on whole outer base area		75%	
Passenger loading (average of seating and standing area)		4	Pers / m²
Average passenger weight		75	kg
Weight per length (full)		1796,25	kg/m
Section length		9	m
Number of wheelsets per section		5	
Number of tyres per wheelset		8	
Tyre load in case of evenly distributed weight		404	kg
Maximum share of weight on driven wheels		40%	
Maximum tyre load on driven wheels		808	kg
Dimensioning of tyres			
	Driven wheels	Non-driven wheels	
Required tyre load capacity	800	400	kg
Suitable example model	Dunlop SP LT 800[122]	Maxxis AP2 All Season[123]	
Suitable tyre code	185 R 14 C / 102/100 Q	145/80 R13 79T	
Tyre diameter	665	562	mm
Tyre width	203	145	mm
Aisle width in the vehicle's center	605	580	mm
Minimum curve radius		17	m

Table 15: Exemplary dimensioning of a rubber-tyred LCRT vehicle

5.1.2 Variants of radial adjustment of non-driven wheels

There are three options, how to ensure exactly tangential movement of the non-driven wheels in order to minimize wear and friction resistance. These basic principles are applied in different types of conventional rail-wheel-tram vehicles too:

- A self-steering mechanism, where the forces acting onto the wheels together with the type of swivelling bearing between wheels and car body leads to the correct alignment of the wheels

- A mechanical forced-steering-system, using steering rods and additional rail guide rollers in order to define the steering angle of the wheels depending on the lateral shift between wheelset and guiding rail
- An electronic radial adjustment of the wheels, adjusting the steering angle of the wheels to the curve geometry by actuators

Design targets for the radial adjustment system are low height demand below the vehicle's floor (rather a solution without steering rods or mechanical connection between inner and outer wheels) as well as little mechanical stress on the guiding rail.

5.1.3 Modified position of the guiding rail

Concerning the position of the guidance rail on the guideway and the guide rollers on the vehicle, there are considered the following modifications of the Translohr system:

1. Variable height of the guiding rail: The guiding rail of the translohr system is always countersunk into the guideway pavement, so the top of the guiding rail is on the same level as the pavement surface. For the rubber tyre version of LCRT, a construction with less effort is pursued: Using existing pavements, on the major part of the track length, not the whole rail shall be countersunk into the pavement, but there should be milled only a shallow strip into the pavement surface, corresponding to the thickness of the rail foot, the rest of the guide rail remains above the pavement surface. The guidance rail will be completely countersunk into the pavement only at level crossings and in curves of such small radius, that the non-driven wheels run over the guidance rail (When applying the original dimensions of the Translohr rail and the vehicle dimensions described in Table 15, this would be the case at curve radii under 70m).
2. Asymmetric alignment of the guiding rail: In contrary to the central guide rail alignment of the original Translohr system, in case of the rubber tyred LCRT the guide rail might be arranged asymmetrically, running between the inner and the outer pair of wheels (twin-tyres) – see Figure 61. With such an alignment of the guidance rail, a lower floor height could become feasible despite the higher position of the guide rail and in case of a single track line, an asymmetric guidance system without switches could be realised (see 5.3.4).

5.1.4 Advantages and disadvantages of the rubber tyred version

The main advantage of the rubber tyred LCRT version is the minimization of pavement stress: According to the "generalized fourth power law", road damage caused by vehicles is approximately related to the fourth power of their axle weight, so an axle of 5t load, passing a cross-section once has the same effect, than 10.000 axles of 500kg load[124]. Under the assumption, that the distribution of load on wider or narrower tyres results in a proportionally lower resp. higher specific load, this means the following relationships between a five-section LCRT vehicle (as displayed in Figure 60 and described in Table 15) and other vehicles:

- 1 five-section LCRT vehicle causes the same pavement wear out as 24 passenger cars[125]
- 16 five-section LCRT vehicles cause the same pavement wear out as 1 three-axle Truck[126]
- 20 five-section LCRT vehicles cause the same pavement wear out as 1 two-axle Bus[127]

In contrary, the original Translohr system stresses the pavement more than conventional public transport busses, because similar axle loads rest on single tyres instead of twin tyres. Therefore, Translohr tram tracks are always built completely new with sufficient load bearing capacity.

If a part of the vehicles mass is shifted onto the driven wheels in order to enable steeper incline or higher acceleration, the pavement on these line sections, during these times wears out about 30%

faster. Apart from that, more axle load at same tyre pressure might also lead to more energy consumption instead of more pavement stress, because of more tyre deformation and a bigger contact area between tyre and pavement.

An urban track, frequented every 2,5 minutes by a five-section LCRT vehicle has the same wear out as a road, frequented every 40-45 minutes by a bus or truck. A rural or suburban LCRT track with a half-hour interval between 5 am and midnight has a similar wear out as a traffic lane with two buses daily (and no trucks).

The described, pavement-friendly modification of the rubber-tyred LCRT should contribute to low infrastructure costs as follows:

1. For urban LCRT lines, outside the short underpasses existing road surfaces could be utilized without building a new, improved pavement. This is facilitated not only by less axle load, but also because the guiding rail is not countersunk into the pavement, but mainly above it (see 5.1.3). Furthermore, there is no need to remove sewage canals below the track as usually done before building tram tracks: The pavement load is not higher than that of other traffic and in contrary to complex rail tracks, it is easier to remove or shift the guiding rail temporarily during construction works.
2. Because of less axle load, the thickness of the pavement and the supporting structures below it can be reduced, leading to less excavation depth and volume for the underpasses. The probability, that an underpass can be constructed without relocation of pipes or cables under the pavement is increased as well.
3. If an LCRT network is enlarged to the city's surroundings, longer distances and intervals change the relationship between track and vehicle costs. Less infrastructure construction and amortization costs thanks to less wear out resp. lower durability requirements to the road construction have in this situation more impact on total costs, than the vehicle costs.

Optimized interaction between the vehicle guidance via the central metal rail and force transfer via rubber tyres can reduce costs via the following effects:

- Ideally, the radial adjustment of the individual wheels is solved in such a way, that the guidance rail controls the steering movements but only in case of insufficient adhesive friction it prevents the vehicle from leaving the guideway in a direct, mechanical way. In regular conditions, longitudinal as well as lateral forces are transmitted to the pavement surface primarily via the tyres and their friction, so there is very low wear out of the guide rail.
- On the other hand, the mechanical guiding system as a backup system reduces the requirements to the interaction of pavement and tyre: In case of non-track-guided vehicles, the resultant of longitudinal and centrifugal forces has to be transmitted to the road surface with maximum safety and the vehicles steerability must be ensured also in extreme situations as emergency braking, aquaplaning and similar. Regarding a track-guided vehicle, there are no fatal consequences if tyres temporarily fail to transmit lateral forces by adhesive friction. Also the maximum considered deceleration of a public transport vehicle with standing passengers has to be less than that of individual passenger cars or trucks. Therefore, it is possible to use tyre and/or pavement materials which are less safe concerning adhesive friction but cheaper, more durable, less noisy or more energy efficient.

Another advantage of the rubber-tyred version is the lower noise level, particularly in comparison to worn-out tram rails and their switches and crossings. This advantage can be quite crucial if an LCRT line should be realized in a narrow, so far quiet street.

Translohr type rubber tyre trams have a floor level of 25 cm above top-of-rail, this is about 5-10 cm lower than that of rail-wheel-trams (except the Siemens ULF), facilitating underpasses with low clearance height. In general, the functional separation into a guidance system based on a single rail and the force transmission via rubber tyres reduces technological complexity as there is no need to adjust the wheels exactly tangentially and in correct distance to the rail. Particularly these requirements make low-floor-trams technologically complicated, having the choice between continuous wheelset axles (relatively high floor) and complex mechanical or electronical steering systems, often leading to high wear of rail or wheel because of very small wheels, the slip caused by speed difference between inner and outer wheel in curves or incorrect radial adjustment.

Concerning possible malfunctions, the rubber-tyred versions represent the additional risk of air loss or tyre blow-outs. On the other hand, in case of a derailment within an underpass the rubber-tyred vehicle can be towed out and put back onto the guide rail outside the underpass, whereas the same procedure seems much more complicated in case of a rail-wheel tram, that has to be put back onto track with nearly no vertical space for manoeuvring.

Disadvantages of the rubber-tyred version are the lower durability of tyres compared to steel wheels and the significantly higher friction resistance.

5.2. Alternative solutions with less track thickness

In order to reduce the length and/or the depth of underpasses, it is conceivable to use not only conventional tram rails, but also other rail profiles as shown in Figure 64:

Conventional tram rail	Flat rail for flanged wheels without stiffening braces	Flat rail for flanged wheels with stiffening braces on both sides	Flat rail for flanged wheels with stiffening braces on the outer side only	Flat rail for flangeless wheels with stiffening braces on both sides	Flat rail for flangeless wheels with stiffening braces on the outer side only	Rail of conventional height for flangeless wheels

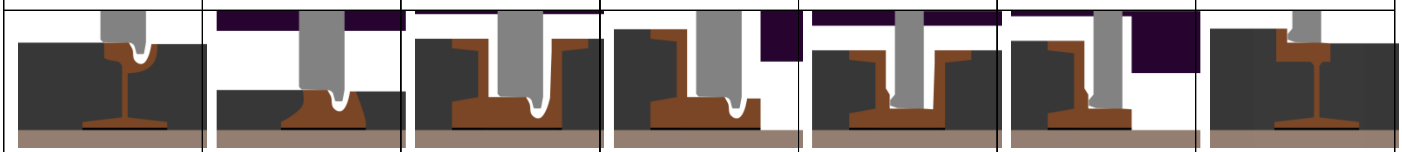


Figure 64: Rail profiles, considered for the reduction of the excavation depth

Starting from conventional tram track construction (see Figure 65) it appears obvious to remove the web of the rail and put the head directly onto the foot. Such a flat rail without any stiffening brace (see Figure 66) has no specific influence onto the vehicle, but it is doubtful, whether the rail would be stiff enough against vertical bending.

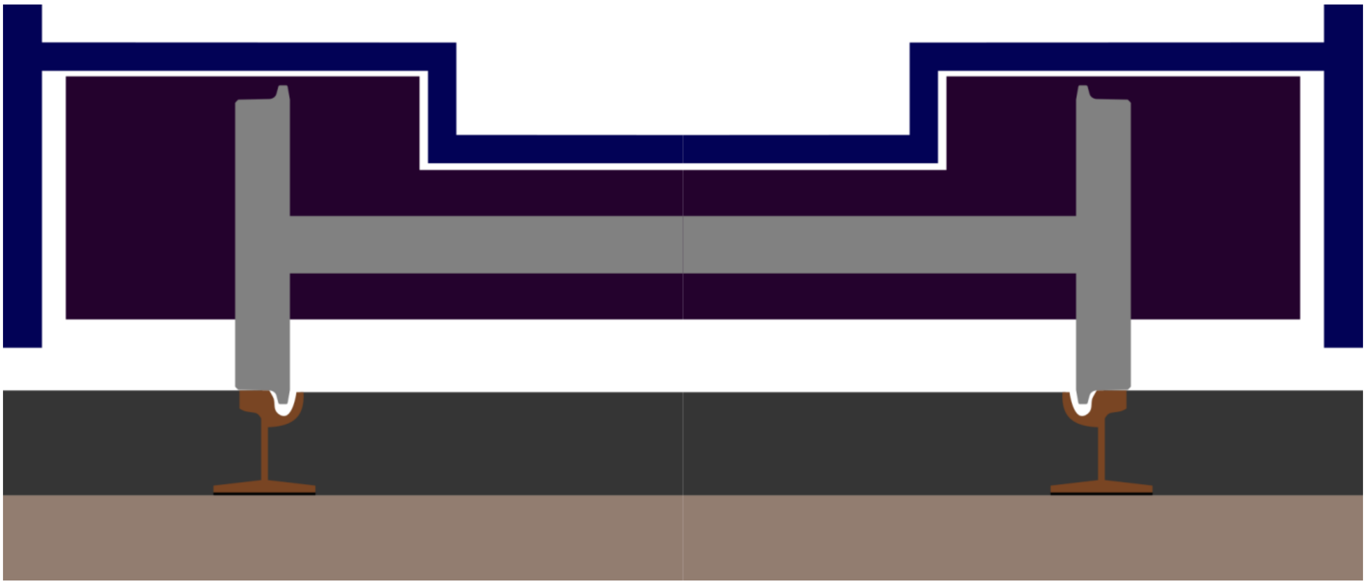


Figure 65: Conventional tram track, displayed with wheelset (grey), running gear (violet) and car body (blue)

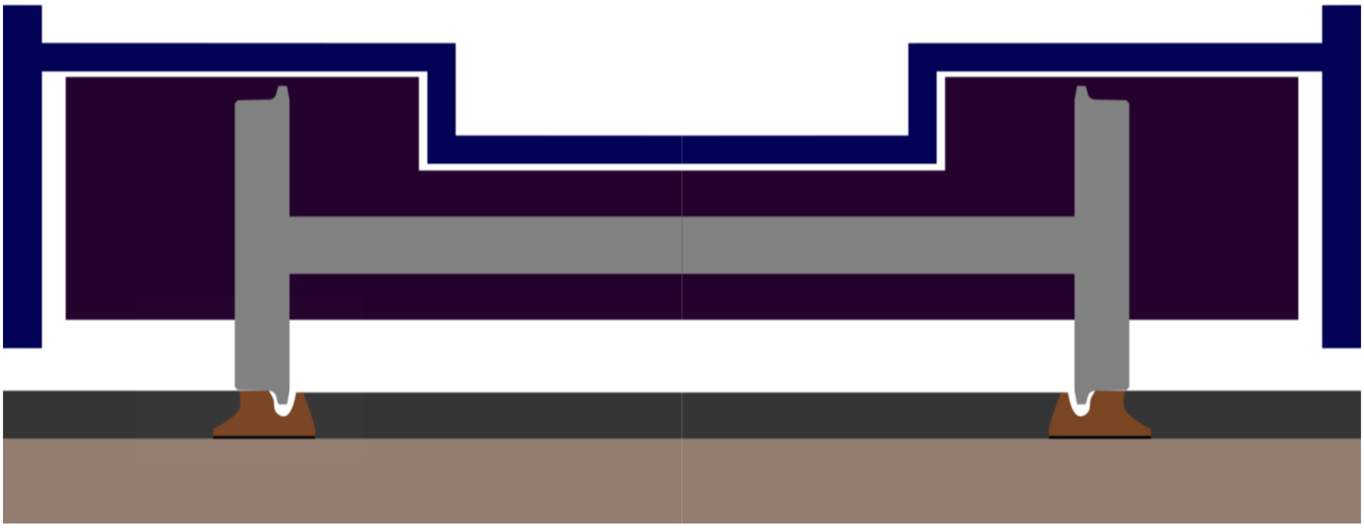


Figure 66: LCRT track with flat rails without any stiffening braces, displayed with wheelset (grey), running gear (violet) and car body (blue).

As another option, instead of the rail web there can be mounted stiffening braces on both sides next to the running surface (see Figure 67). Although these stiffening braces cannot be combined with a very low floor height as achievable with portal wheelsets (see 2.1.4.2) or lateral aisles around running gear (see 2.1.4.3), they make it easier to use running gear with maintenance-friendly continuous wheelset axles while keeping the platform and clearance height low.

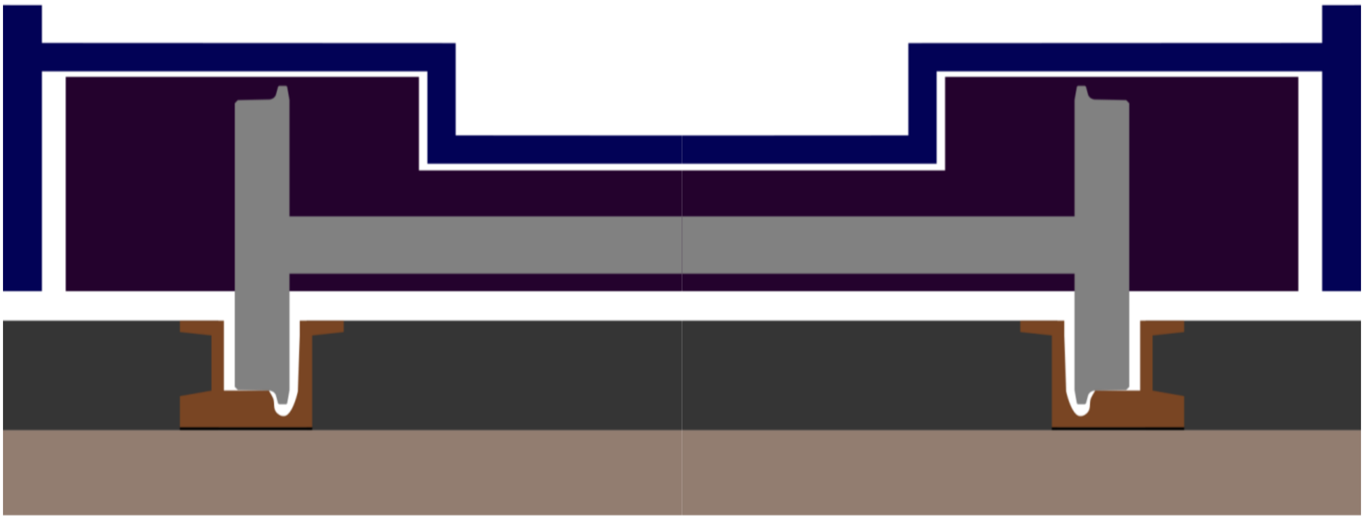


Figure 67: LCRT track with flat rails for flanged wheels with stiffening braces on both sides, displayed with wheelset (grey), running gear (violet) and car body (blue).

In order to gain more space for powertrain components within the running gear, the rails might be fitted with stiffening braces only on their outer side as well. In this case, in the middle between the rails, a trench remains (see Figure 68). With regard to sufficient resistance against vertical bending, the remaining stiffening brace must probably be higher and/or thicker.

Figure 68: LCRT track with flat rails for flanged wheels with stiffening braces on their outer side, displayed with wheelset (grey), running gear (violet) and car body (blue).

The described solutions for LCRT with flat rails and stiffening braces would be applied only in underpasses and along platforms. In between, particularly at level crossings and in switch areas, conventional rails would be applied.

Following the concept of equipping rails with stiffening braces from the running surface upwards, the next option would be omitting of flanges and the slot of grooved rails and providing lateral contact surfaces on wheel and outer stiffening brace instead. Also this option can be realized with stiffening braces on both sides (see Figure 69) or only on the outer side (see Figure 70) but when using rails with rail web of conventional height, an adapted rail head is necessary (see Figure 71).

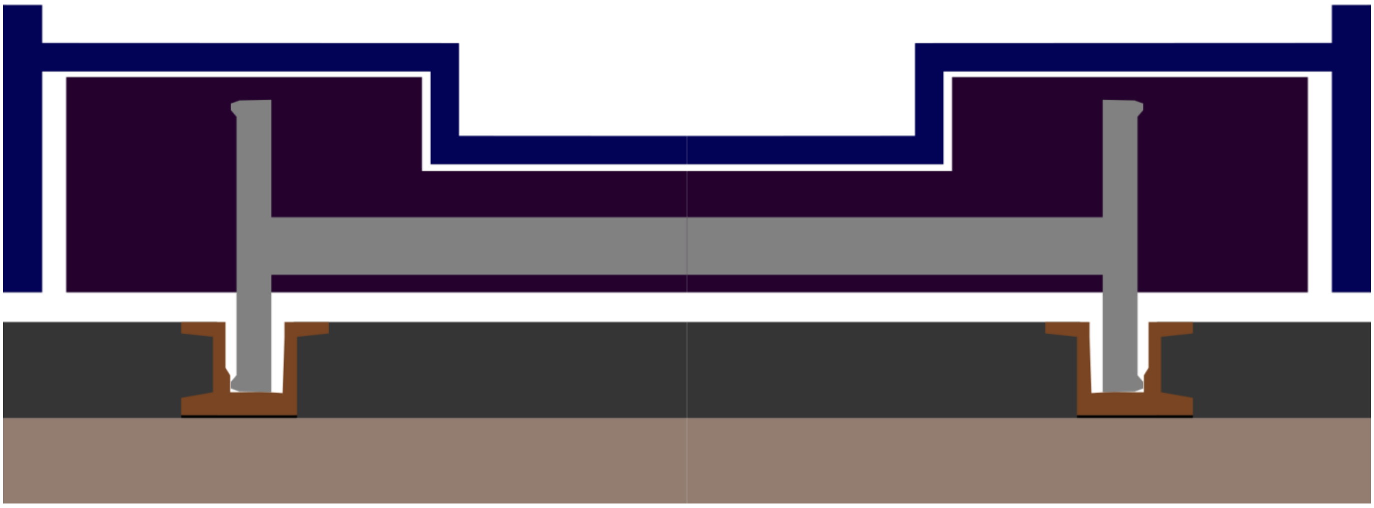


Figure 69: LCRT track with flat rails for flangeless wheels with stiffening braces on both sides, displayed with wheelset (grey), running gear (violet) and car body (blue).

Figure 70: LCRT track with flat rails for flangeless wheels with stiffening braces on the outer side, displayed with wheelset (grey), running gear (violet) and car body (blue).

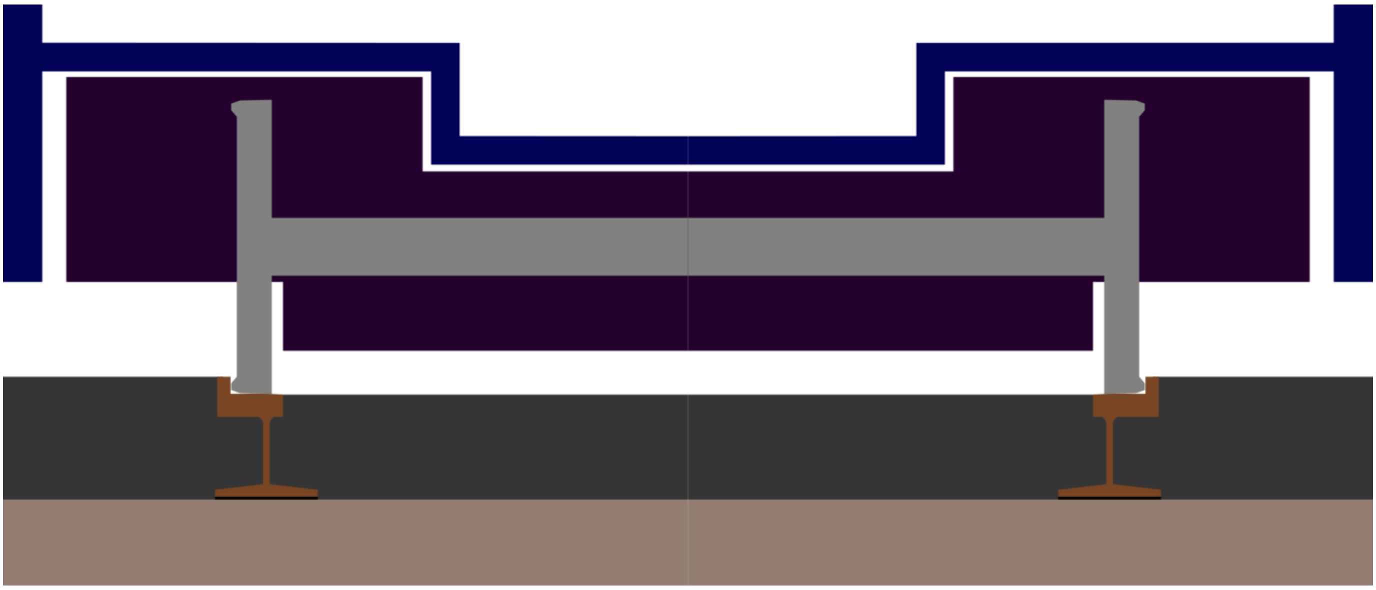


Figure 71: LCRT track of conventional height but with rail head adapted for flangeless wheels, displayed with wheelset (grey), running gear (violet) and car body (blue).

5.3. Single track variants

5.3.1 Reasons why to consider single-track sections

Nowadays, single track lines are quite unusual in urban rail transportation: The majority of trams lines and virtually all subway networks are double-tracked. However, for LCRT, single-track sections should not be discarded too early:

- Compared to conventional trams, the complete separation between LCRT and car traffic means significant less risk of delays, so the negative effect of single track operation (with passing loops) on timetable stability will be much less, than in case of a conventional tram.
- Thanks to much lower costs, LCRT can be realised in substantially smaller cities than conventional metro systems and tram-train-styled suburban network extensions become economically feasible. In both cases, the required transportation capacity can be covered by longer intervals, which might be manageable and stable on single-track infrastructure as well.
- In case of narrow urban roads, short single-track sections could be the crucial factor for making an LCRT line feasible

5.3.2 Possible measures for timetable stability

Apart from common measures on single-track lines like sufficient time reserve or properly dimensioned turning facilities at the terminal stations, the following measures are proposed in order to avoid influence of single train delays on the opposite direction and the following trains:

- If time and location where trains pass each other are planned optimally (trains arrive from both directions simultaneously and depart again simultaneously), a delay up to the dwell time[n] does not cause a delay of the trains in the opposite direction. If every station is designed as a passing loop, a high percentage of the overall time between passing of trains in one station and in the next is just the dwell time in the station, so only a significant delay (compared to the running time between the stops) leads to a persisting delay in both directions.

[n] More precisely the dwell time minus the reaction time of the train control system and the switch, plus a part of the time for acceleration

- Occasionally, delays can be made up by passing through a station without stop (of course with appropriate passenger information).
- In order to manage more significant delays too, it is worth to consider additionally the following two variants how to avoid influence between the directions:
    1. Spare passing loops: All stops are designed as passing loops, but if trains run on time, only half of them is used, between two stops where trains pass each other, the trains stop at a passing loop without an oncoming train. If a train is late, it will wait in one of these intermediate stations for the oncoming train. In the effect, this one train will continue its journey until the terminal with a delay of nearly a half interval, but neither the oncoming train, nor further trains of both directions will be affected by the delay.

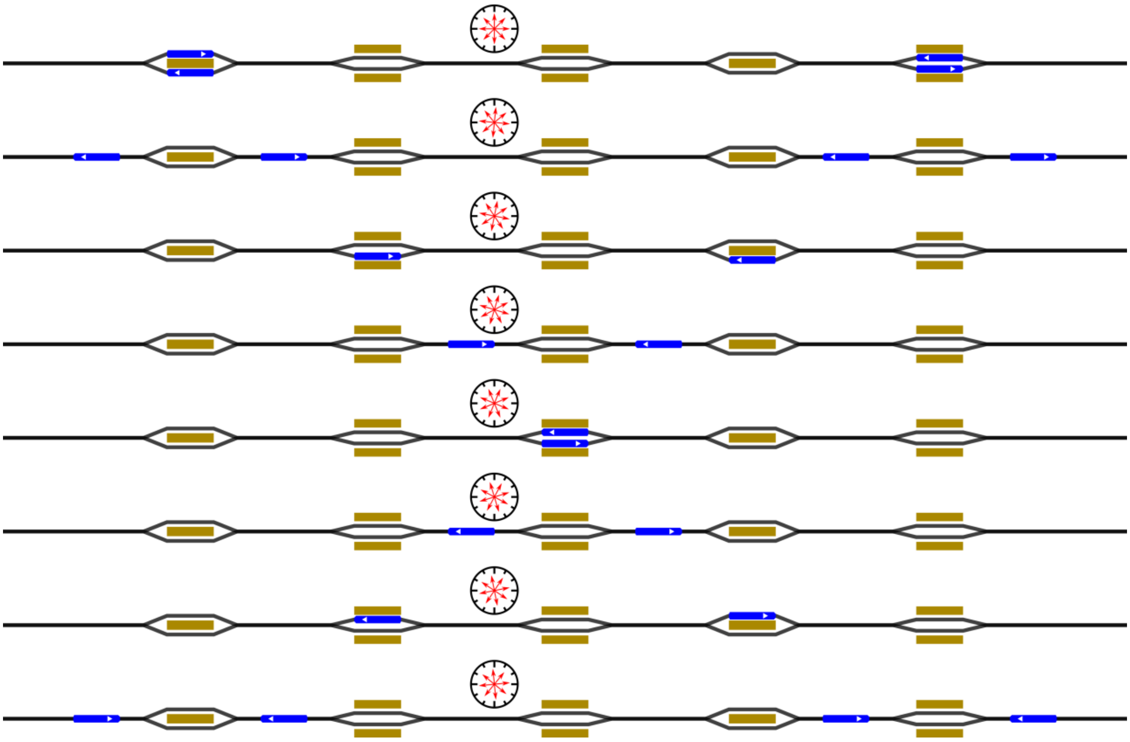


Figure 72: Single track operation with spare passing loops, presented using the example of a 7,5-minute interval: operation without delay, only half of the passing loops in use (different rows show the same line at consecutive time steps).

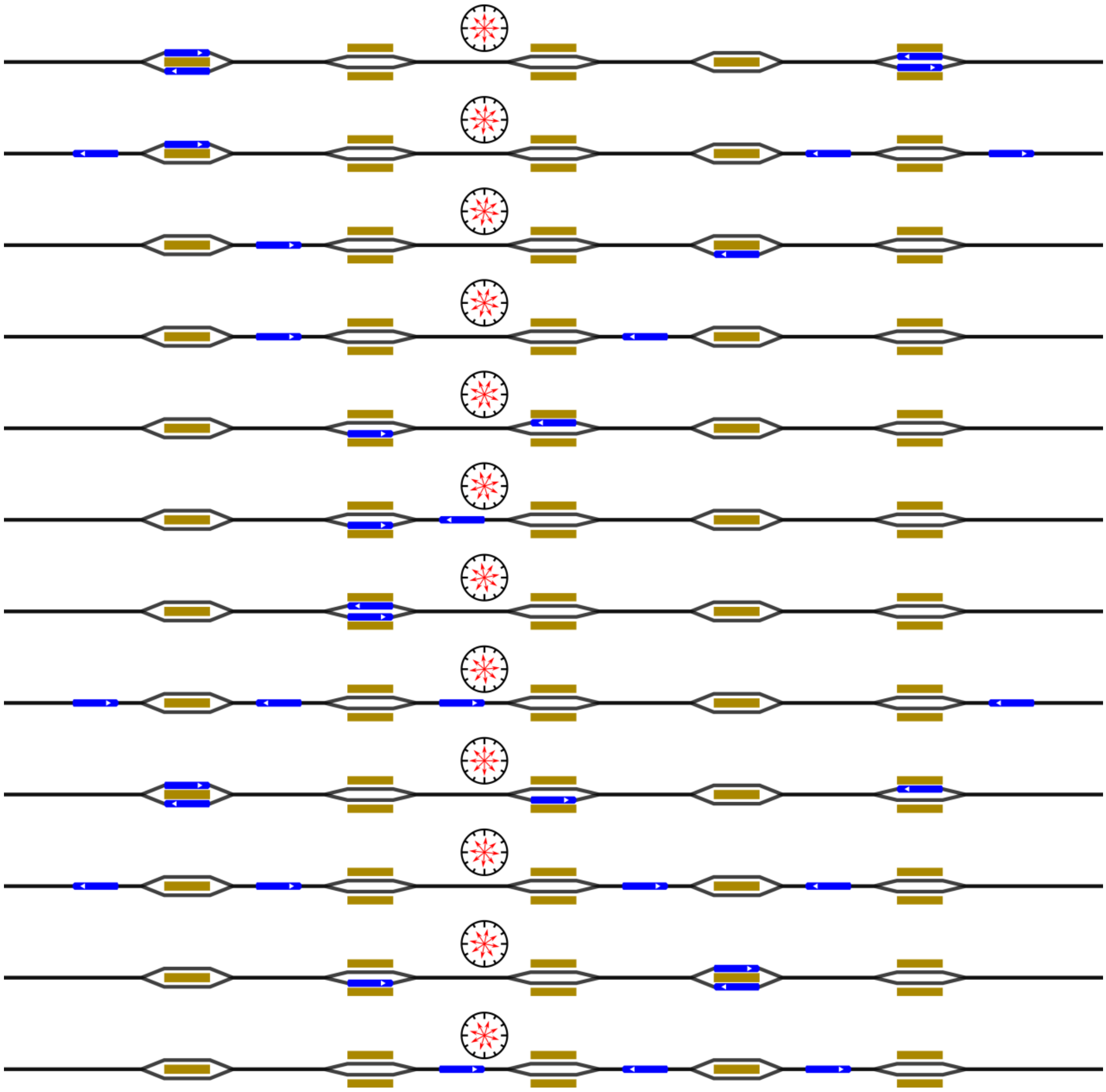


Figure 73: Single track operation with spare passing loops, presented using the example of a 7,5-minute interval: operation with significant delay of one train, using the spare passing loops instead of the regular ones (different rows show the same line at consecutive time steps).

2. Design of all stations and vehicles for quick coupling: If all passing loops are dimensioned for double train length and couplers as well as vehicle electronics are suitable for quick coupling, a delayed train can wait in a stop a whole interval and continue together with the next train.

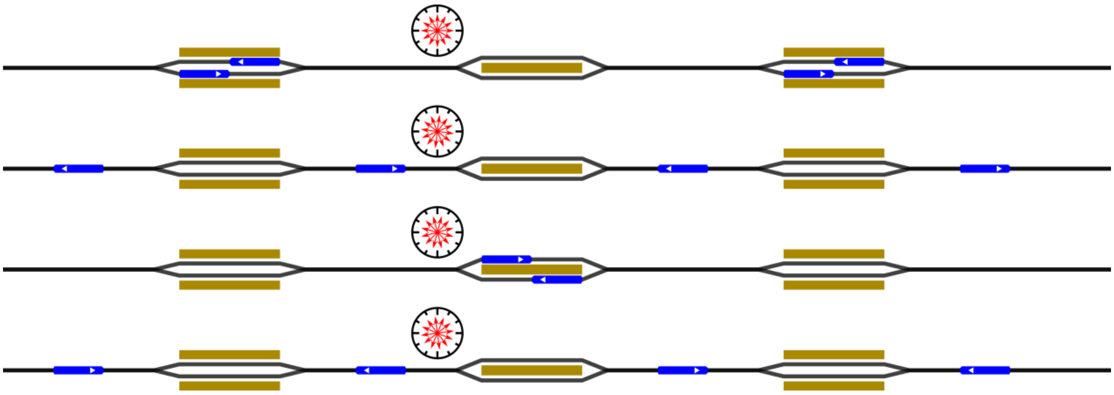


Figure 74: Design of all trains and stops for quick coupling, presented using the example of a 5-minute-interval: operation without delay (different rows show the same line at consecutive time steps).

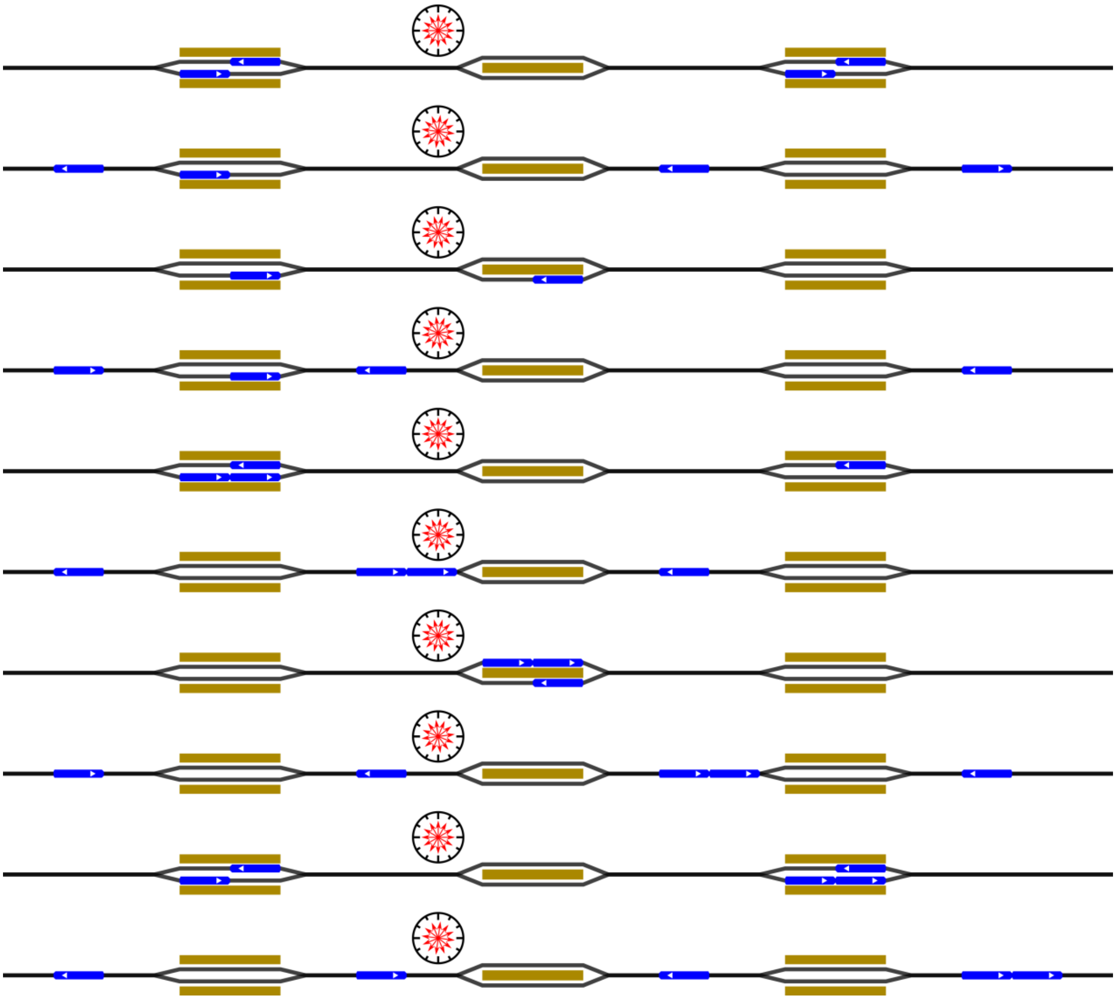


Figure 75: Design of all trains and stops for quick coupling, presented using the example of a 5-minute-interval: coupling of trains in response to a delay (different rows show the same line at consecutive time steps).

5.3.3 Feasible intervals and stop spacing

If every stop is used as a passing loop (with or without spare passing loops), the appropriate stop spacing is a result of interval and speed resp. other factors influencing travel time (see 2.2.3.1):

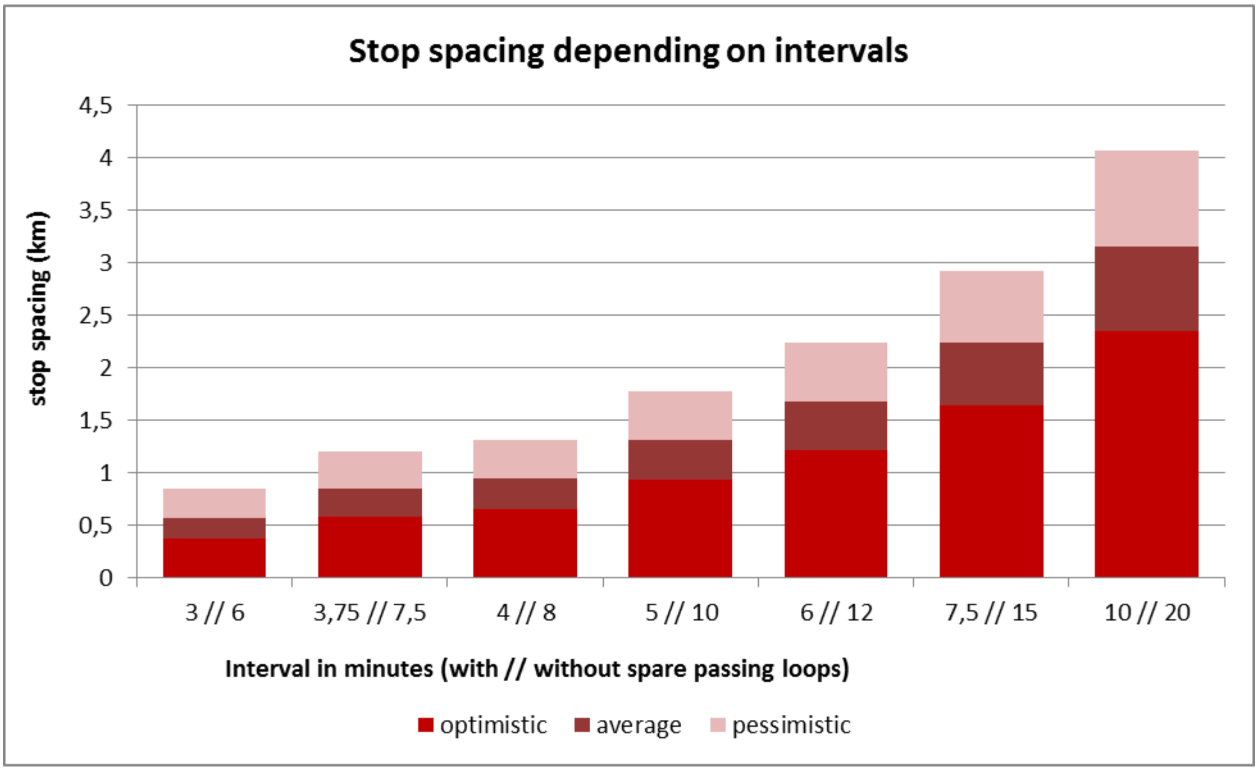


Figure 76: Stop spacing, depending on the interval and assumptions for travel time calculation:

Optimistic: 60 km/h top speed, 15s dwell time, no speed restrictions, 8% reserve time.

Pessimistic: 40 km/h top speed, 25s dwell time, one 15-km/h-speed restricted cross-section between two stops, 15% reserve time.

Average: Arithmetic average of all combinations of optimistic and pessimistic input variables.

The shortest intervals, resulting in a reasonable stop spacing for local urban transport are 3,75 minutes without and 7,5 minutes[o] with spare passing loops. Longer distances between stops, appropriate for suburban services, correspond to an interval of 7,5 or 10 minutes if delays are solved by coupling of trains resp. 15 to 20 minutes if timetable stability is ensured by spare passing loops. The mathematical relationship between travel speed, interval and stop spacing of course does not mean, that stops should be positioned only from the point of view of optimal conditions for single-track operation: If other locations promise more potential demand or a longer stop spacing is intended as corresponding to the planned intervals, this can be realized without problems using double-track sections. The stop spacing shown in Figure 76 rather represents the maximum length of a continuous single track section.

5.3.4 Detailed variants of the guidance system

Usually, passing loops of single-track railway or tram lines have switches on either ends, branching out one track (two rails) to two tracks (four rails) on one end resp. joining them again on the other end of the passing loop (Figure 77). Sometimes, trailable turnouts are applied for routine operation without human interaction.

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[o] As 1/8 resp. 1/16 hour, these intervals are particularly suitable for a timetable, harmonized with interurban public transport, operating as an integrated clock-face timetable.

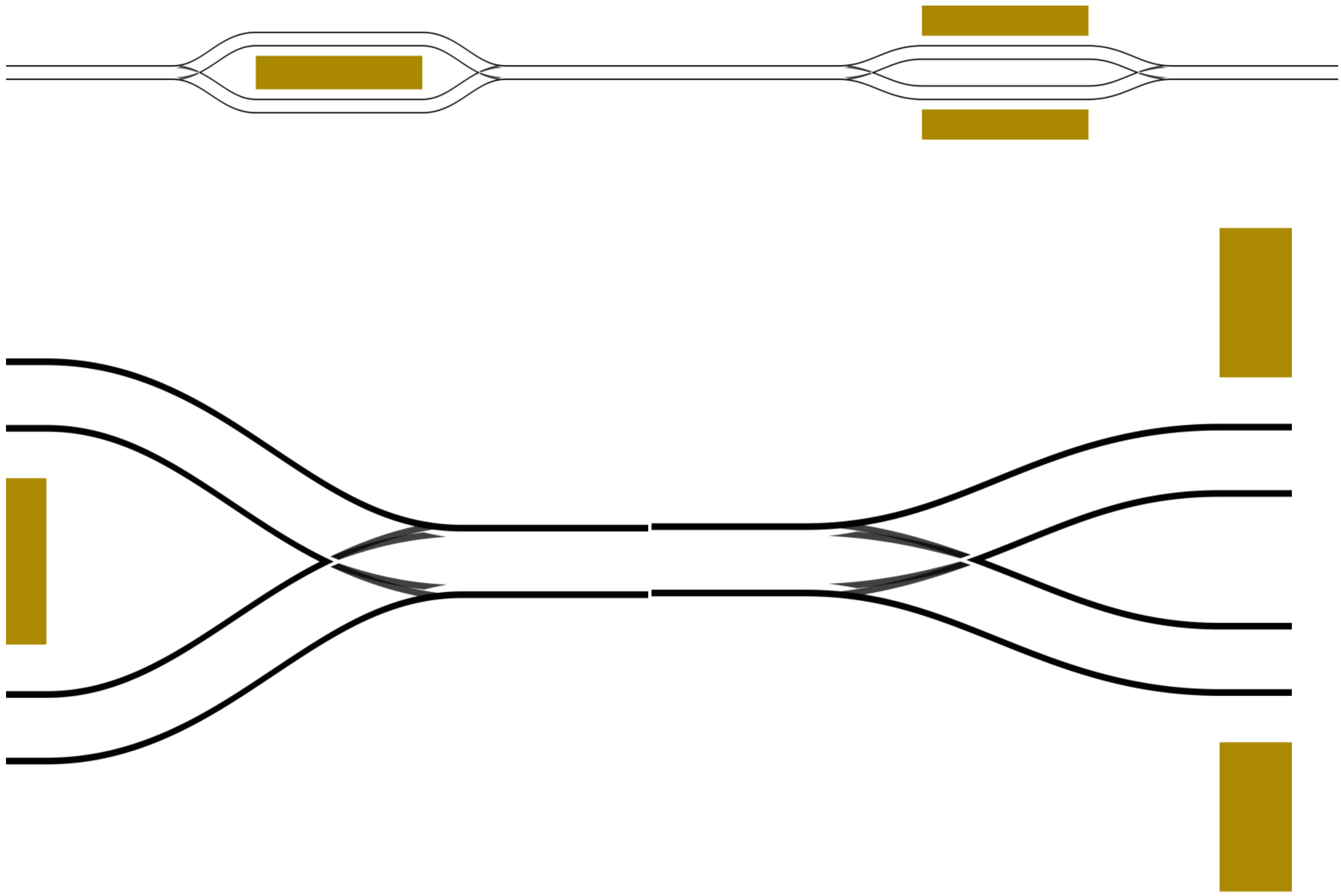

Figure 77: Single track railroad with conventional switches. Upper row: Overview with two passing loops (one with an island platform and one with side platforms); Lower row: detailed view of the switch area.

If the LCRT line is realized as a rubber-tyred tram (see 5.1) applying the unmodified Translohr system, at passing loops the single, central guidance rail splits up using switches too:

Figure 78: Single-track line for rubber-tyred vehicles with central guiding rail (Translohr System) with switches, Overview with two passing loops, one with an island platform and one with side platforms.

Very short single-track line sections resp. short distances between passing loops represent a high number of switches per line length (and thus per avoided rail length compared to a double-track line). In order to reduce effort for maintenance and control of the switches, a conceivable alternative to a classical single track line is a gauntlet track, as sometimes used in tram systems (Figure 79): In this case, trains of different directions run on different rails, but in contrary to a double-track railway, the rails of different directions are mounted close together, so trains of opposite directions cannot pass each other and the necessary width of the whole line is nearly the same of a conventional single-track line. This alternative leads to the double demand of rail length per single-track section length compared to a conventional single-track line, but each of these rails will last the double time because the train frequency per rail is only the half.

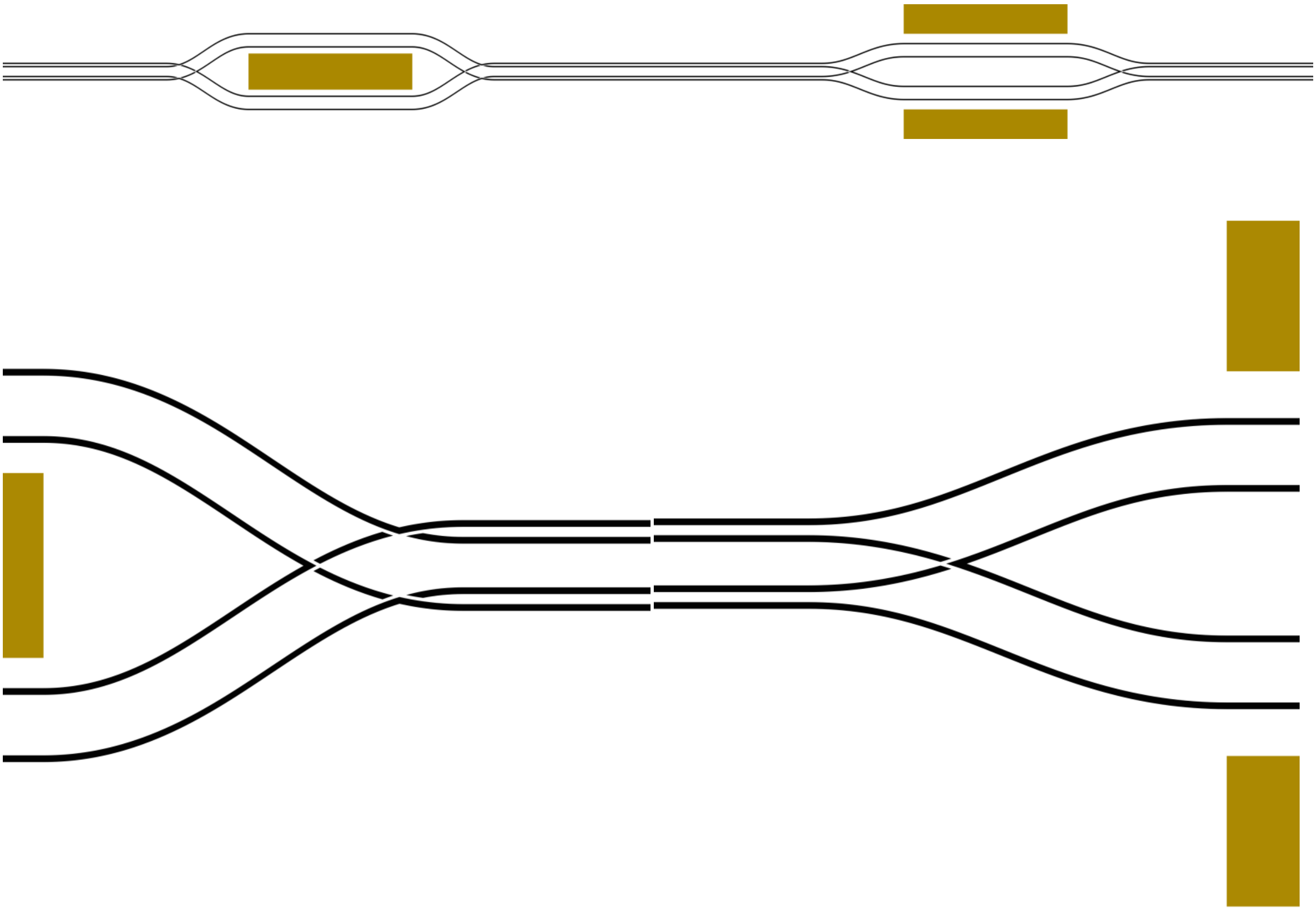

Figure 79: Gauntlet track in the Rail-wheel-version. Upper row: Overview with two passing loops (one with an island platform and one with side platforms); Lower row: detailed view of the ends of the gauntlet track section.

In order to avoid effort for switches with moving parts as well as unnecessary total rail length, an asymmetric guidance system similar to the Abt switch of funiculars could be used: Instead of one flange on either wheels (usually on their inner side), the wheels on one side of the vehicle (e.g. the right ones) are equipped with two flanges (inner and outer side of the wheel), whereas the wheels on the other side (e.g. the left ones) have no flanges at all. In this case, one of the rails guides the vehicles running in one direction, the other one those running in the other direction. The other rail does only support the vehicles weight, but it does not contribute to the guiding of the vehicle (Figure 80).

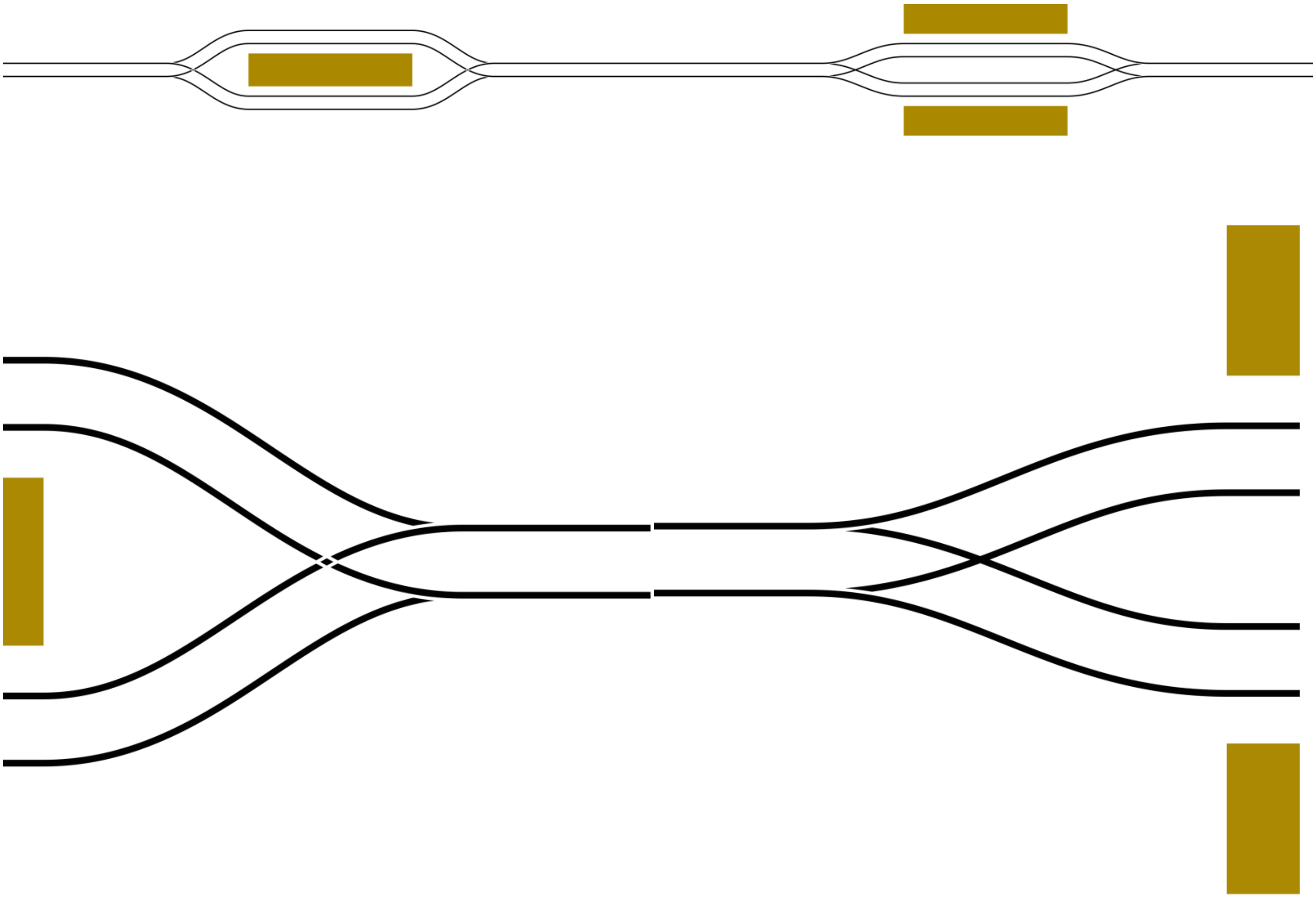

Figure 80: Track configuration for a single-track LCRT line with asymmetric guidance (wheel-rail system). Upper row: Overview with two passing loops (one with an island platform and one with side platforms); Lower row: detailed view of the ends of the single-track section.

In case of bidirectional vehicles, such a functional principle can be realized only with additional flanged wheels that can be lifted or lowered depending on the direction of movement (Figure 81). In case of unidirectional vehicles and turning loops, the wheels on one side of the vehicle (e.g. the right one in direction of movement) are permanently equipped with flanges and the wheels on the other side are not (Figure 82 & Figure 83). Such a solution could facilitate the running gear construction in that sense, that the wheels without flanges do not require as exact radial alignment as conventional flanged wheels and the spacing between the wheels does not need to be exactly the gauge width.

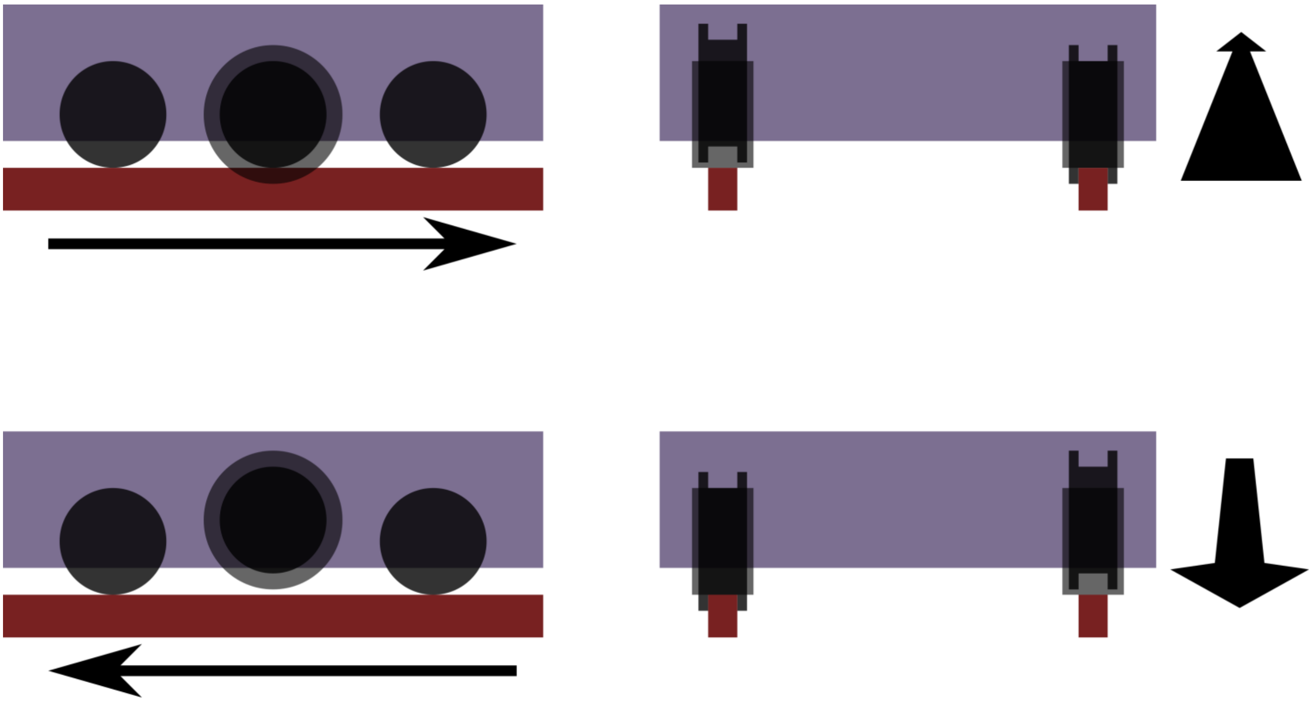

Figure 81: Schematic detail of the asymmetric guidance system in case of a bidirectional vehicle (lifting and lowering of the flanged wheels on one side of the vehicle)

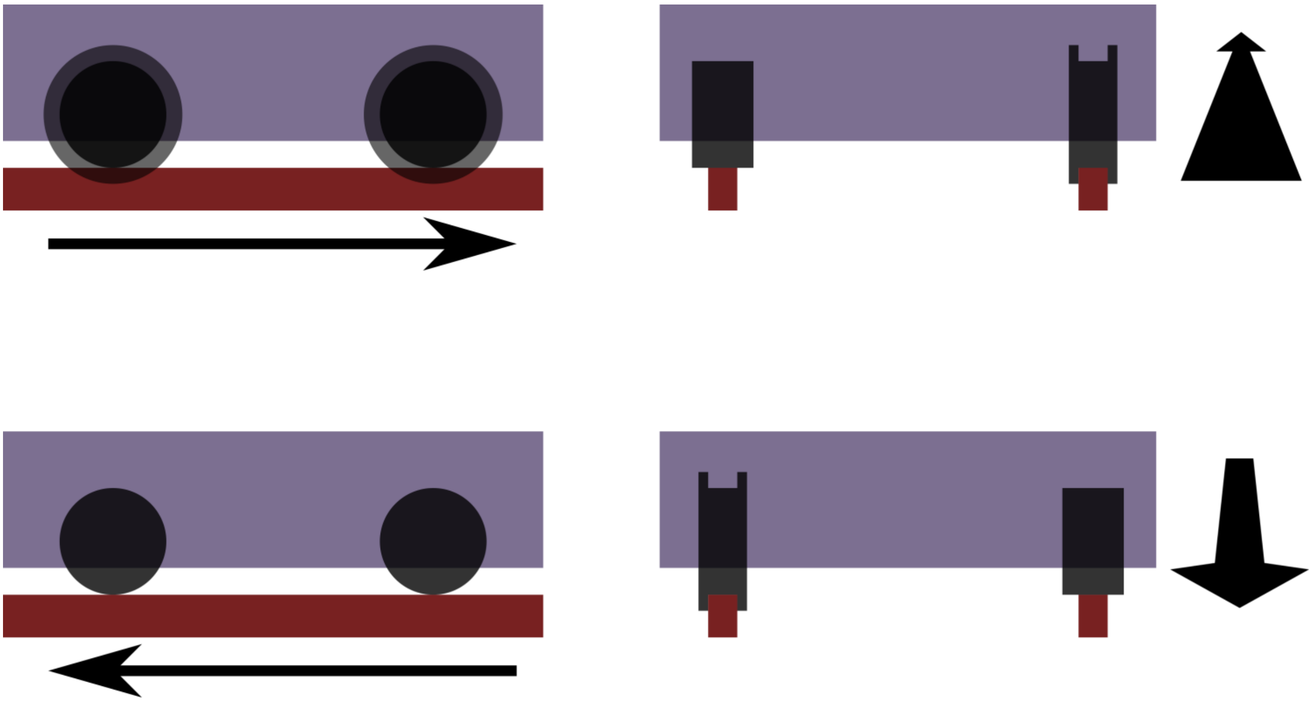

Figure 82: Schematical detail of the asymmetric guidance system on a unidirectional vehicle (flanged wheels permanently only on one side of the vehicle)

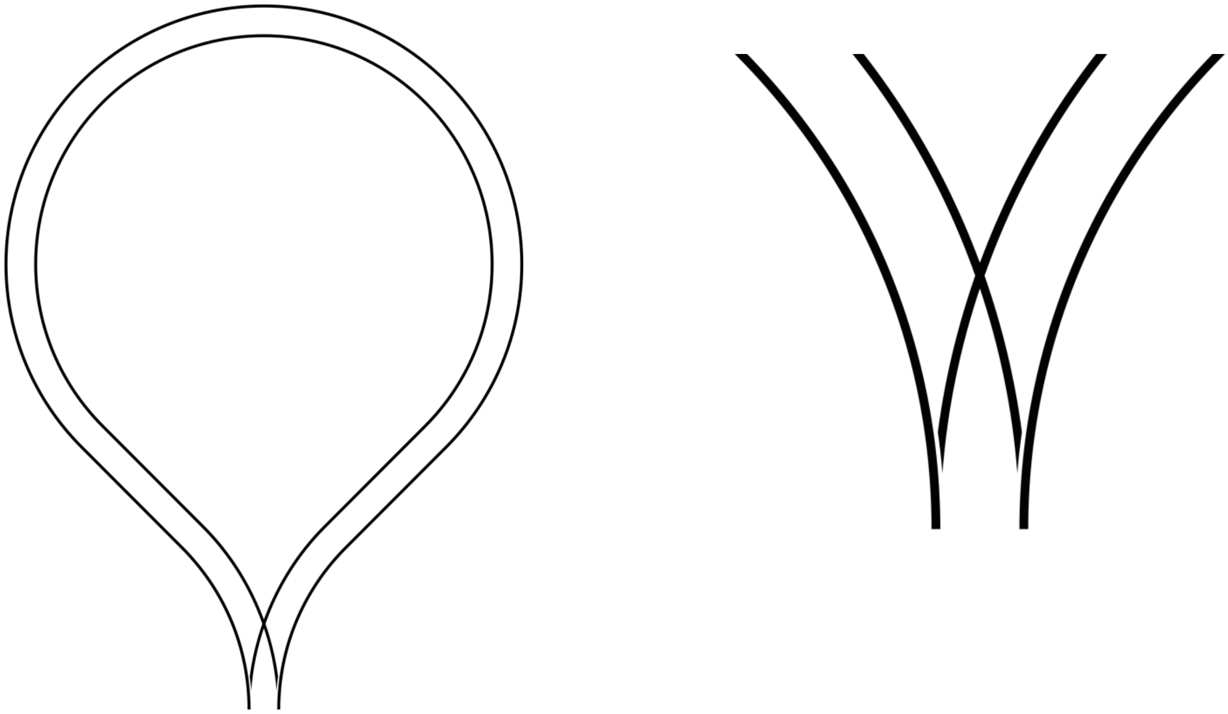

Figure 83: Turning loop for single-track operation with unidirectional vehicles and asymmetric guidance system (Wheel-rail system). Left: Overveiw, right: switch area in detail.

In case of the rubber tyre version with asymmetric guiding rail as described in 5.1.3, a mixed solution between gauntlet track and asymmetric flange position is applied: Within the single-track section, under each side of the vehicle there is a guiding rail running between the two pairs of tyres, but only one of them is really used for guiding the vehicle in the respective direction. Within the passing loop, there is only one guiding rail on each track, that responsible for guidance of the respective direction. In the area of the switch, rails are countersunk into the pavement, so the tyres can roll over the guiding rail for the opposite direction.

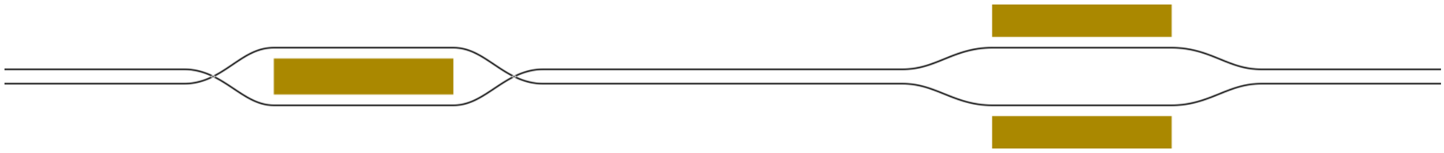

Figure 84: Single-track line for rubber-tyred vehicles with asymmetric guiding rail (modified Translohr system) with two passing loops, one with an island platform and one with side platforms.

Similary to the wheel-rail-version of the asymmetric guidance system, bidirectional vehicles require a more complicated construction with retractable guiding wheels (Figure 85) than unidirectional vehicles turning at turning loops (Figure 86 & Figure 87).

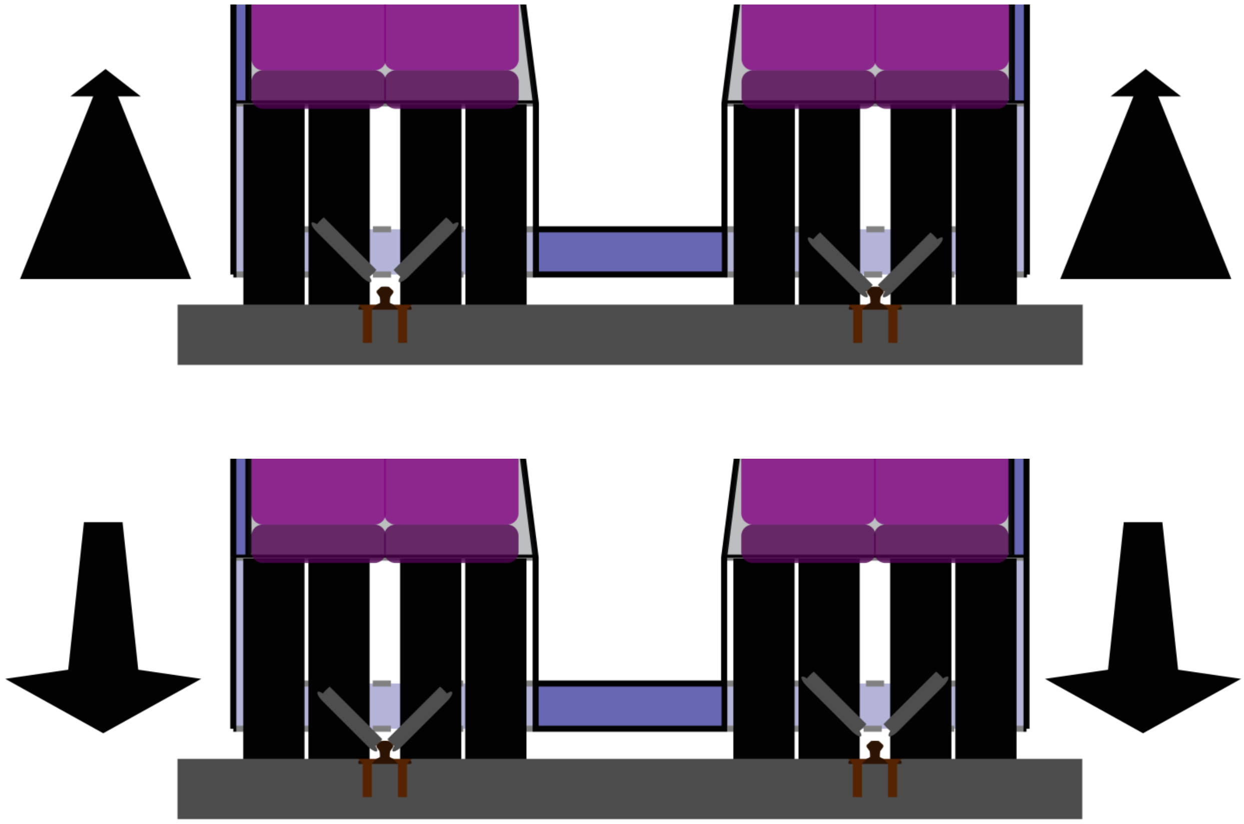

Figure 85: Schematic details of asymmetric guidance system in case of a bidirectional, rubber-tyred vehicle (lifting and lowering of guiding wheels on one side of the vehicle)

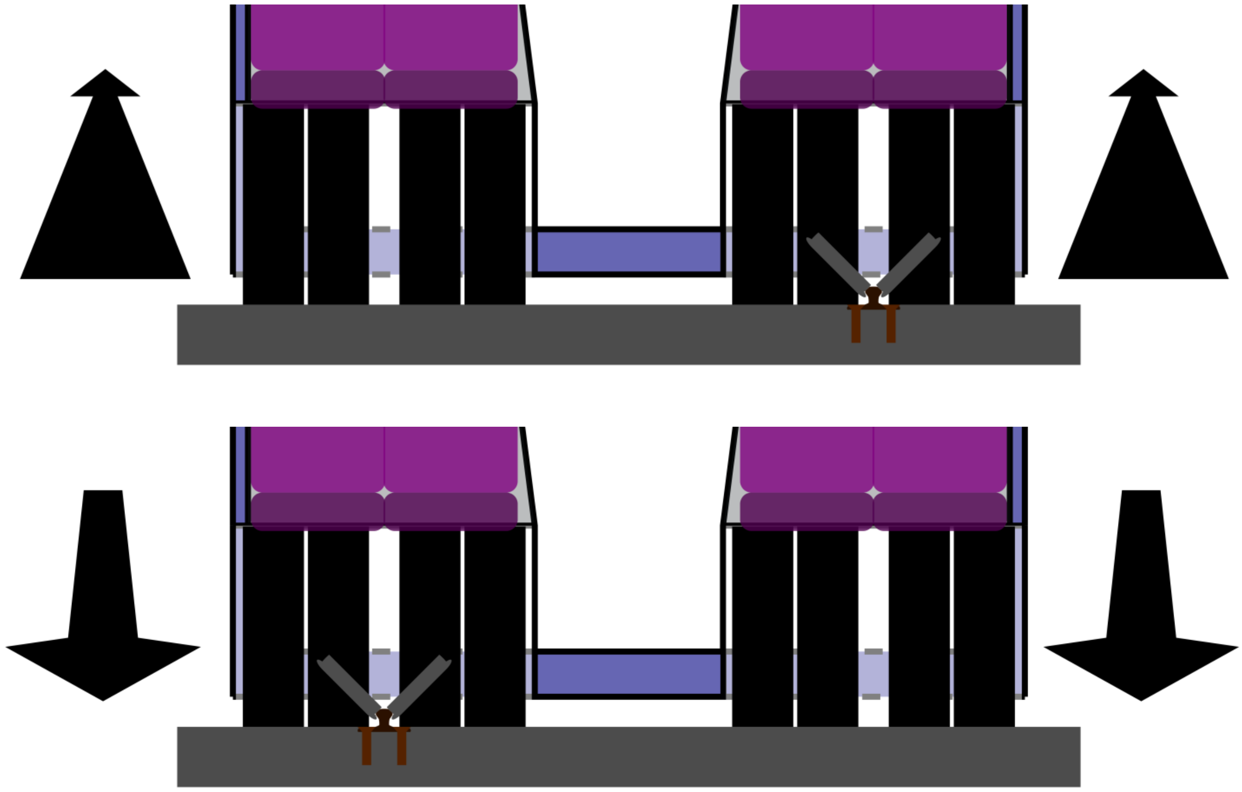

Figure 86: Schematic details of asymmetric guidance system in case of a unidirectional, rubber-tyred vehicle (guiding wheels permanently mounted on one vehicle side only)

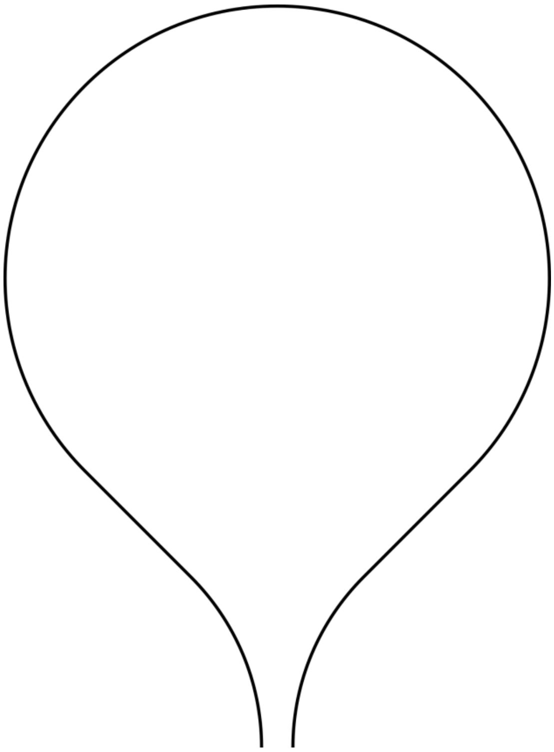

Figure 87: Turning loop for single-track operation with unidirectional rubber-tyred vehicles and asymmetric guiding system

5.4. Interchange station arrangement

As soon as there is more than one LCRT line in a city, the question of optimally designed interchange stations arises. When planning interchange stations, the following aims are to be considered:

1. Avoidance of capacity loss or operational instability caused by unfavourably positioned level-crossings between lines
2. Short and convenient walking distances between the platforms of the individual lines (e.g. no need to cross lanes or tracks)
3. Low construction costs, particularly through avoiding of underground station buidlings

Transfer stations of similar design like conventional subway junctions would perfectly fulfil the first aim (completely level-free), the second to some extent (convenient, but often long walking distances) but the third not at all. In opposite, a level-free crossroad with tram tracks and adjacent platforms would fulfil the third aim optimally, but not the first and the second. Therefore, the following solutions were drafted specifically for LCRT:

5.4.1 Rectangular crossing with interrupted platforms

In this case, tracks of two lines are crossing at-grade approximately at right angles. The platforms are positioned around the track crossing in such way, that one half of every platform is in front and the other half is beyond the two crossing tracks, in between the platform is interrupted by the crossing tracks. The result are four L-shaped platform-fragments (in Figure 88 (left) drawn in grey color with yellow safety lines). According to the LCRT principle of short underpasses, the whole station is situated below the driving lanes. Staircases are positioned at the platform corners, ramps at the platform ends serve as barrier-free access (Arrangement of the interchange station and the driving lanes see Figure 88 (right)).

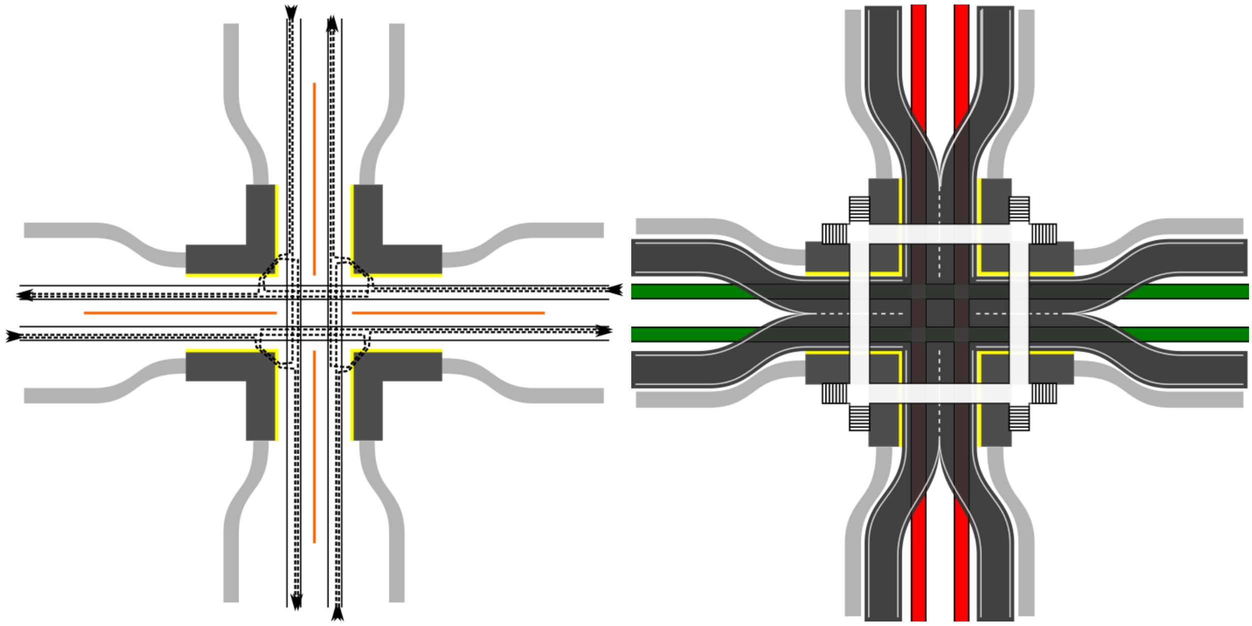

Figure 88: Rectangular crossing with interrupted platforms. Left: track level with pathways of interchanging passengers (dotted lines); Right: Arrangement of track and driving lanes level

The functional principle of such an interchange station requires a compatible arrangement of the vehicle's doors: In the middle of the vehicle, over a length of more than the width of a double track, there must be a section without doors. Thus, the doors of the front and the rear half of the vehicle lead to different halves of the platform (see Figure 88). Depending on which direction the passenger wants to change to, he/she uses one of the front doors or one of the rear doors and makes use of a very short interchange walk. (Overview of possible interchange relationships see Figure 88 (left)). Unexperienced passengers who leave the vehicle through a wrong door have to take the roundabout via street level, between the tracks there are fences or partition walls in order to prevent passengers from crossing the track (in figures painted orange).

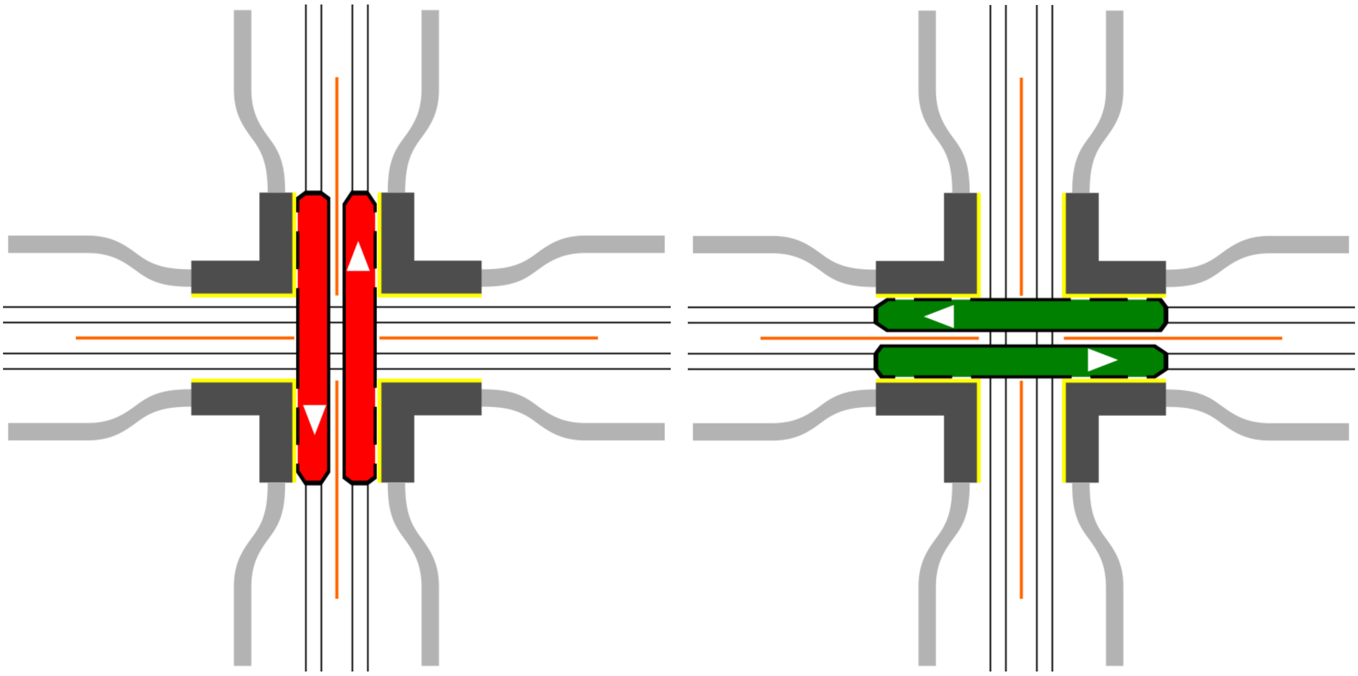

Figure 89: Stopping positions of the LCRT vehicles in an interchange station with interrupted platforms.

In order to reduce the risk of delays, caused by two trains of different directions reaching the interchange station at the same time, trains of the same line meet exactly in the station and following the timetable, the times when trains of one line meet are exactly between the times, when trains of the other line meet. Thus, the time for changing is exactly half of the interval, e.g. 2,5 minutes in case of a 5-minute interval (Figure 90).

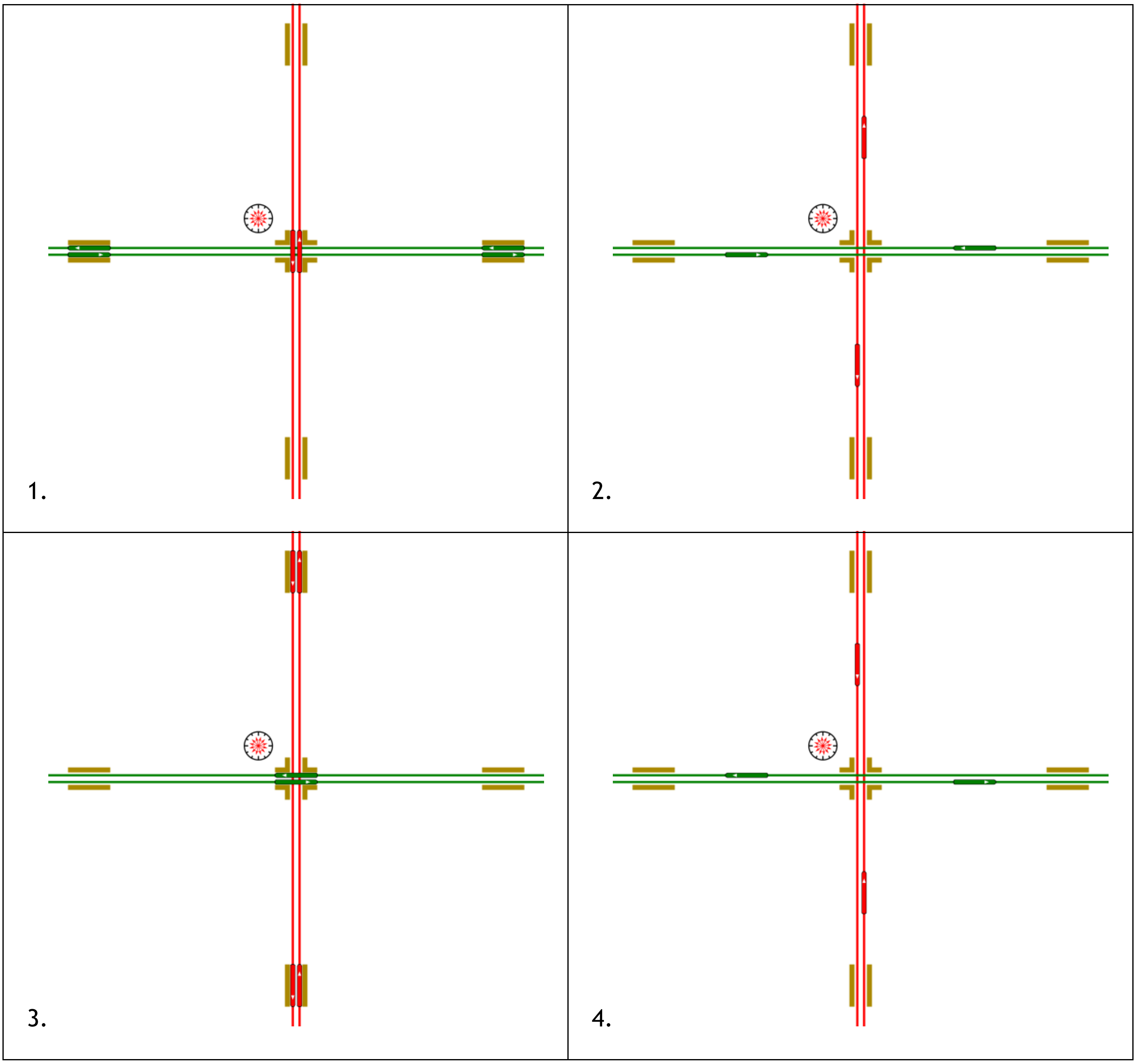

Figure 90: Time sequence of stops at a rectangular interchange station with interrupted platforms.

5.4.2 Four-track station with one island platform

A junction station of two lines can be realized with low space demand and short walkways by concentrating all interchanges onto a single island platform: Near the station, the two lines are bundled as four parallel tracks. The platform of the station is slightly longer than the double vehicle length and in the middle of the platform's length there is a crossing of the inner and the outer tracks. Thus, vehicles of one line stop always at the front half of the platform, vehicles of the other line stop at the rear half of the platform. Passengers who do not use the station for changing between lines, but start or end their journey there, reach and leave the island platform via a pedestrian overpass, equipped with elevators for barrier-free access. In contrary to the rectangular interchange station with interrupted platforms, the four-track station with one island platform forms a simultaneous hub: According to the timetable, trains of both directions and both lines arrive at the same time, stay a sufficient dwell time for interchange walkways and depart then again simultaneously (Figure 91).

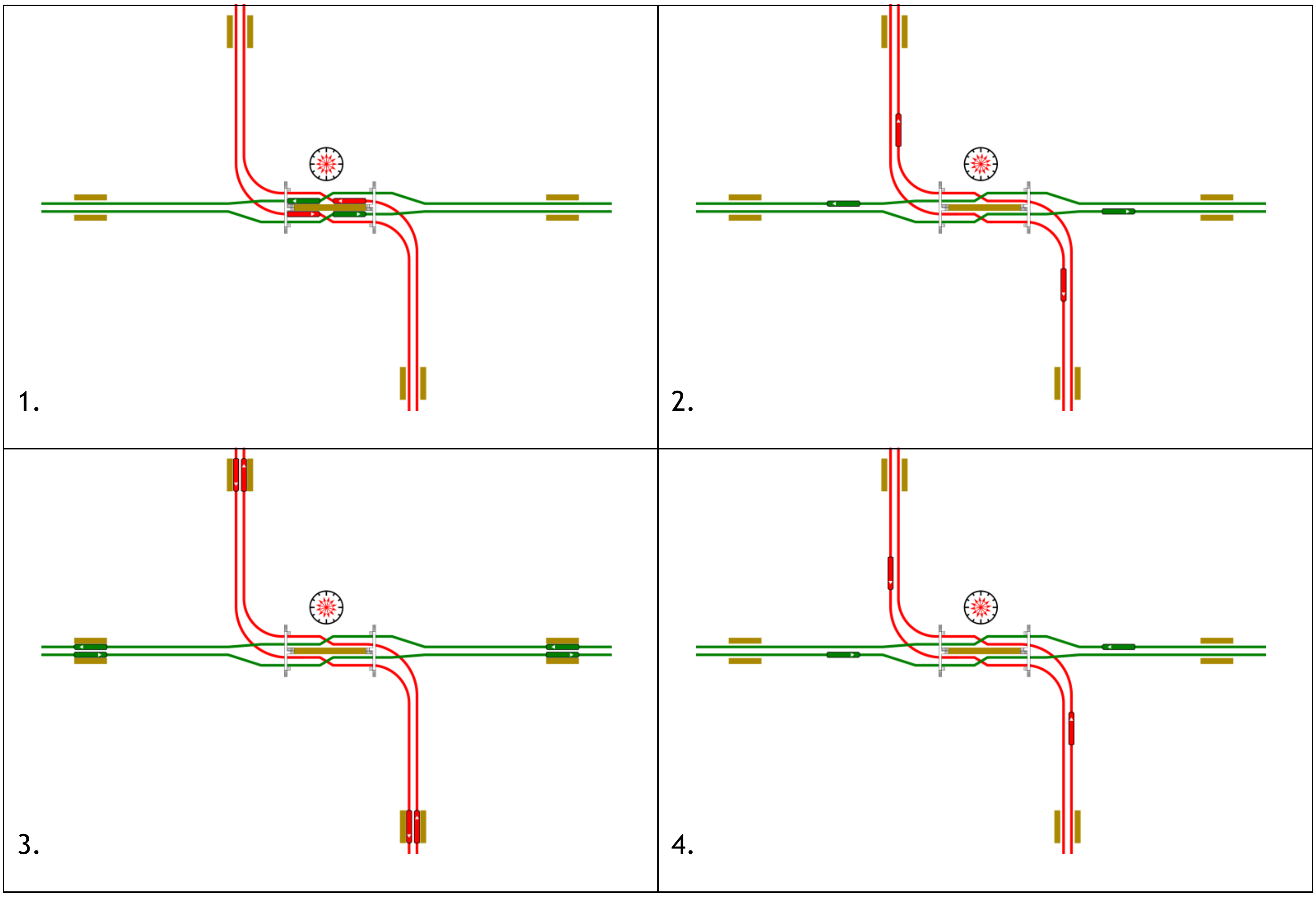

Figure 91: Time sequence of movements at a four-track station with one island platform

There are in total five differend sub-versions depending on the following circumstances:

- Vehicles with doors on both sides or only on one side (right side in case of classical unidirectional vehicles in right-hand traffic)
- Double-track or single-track operation on adjacent line sections
- Space available for level-free crossings between the branch tracks

All these sub-version, displayed in in Figure 92 until Figure 96 have in common, that they don't do completely without level-crossings between tracks (2 to 8 depending on the sub-version). Nevertheless, the time sequence of the stops at the interchange station in all sub-versions can be divided into an entry phase until the last arrival and then an exit phase from the first departure, whereas vehicle movements of the entry phase cross only vehicle movements of the exit phase and vice versa. If a train control system ensures, that no train departs while another one arrives, arrivals as well as departures can take place without mutual obstruction or speed reductions caused by the crossing process.

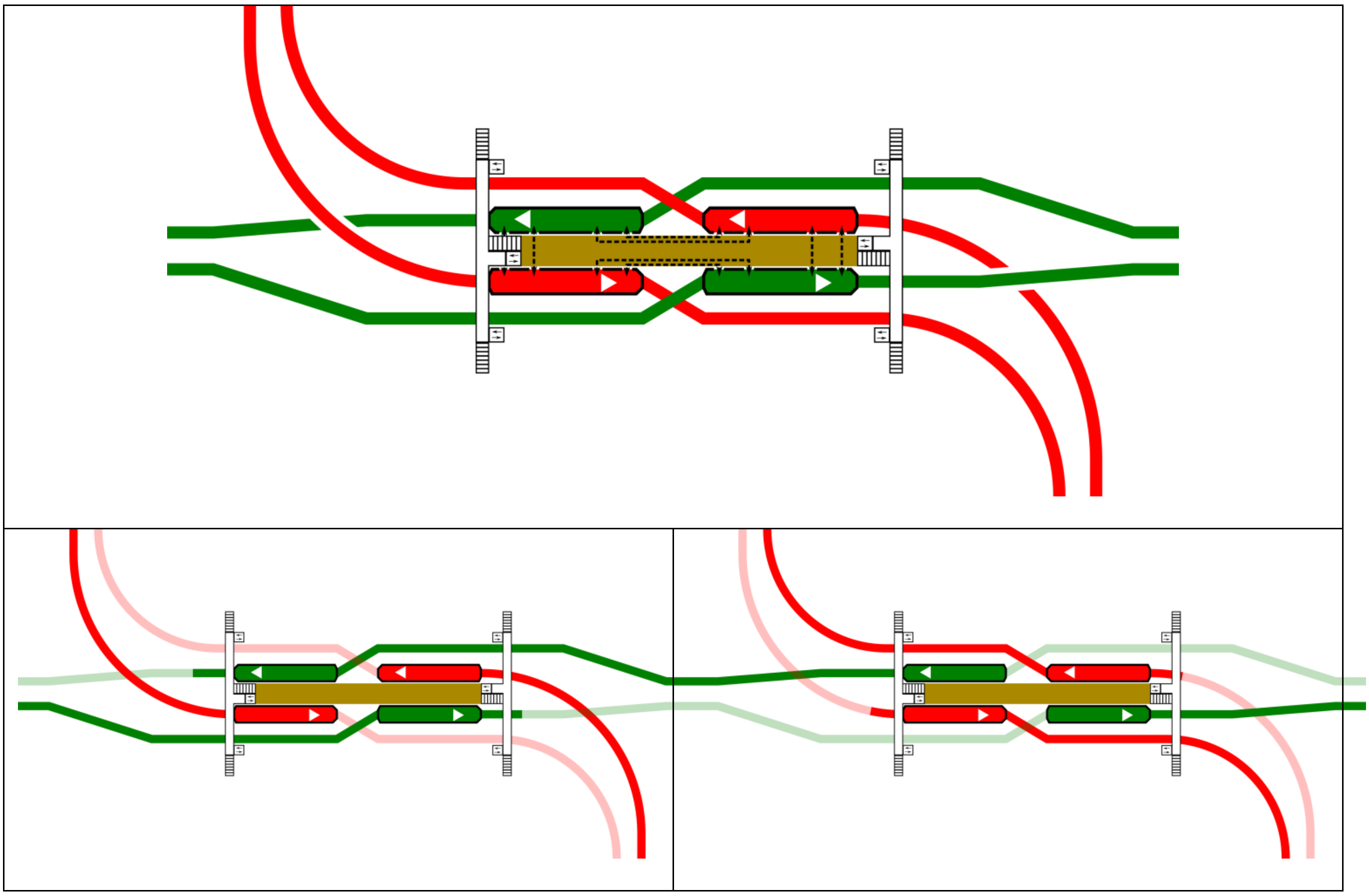

Figure 92: Interchange station with four tracks and one island platform, sub-version with double-track lines, doors on both sides of the vehicles and only two level track crossings.

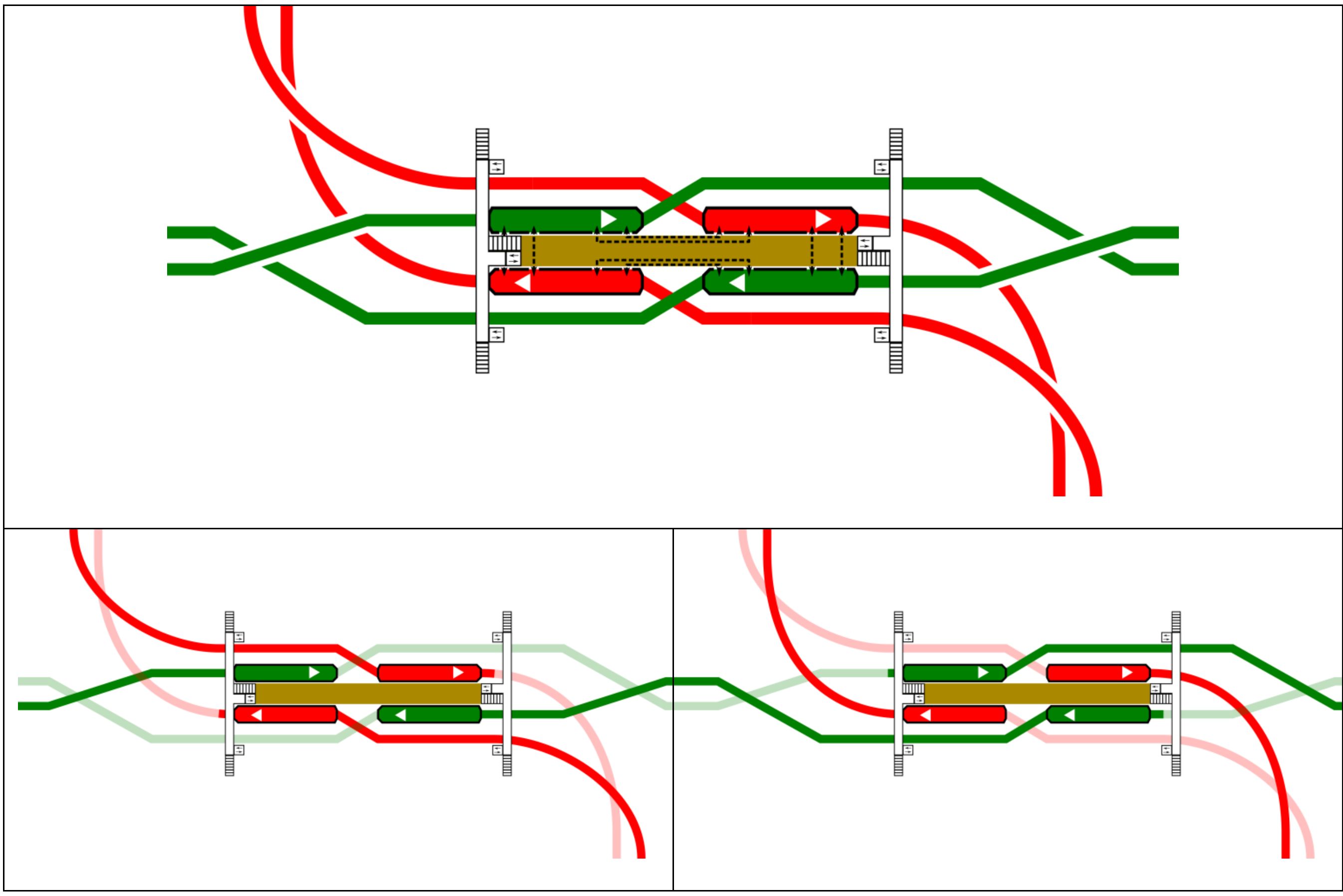

Figure 93: Interchange station with four tracks and one island platform, sub-version with double-track lines, doors only on one side of the vehicles and only two level track crossings.

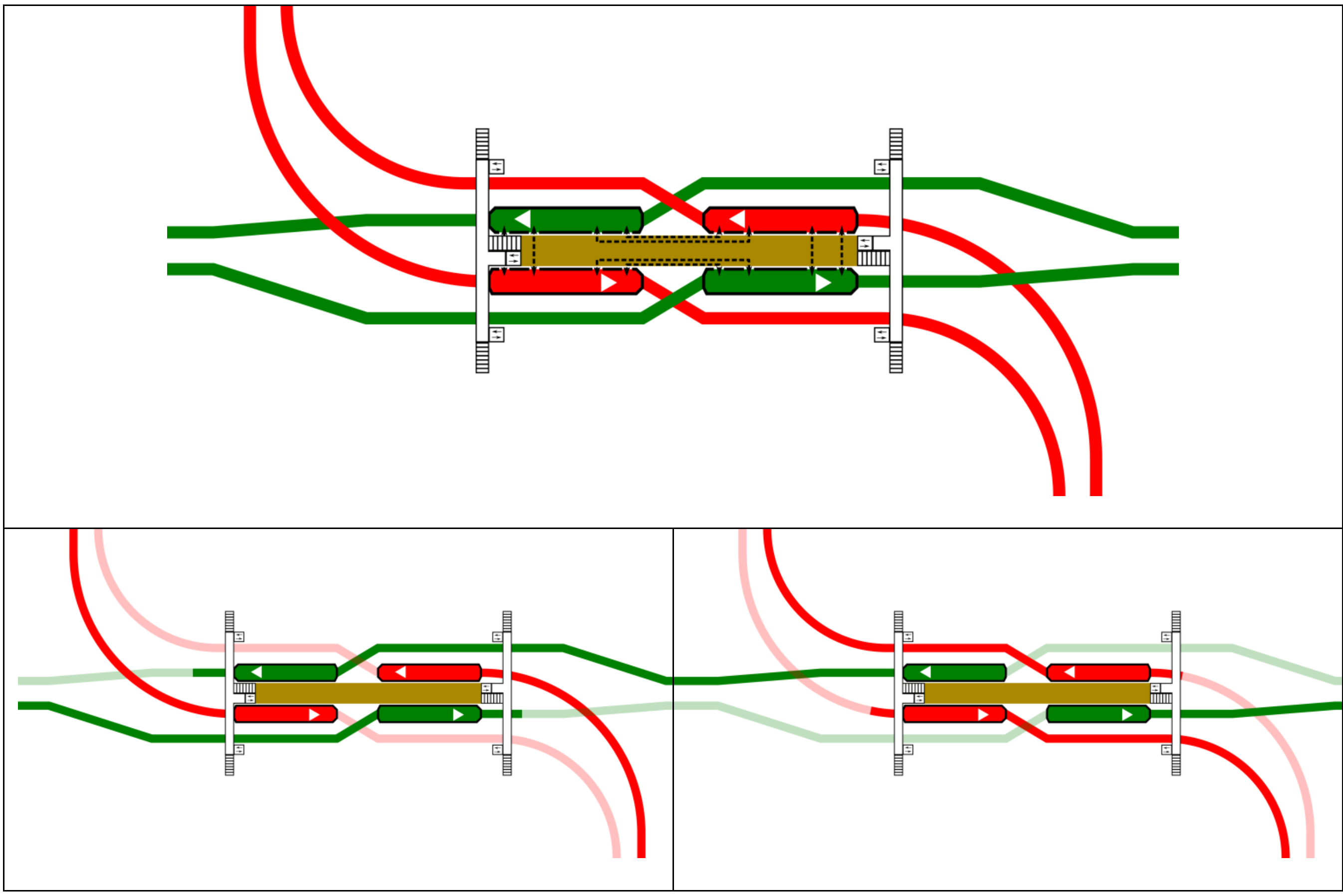

Figure 94: Interchange station with four tracks and one island platform, sub-version with double-track lines, doors on both sides of the vehicles and several level track crossings.

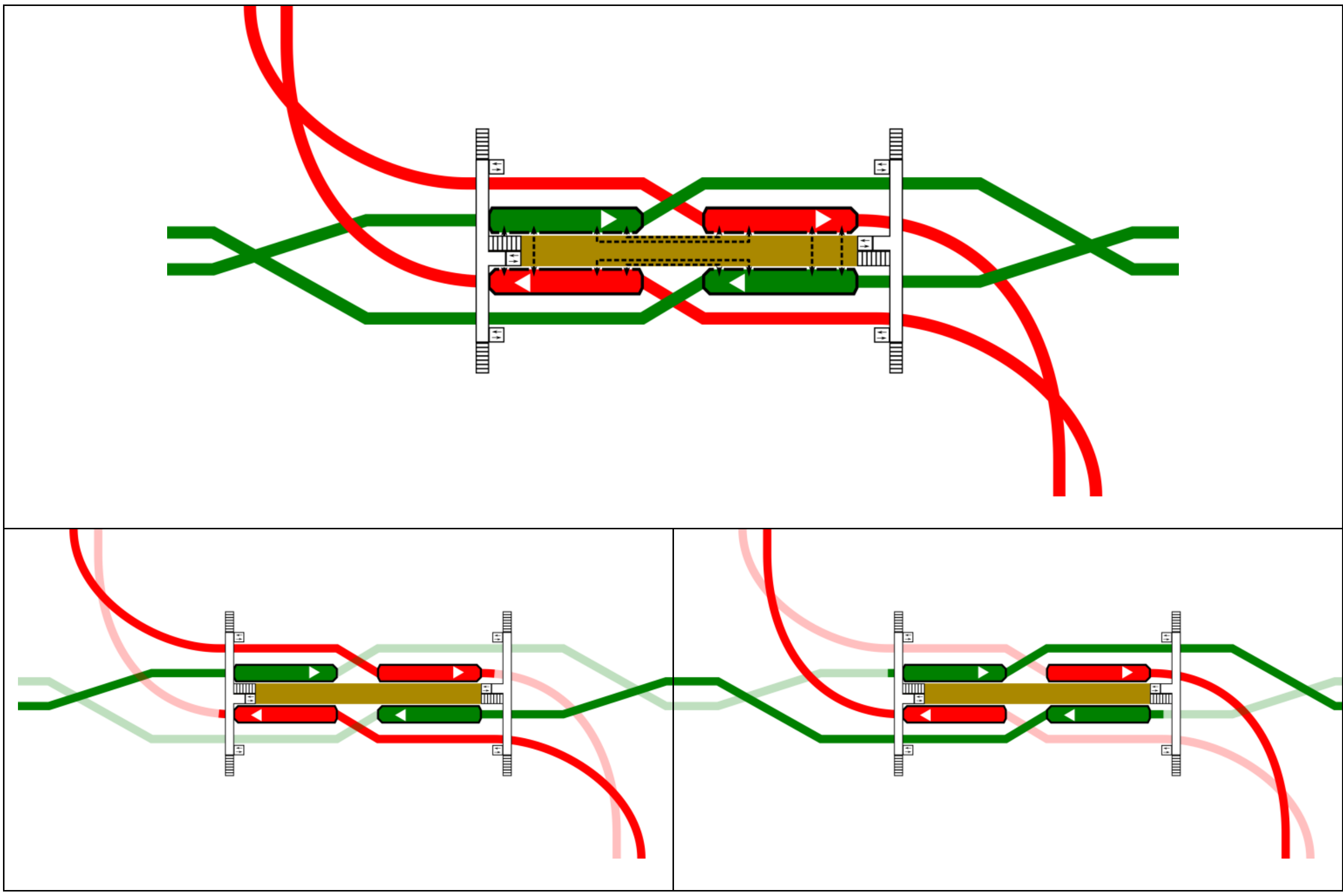

Figure 95: Interchange station with four tracks and one island platform, sub-version with double-track lines, doors only on one side of the vehicles and several level track crossings.

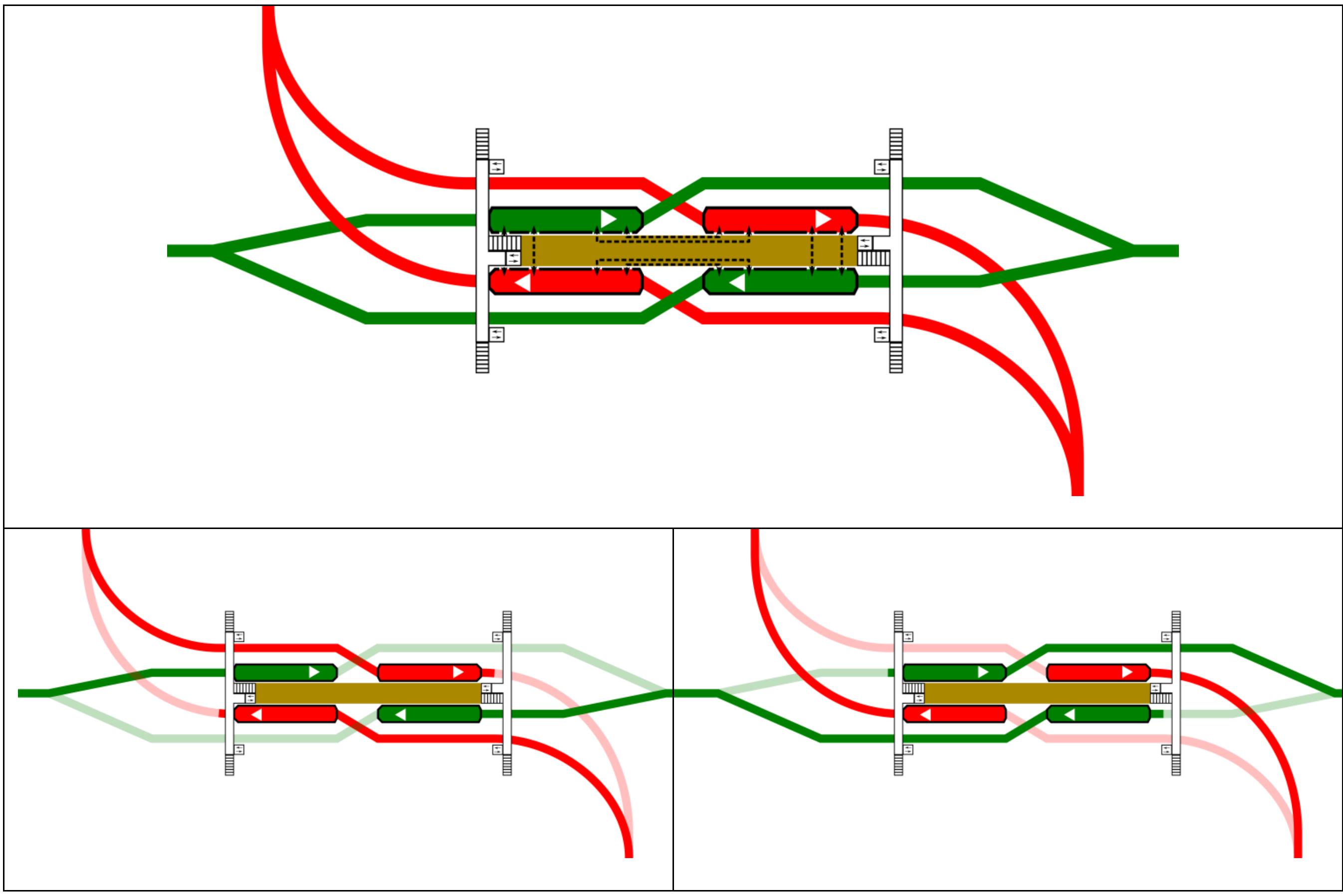

Figure 96: Interchange station with four tracks and one island platform, sub-version with single-track lines.

When all trains run on schedule, all mentioned sub-versions can be operated equally and the effort for level-free crossings between various tracks seems not to be justified. Anyway, in case of schedule deviations, any simplification of the track topology can be useful: If a vehicle is delayed to that extent, that it is not justified any more to let the other vehicles wait for interchanging passengers, the delayed vehicle has to stop and wait for all departures crossing its track before entering the station. In case of the sub-versions with only two level track crossings, only the departure of one line is dependent on the previous arrival of another one, the other vehicle does not cross any other line after departure. When applying the sub-version with eight level track crossings, every departing vehicle crosses the tracks of arriving vehicles of both other lines.

5.4.3 Completely level-free variant with four parallel tracks

An interchange station combining completely level-free operation with short walking distances can be created, if tracks in the station area are not totally horizontally, but inversely inclined, so at one end of the platforms, all tracks are on the same level but on the other end of the platforms, there is a height difference corresponding to the clearance height. With a clearance height of 2,8 meters applied (including the thickness of the supporting structure) and a platform length of 50m, this means an incline of 2,8% in the platform area, not unusual for roads and tram tracks. In order to facilitate quick at-level interchange, this variant requires doors on both sides of the vehicle, because on the two central tracks there are platforms on both sides of the vehicle ("spanish solution"). Such an interchange station can also form a simultaneous hub for changing between four vehicles stopping at the same time, but this is not necessary for unbundling arrivals and departures on tracks, crossing each other. This means less risk, that delays on one line cause further delays on other lines or the opposite direction and in peak hours, when the system is operated in very short intervals, there is no need to prolong the dwell time in the interchange station in order to wait for changing passengers.

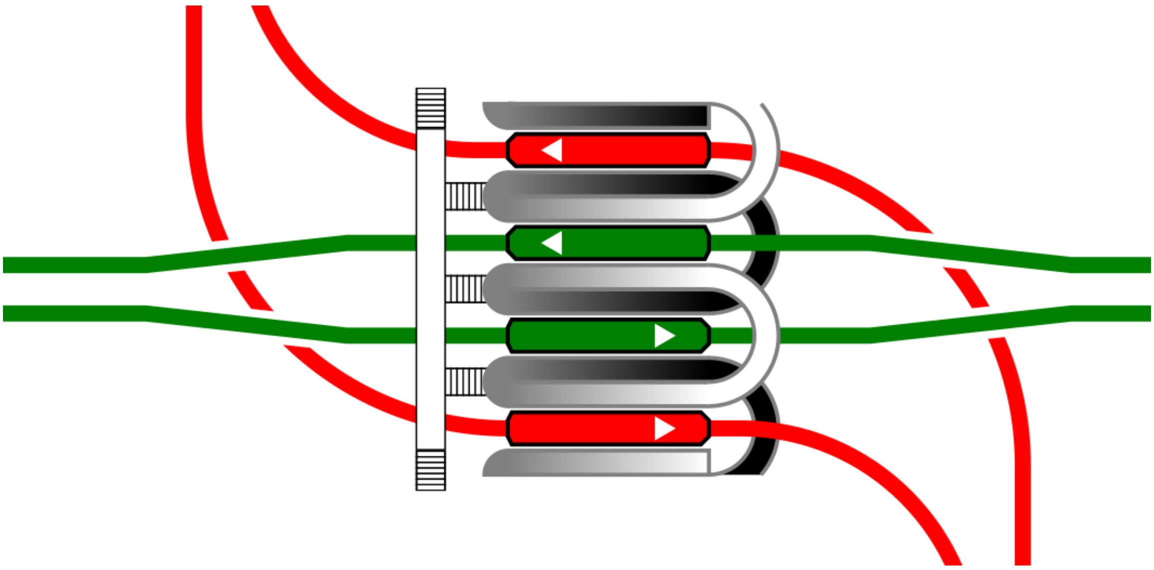

Figure 97: Completely level free interchange station with four parallel, inclined tracks and platforms on both sides of the vehicle

5.4.4 Interchange stations with overlapping lines

Concerning track topology, the easiest type of interchange station results from two lines, partly operating on the same tracks. Unfortunately, this reduces the maximum capacity of each line by the half, so this solution is suitable only for applications with a capacity demand significantly below usual metro capacity, similar to the single-track variants described in chapter 5.2. In order to achieve additional capacity resp. timetable stability, this variant is proposed only with level-free track crossings at the adjacent junctions:

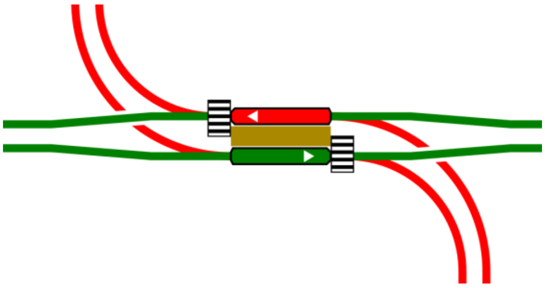

Figure 98: Junction station with overlapping lines

The shortest average interchange waiting times are achieved, if in the respective station meet the vehicles of different lines, moving in different directions: Passengers can change to one direction of the other line immediately, to the other direction of the other line after waiting a half interval:

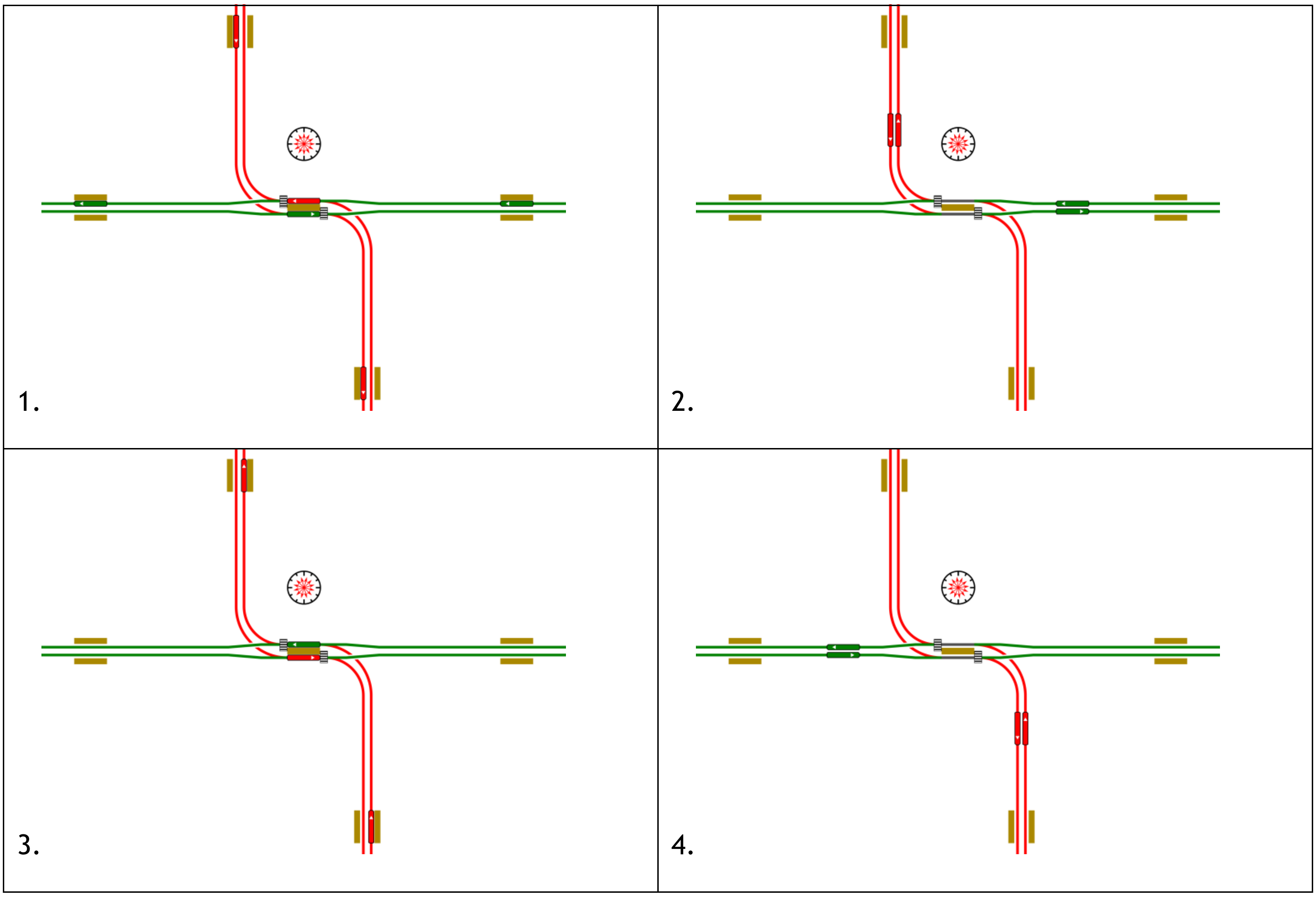

Figure 99: Time sequence of movements at a double-track interchange station with an island platform (overlapping lines)

[1] International Tunneling Organization: Underground or aboveground? Making the choice for urban mass transit Systems - A report by the International Tunnelling Association (ITA) Prepared by Working Group Number 13 (WG13) 'Direct and indirect advantages of underground structures': https://www.ita-aites.org/media/k2/attachments/public/Tust_Vol_19_1_3-28.pdf; 6.2.2017

[2] Example: Harald Buschbacher: Effizienzsteigerung im Eisenbahnverkehr: Geringere Kosten für Verdichtung und Qualitätssteigerung im Regional- und Vorortverkehr Südmährens, S.291: http://buschbacher.at/dissertation.pdf;

[3] Example: Stadler KISS, Version S-Bahn SBB: http://stadlerrail.com/media/uploads/KISS_DOSBBZ0708d.pdf; 19.02.2016

[4] Example: Berliner Verkehrsseiten: DL 04 (MAN Lion`s City DD): http://www.berliner-verkehrsseiten.de/bus/Fahrzeuge/Typen/DN04/body_dn04.html; 30.05.2015
[5] Straßenbahnverordnung (StrabVO), § 34 (5): https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20000465; 15.01.2017
[6] Example Calculation: CAF Urbos 3 for Budapest with 600 V nominal Voltage,12 x 70 kW nominal power and 67 t of weight: Varga Károly: Az új „Budafoki villamosvasúti kocsiszín": http://epa.oszk.hu/03000/03006/00004/pdf/EPA03006_ktsz_2016_4_71-74.pdf; 2.6.2019
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