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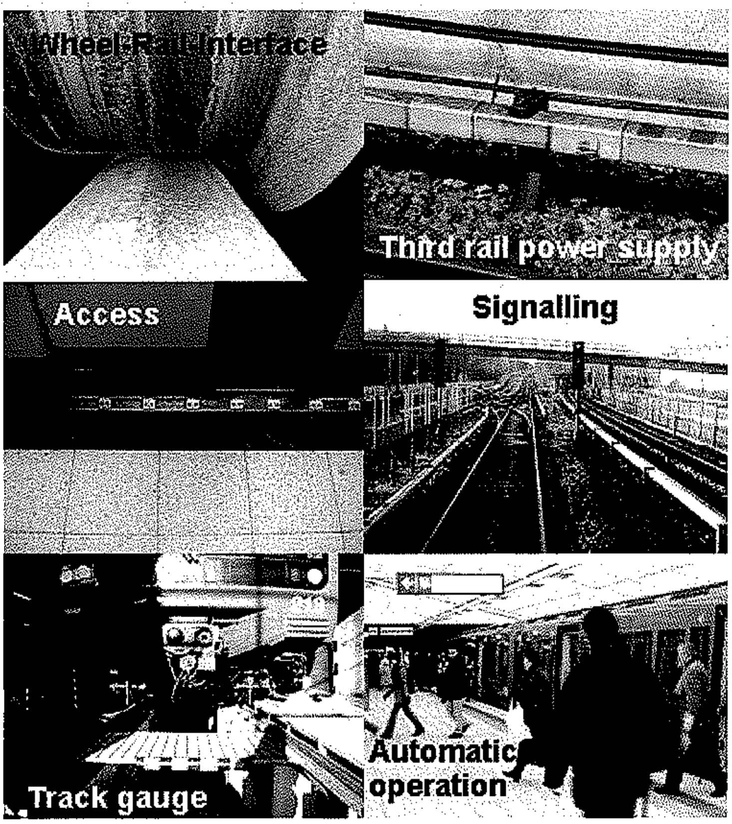
Final report

Metro + light rail integration Technical case study for Helsinki / Espoo



Karlsruhe, February 2004

TransportTechnologie-
Consult Karlsruhe GmbH

Final report

Metro + light rail integration Technical case study for Helsinki / Espoo

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City planning departments

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Karlsruhe, February 2004

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TransportTechnologie-
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TransportTechnologie-Consult Karlsruhe (TTK) GmbH has therefore been asked to carry out a technical case study of the feasibility on the basis of the scenario 3 (agreed at the kick-off-meeting in Helsinki at the 14.11.2003) of such a joint operations scheme to the City Planning Department of the City of Espoo and Helsinki.

At this kick-off-meeting it was agreed, to base the study on two vehicle concepts: High-floor and low floor. It is (even without a detailed study) obvious that both concepts have advantages and disadvantages and therefore a principle evaluation of both concepts will provide the main requested answers to the client.

- The advantage of a high floor concept is a better integration into the existing metro environment without extensive adaptations of the metro infrastructure. In addition to this aspect high floor LRVs are easier to maintain resulting finally in lower LCC. The disadvantage is the need for higher platforms on the Jokeri line leading to visual intrusion and slightly higher investment costs for the stops on the surface.
- The advantage of a low floor concept is for sure the better integration and the easier access on the Jokeri surface line. But when entering the metro section low floor LRVs will create more problems due to the high platforms in the stations or the mixed traffic with metros, e.g. buffer load.

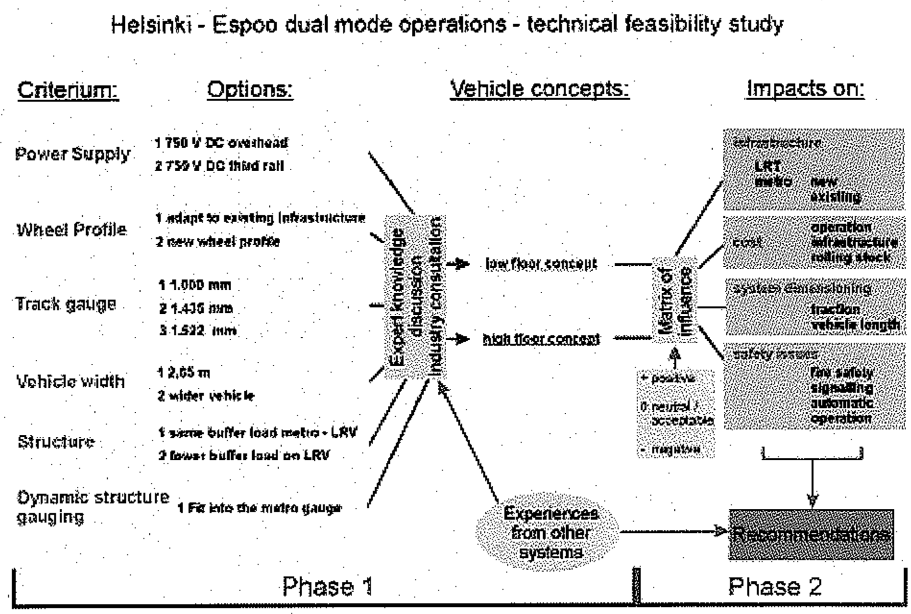
At the end this study will clarify two mains issues. If the joint operation metro / light rail should be realised,

- what vehicle concept is technically the best (phase 1) and
- what are the additional costs to be expected (phase 2).

1.2 Specific approach

After a preliminary discussion between TTK and the customer (cities of Espoo and Helsinki) it was decided to implement a two phase approach to the study, due to the big time constraints on the project.

The approach is illustrated in Graphic 1.



Graphic 1: Project flowchart

Phase 1 one of the project will include all the technical discussions concerning the project and will lead to the two possible solutions "low floor" and "high floor" for joint operations between light rail vehicles and heavy metro.

All blue areas are based on facts and figures. A chapter in this report exists for each of the blue boxes in Phase 1. Yellow areas are information based and include external input. This can be expert know-how and discussion, additional research, best practice examples etc. Any input from these areas will be directly fed into the corresponding chapters of this document.

Phase 2 of the project will mainly deal with the issues depicted as green fields in the above flow chart. They will be directly influenced or determined by the factors shown as blue fields. For each topic shown in a green field, a separate chapter will be included in Phase 2 of this report.

The time-plan foresees to finalise Phase 1 of the project before the end of 2003. Phase 2 will directly follow and will last until the end of January 2004. The the complete study will be presented to the customer at 12th and 13th February 2004.

This approach was discussed and agreed on by the client at the kick-off meeting for the study, which has taken place 14th November, 2003. At this kick-off meeting TTK received all required data of the Helsinki metro system and the LRT-plannings for the Jokeri line. The metro depot was visited and first technical details were discussed with HKL.

The question about automatic operation will be mainly discussed as part of phase 2 of this study. This is due to the fact that automatic train protection and operations equipment can generally be fitted in both a high floor and a low floor vehicle concept. Issues directly relating to the different train protection equipment will be dealt with in phase 2 as well. However it has to be pointed out that fully automatic operation for a mixed system of metro and light rail that has to be implemented on an existing metro infrastructure is definitely not state of the art and will require a lot of newly developed non standard equipment.

As no information about the future system is available (currently a tender is being prepared for this system by HKL) a final statement on the feasibility of joint operation on such a system cannot be given.

Nevertheless the following outlook can be given:

- It will be far easier to achieve mixed operations in an environment of semi-automatic operations,
- Introducing fully automatic operations and mixed operations into an existing system will be a very difficult task, most probably leading to longer periods where operations have to be closed down.

2 Main technical criteria and available options

This chapter, together with chapter 3, is part of the first Phase of the study. It will deal with all technical issues which are relevant for the possibility to introduce operation with light rail vehicles on existing (heavy) metro infrastructure.

The question of high or low floor will not be covered as part of this chapter, as both a low and a high floor concept will be presented as a result of the technical discussions. These will be reviewed in chapter 4 regarding their respective influences on infrastructure, cost, system dimensioning and safety issues.

All influences will only be evaluated with regard to the effects of the introduction of the mixed operations, not the complete light rail system itself. Therefore the reached conclusions are only valid if such a system will be introduced. If a separate light rail system will be realised, the conclusions must be reconsidered.

2.1 Power supply

The existing metro network in Helsinki operates on a 750 V DC system. Electrical power is supplied via third rail to the vehicles. Most modern light rail systems also operate with 750 V direct current, however, power is generally supplied to the vehicle via an overhead line (catenary). This means that while the operating current is the same and the light rail vehicles will generally use less power (i.e. demand lower amperage) than the heavy metros. The available power on the existing metro sections should therefore be sufficient to also support the light rail vehicles.

However, the question remains how the available power can be supplied to the light rail vehicle.

There are three basic possibilities for the power supply of both metro and light rail vehicles in the joint running area:

1. Power supply to both metro and light rail vehicles via third rail
2. Power supply to the light rail vehicle via overhead line, via third rail to the metro vehicles
3. Power supply to both metro and light rail vehicles via overhead line

Regarding the first possibility, this option can only be used on the high floor vehicle concept. Such a system using both overhead and third rail power supply on high floor light rail vehicles is currently operating in Amsterdam, where a Sneltram line (51) uses overhead power until the "Zuid WTC" stop and enters the metro tunnel there to operate jointly with heavy metro vehicles. During operation on the light rail sections, the third rail power pick-up is folded away and grounded to ensure safe operation within the proximity of passengers and other traffic participants. This also ensures that the third rail power pick-up stays within the smaller dynamic gauge of the light rail network.

Low floor vehicles cannot be operated using third rail power supply due to the limited space around the bogies and the fact that low floor architecture usually uses completely enclosed bogies to avoid the contact of passengers to any moving parts. Additionally, it would be impossible on the third rail section to ensure passenger safety from the power pick-up arms of the third rail system on the low platforms.

On option number 2 it needs to be said, that it is possible to have both an overhead power supply and a third rail system, because both can use the same power source for the supply of 750 V DC. This would, however, lead to substantial extra cost (further evaluated in chapter 4.3.2) due to the fact that two different power supply infrastructures need to be constructed and maintained in the metro area.

Technically both a high floor and a low floor concept could operate on an infrastructure as described by option 2.

An important question to be dealt with for option 2 is the question of the gauge available for the vehicle plus the additional overhead line in the tunnel. This is dealt with in chapter 2.6.

Option number 3 will be kept in mind as a possibility. However, as this would require to change at least a number of existing heavy metro vehicles to overhead operation by adding pantographs and electrical equipment to the roof, this option is not very interesting. Especially in existing sections this would mean to remove the third rail already in place and introduce an overhead line. Thus option 3 will only be considered, if options 1 and 2 prove to be impossible.

The issue of power supply is closely linked to the chosen track gauge of the system. One issue for example is the impossibility to use a third rail power supply with 1,000 mm track gauge. This is more closely dealt with in chapter 2.3. As a result it can be said that option 1 is only available when the chosen track gauge for the light rail system will be 1,522 mm. Otherwise it is advisable for both a high or a low floor concept to opt for option 2 with overhead line for light rail and third rail power supply for the metro in the joint operation section. As said before, however, the most economical solution for the supply is to use a third rail system on the metro and an overhead line on the light rail sections of the system.

- ✓ The economically and technically best solution for the question of power supply therefore would be to use third rail in the tunnel and overhead line on the surface for the high floor concept.
- ✓ On the low floor concept only overhead line is technically feasible.

2.2 Wheel profile

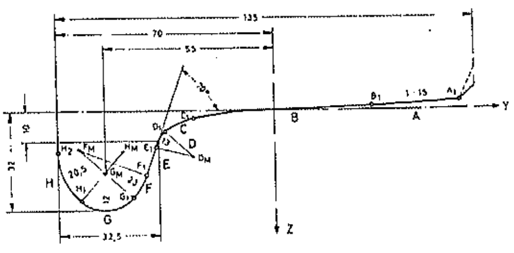
The question of the wheel profile, or better the discussion of the wheel – rail interface needs to be looked at very carefully, especially concerning the possible safety and maintainability problems to the existing metro system, in case a new wheel profile needs to be introduced on the light rail vehicles.

In a first discussion between experts from HKL and TTK consensus was found that, if possible, the existing wheel profile of the metro should be used on light rail vehicles. This is especially important, as Helsinki metro does not use raised guard rails in the switches on the existing metro system. This means that existing mixed operation profiles for heavy and light rail which are for example used in Karlsruhe cannot be introduced to the Helsinki metro system without major adaptations of the existing rail infrastructure (raising of guard rails) and possibly also to the metro vehicles (height of magnetic track brake).

The question that needs to be discussed here is therefore not the possibility to introduced a mixed operations profile but the necessity to use a heavy rail wheel profile on a proposed light rail system.

Mixed operations wheel profiles are only needed, where two existing systems using different rail infrastructure (i.e. different rail head geometry) need to be connected. This had to be done for example in the Karlsruhe case, where the existing light rail system was connected to the heavy rail network. However, this is not the case for the Helsinki – Espoo light rail system, where only the metro is existing.

A similar case (to the Helsinki one) can be found in Saarbrücken, where existing heavy rail infrastructure was connected to a new light rail system, that was not existing yet. Planners in Saarbrücken decided to operate light rail vehicles using heavy rail wheel profiles. These German heavy rail profiles (according to EBO and DIN 5573) are identical except for very minor details to the profile used on the Helsinki metro (ERRI (ORE) S 1002 / RP 2). Saarbrücken is thus a very good example of what can be achieved with light rail vehicles using heavy rail wheel profiles.



Graphic 2: Wheel profile ERRI (ORE) S 1002 / RP 2 as used on Helsinki metro (Source: HKL)

There are some problems resulting from this.

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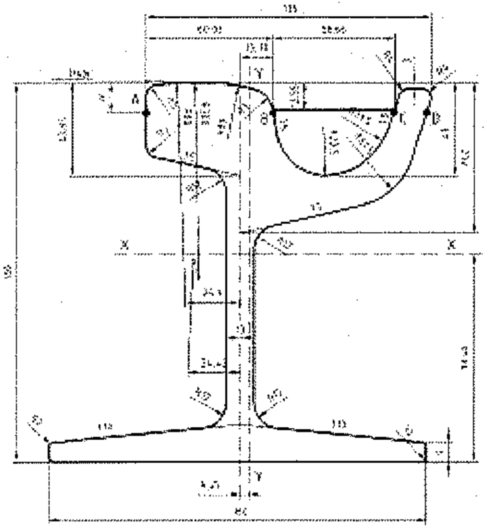
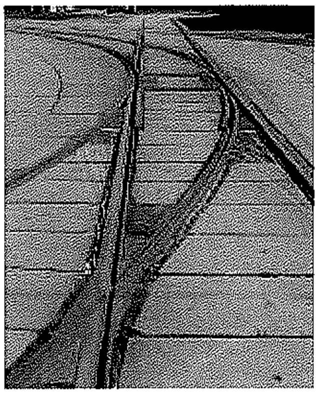
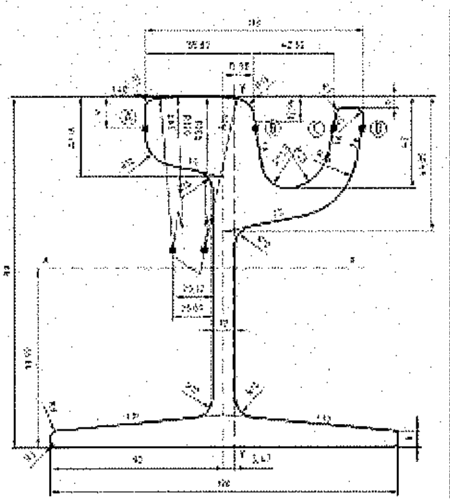
1. Light Rail sections should all be operated as segregated track formations, i.e. separated from parallel running other traffic by a high board or similar.
2. The light rail system needs deep groove rail wherever embedded rail sections are necessary. This can for example be grooved rail 67 Ri 1 (formerly Phoenix 37 a) as shown in Graphic 3 for switches and curves with a radius of less than 300 m, or 59 Ri 2 (formerly Ri 95N,) in straight sections.
3. Only crossing traffic should be allowed, especially for bicycles, as the suggested rail type has rather wide grooves.
4. Wherever possible, independent track formations (completely separate from other traffic, e.g. ballasted track or green track) should be used.



Graphic 3: Grooved rail profile 67 Ri 1 according to prEN 14811-1 (former Ph 37a) (Source prEN 14811-1 at enquiry status)



Graphic 4: Picture of Phoenix 37a switch (Source: AVG, Karlsruhe)



Graphic 5: Grooved rail profile 59 Ri 2 according to prEN 14811-1 (former Ri 59N) (Source prEN 14811-1 at enquiry status)

As can be seen from Graphic 6 a light rail system which is non-intrusive to the surrounding architecture and blends in very well with the city is possible using this approach.

Graphic 6: Separate Track, Saarbrücken

First impressions from a site visit to Espoo suggest that such an approach should be possible. It has also the added value that the operating speed of the light rail system is significantly increased by using this approach.

Industry consultation has revealed that these wheel profiles can be fitted to all high floor and most low floor vehicle concepts currently on the market.

Furthermore, it is economically much better to adapt the wheels of the light rail vehicles to the existing situation than to change the infrastructure of the metro. The

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metro wheel/rail interface has been optimised over many years and has lead to low maintenance cost. Therefore it is strongly recommended not to change anything in this area. Another very important aspect would be the time needed to adapt the existing infrastructure and the interference with the daily service over a long period.

- ✓ For both the high and the low floor concept it is suggested to use the wheel profile ERRI S 1002 / RP 2 and grooved rail profile 67 Ri 1 according to prEN 14811-1 (former Ph 37a) in curves and switches, 59 Ri 2 on embedded straight sections and vignol rail (e.g. UIC 54) on open sections.
- ✓ If possible, radii of less than 40 m should be avoided along the whole LRT route when this profile is used. This is also the case when no mixed operation is planned.

2.3 Track gauge

For the track gauge three possibilities are available:

1. 1,435 mm "standard gauge" track, as used on most heavy rail and light rail systems in Europe, but not in Finland
2. 1,000 mm metre gauge track, as used on the Helsinki tram system
3. 1,522 mm "broad gauge" track, not commonly used on European light rail systems, but close to "standard" gauge (1,524 mm) in Finland and used on Helsinki metro

While European standard gauge of 1,435 mm is commonly used on new light rail systems in Europe, this option should not be chosen for the proposed Helsinki light rail system, because the introduction of a third track gauge to Helsinki would annihilate all possible synergy effects between the existing systems and the proposed light rail system.

A further problem related to 1,435 mm gauge is the problem to introduce this second gauge into existing or to be build metro sections. While a three rail system could be possible for the 1,000 mm gauge, this is impossible for the 1,435 mm system. Therefore four rail sections would have to be build which would be very costly and would cause big problems when the 1,435 mm vehicles should stop at existing stations.

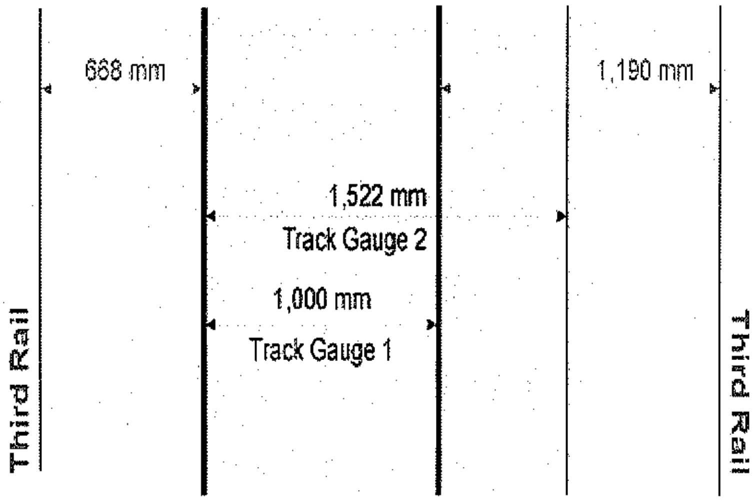
A gauge of 1,000 mm could lead to two advantages:

- On the new infrastructure to be built on the Jokeri line double separate tracks need less space compared to other gauges. But after a first site visit space seems not to be the problem at this line.

- If a connection to the existing tram infrastructure could be established it might be possible to use their maintenance facilities. But the tram maintenance facilities are properly used and it will probably not be possible to maintain ca. 30 additional LRV there. In addition to this the aspect for the use of the tram depot the LRV must fit to the narrow curves (under 20 m) of the tram system, which is not necessary for the Jokeri line and in the end would result in additional cost. Therefore this option should not be considered.

However, there are two main disadvantages of 1,000 mm:

- The need for a three rail infrastructure in the tunnel. This is technically feasible, but would result in huge investments. All sleepers would need to be replaced to install this third rail.
- The third rail power supply cannot be used in the tunnels (see Graphic 7) and additional costs for the overhead line need to be taken into account.



Graphic 7: Problems of using third rail power source with three rail track

The third possibility for the track gauge of the future light rail system would be to use the existing gauge of the Helsinki metro (1,522 mm) which is also compatible to Finish state railway gauge. This would have the advantage to allow the use of the depot and maintenance facilities of the metro and could therefore save costs. First consultations with the industry have revealed that the introduction of 1,522-gauge bogies poses no big problems for any high floor concept. For low floor concepts bigger problems would have to be solved. These include less space available and reduced turning angles for the wider bogies. However, the problems do not appear so grave that this option could be threatened.

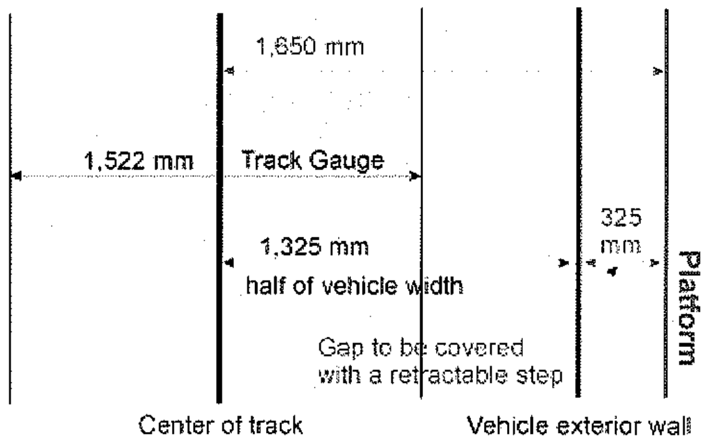
- ✓ Conclusion: Track gauges of 1,000 mm and 1,435 mm are not recommended.
- ✓ For both the low floor and the high floor concept, a gauge of 1,522 mm should be considered.

2.4 Vehicle width

The vehicle width is directly linked to its capacity. In Europe the standard for LRV is 2.65 m and this should also be the minimum width to be considered in Helsinki. This width would allow 4 seats in a row plus additional isolation against low temperatures (as required by HKL in the kick-off meeting in Nov. 03). Therefore lower widths are not recommended (and there are no constraints from the surface infrastructure, as in other cities).

The only question that needs to be answered is whether larger widths would make sense. In principle they are feasible, but may cause problems in sections of the Jokeri line, where mixed traffic with cars is planned. Additionally such a LRV is not standard anymore. Are there any fundamental advantages?

The following picture shows the situation at a metro stop of a 2.65 m wide LRV. The gap of 32.5 cm between the LRV and the platform can be perfectly covered by a retractable step of a width of 25 cm. This picture also makes clear, that even for larger widths up to 3.0 m the retractable step is still required (based on the assumption that the maximum gap is 5 cm between vehicle and platform).



Graphic 8: Distance between vehicle (width 2.65 m) and the platform at the metro stops

Thus the only advantage is a larger capacity in the standing area. Compared to the disadvantages mentioned above this reason is not convincing at all. Therefore a width of 2.65 m is the best solution. The gap of 325 mm is identical to the one encountered by Karlsruhe tramtrain vehicles when operating on heavy rail infrastructure using 550 mm high platforms. While the gap is rather wide, this can be tolerated when the proposed cinematic folding step or moving step is wider than the door opening of the vehicle. An example can be seen in the following picture.

Graphic 9: Possible entry into a 2.65 m wide LRV from a platform which is 1,650 mm from track centre

Vehicles of 2.65 m width still allow very comfortable travelling conditions, as can be seen from the next picture.

Graphic 10: Interior of 2.65 m wide middle section of an LRV

For this vehicle width, it is necessary to close the gap between vehicle and platform either on the vehicle side or on the infrastructural side.

An example of a solution on the infrastructural side can be one that has been used in Kassel (see next picture).

Graphic 11: Pivoting tracks towards the platform – Kassel example

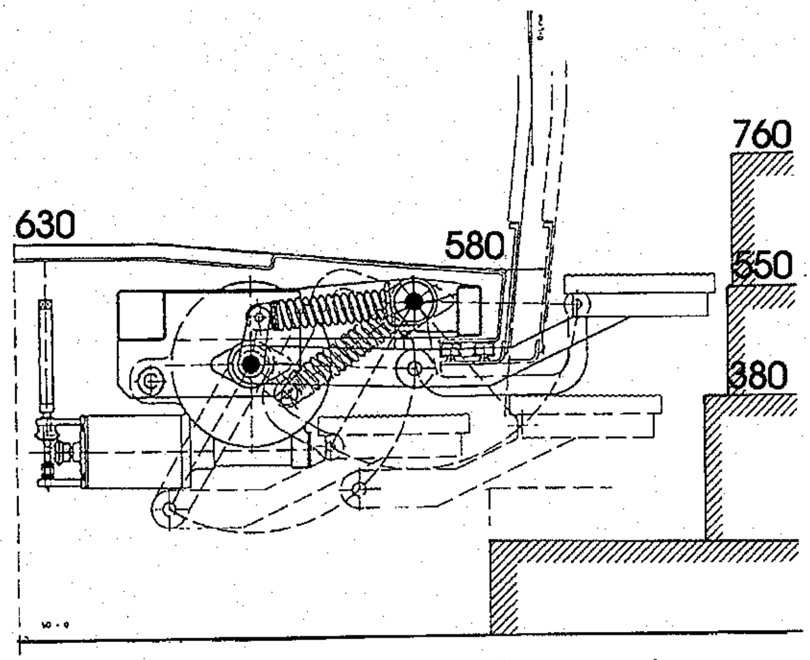
Such a solution has, however, several disadvantages:

- High infrastructural cost (two additional switches, completely new tracks, 4 rail track in the station)
- Signalling cost to ensure that metro trains never use the light rail turnout

In Kassel this solution has only been adopted as the vehicles have only a width of 2.4 m.

It is not recommended to use such a solution for the Helsinki / Espoo joint operations scheme.

Both low and high floor LRV thus require a device to bridge the gap between platform and vehicle. The only difference is the technical layout of the step, because in the high floor LRV much more space is available to integrate this equipment under the vehicle. The following picture provides an overview about the possible high floor solution:



Graphic 12: Cinematic folding step of the Karlsruhe middle-floor LRT-vehicle with platform heights in Karlsruhe region (this kind of step can also be integrated in the Helsinki high floor LRV)

The low floor solution can be realised with a moving step at the level of about 300 to 350 mm directly under the vehicle floor.

However this solution is more susceptible to corrosion from dirt or snow during harsh winters.

✓ Conclusion: A vehicle width of 2.65 m is recommended for both low and high floor LRV.

2.5 Vehicle car body structure (buffer load)

For buffer load, there are two possibilities which will be discussed here:

1. Light rail vehicles that have the same buffer load as the heavy metro vehicles.
2. Light rail vehicles that are allowed to have a lower buffer load than the existing metro vehicles.

In terms of passive safety the first option may at first sight be the best way to achieve similar standards on both the light rail and the heavy rail vehicles. However it has to be kept in mind that the introduction of higher buffer loads always increases the weight and thus construction cost and energy consumption.

The metro vehicles have a buffer load of 850 kN. To achieve this value would be very costly for any light rail vehicle and may be impossible for most standard low floor concepts (e.g. Combino, Citadis).

As the legal situation does not require the two vehicles (metro and light rail) to have the same buffer load, it is recommended to use a value of 600 kN on the high floor concept, as high floor vehicles come with a standard buffer load of 600 kN and there are no economic improvements to be expected when considering a lower buffer load. For the low floor concept, 400 kN are suggested, even if some standard low floor concepts may have problems to reach these values. In Karlsruhe, the mixed operation of 400 kN low floor vehicles with heavy rail (1,500 kN) vehicles is possible, as the light rail vehicles have better braking capabilities.

Additionally, structural crash elements should be implemented on both the high and low floor light rail vehicles which can be derived from the suggestions made by the currently ongoing EU-research project "Safetram". Also the recommendations given by Safetram on the design and configuration of the interior equipment of the light rail vehicles should be followed. In conjunction with these crash elements, passenger risk should be no higher than on the current operations.

Additional safety to the passenger is provided through the high active safety of both the LRV's and the metro. This means that by utilising the high braking capabilities (usually a standard 2.7 m/s^2 for light rail vehicles) more crashes will be avoided than on systems with less braking performance[1].

[1] It has been pointed out that sand for increased friction is not permitted on the Helsinki metro. However, it is not recommended to implement a light rail system without sand on the vehicles (this would not be permitted in Germany; BOStrab requires sand on all LRV). However, it is suggested to switch off the use of sand during operation on the metro section. This can most easily be achieved when sand is only provided by an automatic system in case wheel slip is detected (no direct driver intervention). This system can then be switched off when the vehicle enters the metro section (either by GPS or by activators implemented in the track infrastructure).

The reasons for this recommendation of 600 kN (high floor) and 400 kN (low floor) are:

- Safe operations of 600 kN dual voltage light rail and 1500 kN (!) heavy rail vehicles for more than 10 years in Germany (e.g. Karlsruhe, Saarbrücken)
- Safe operations of 400 kN single voltage low floor light rail and 1500 kN (!) heavy rail vehicles in Karlsruhe
- Introduction of the crash elements increases passive safety
- Buffer load alone does not make a vehicle safe, the incorporation of Safetram results will reduce the risks for passengers
- High performance brakes on both LRV and heavy metro in conjunction with automatic train protection or even automatic train control will increase active safety
- German experience with mixed operation has shown, that these systems are at least as safe as same mode operations. The same approach has been adopted for the introduction of the first French tramtrain systems.

✓ 600 kN buffer load is recommended incl. additional crash elements on the high floor concept. However, the legal restrictions on this possibility need to be evaluated.

✓ 400 kN buffer load is recommended incl. additional crash elements on the low floor concept. However, the legal restrictions on this possibility need to be evaluated.

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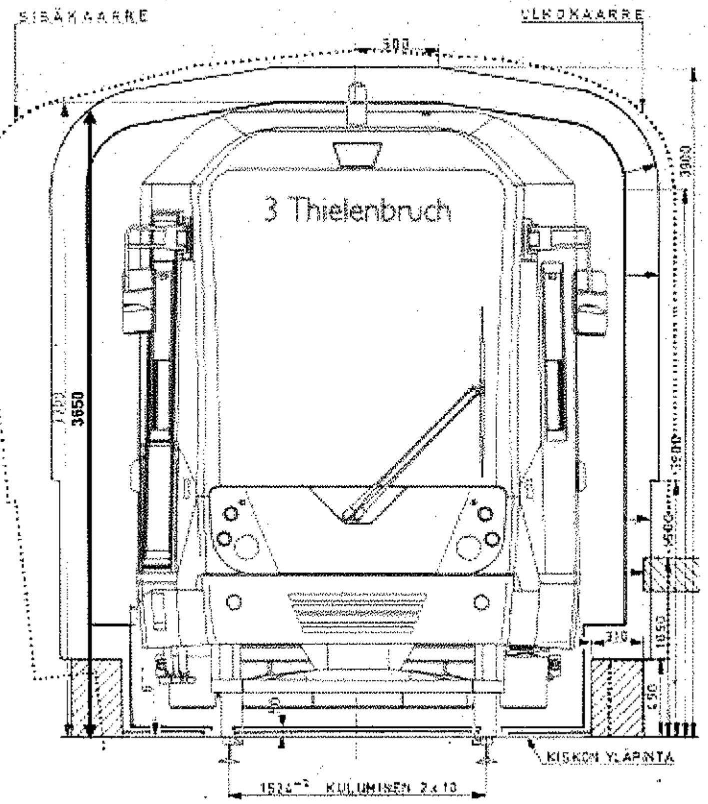
2.6 Dynamic structure gauging

The most demanding situation for the structure gauge would be to operate a high floor vehicle under overhead line in one of the existing metro sections. As can be seen in Graphic 13, the remaining gap between tunnel ceiling and vehicle roof in this example of an existing high floor vehicle (K5000, Cologne) would only be 250 mm (the HKL requirement was a minimum gap of 200 mm as for the metro today). While it may still be possible to introduce an overhead line into this gap, this would have to be a highly sophisticated system and the operation height of the pantograph would be very low.

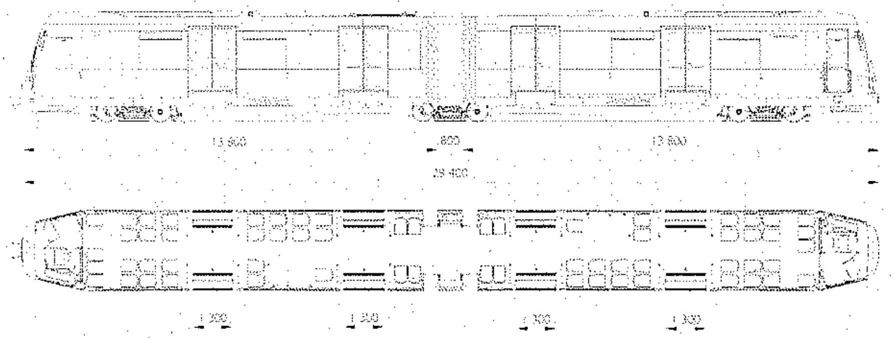


Graphic 13: High floor vehicle in Helsinki metro envelope (sources: HKL and Bombardier Transportation)

Graphic 14 shows that a standard high floor concept will be able to stay within the gauging envelope set by the existing tunnels, when the pantographs are lowered.

A low floor concept will not have the problem with the tunnel ceiling, as the overall vehicle height can be less than on a high floor vehicle.

Therefore a low floor concept would fit into the existing metro envelope including the additional overhead power supply.



Graphic 14: Top and side view of high floor vehicle concept example (K5000, cologne)

- ✓ Due to gauging restrictions a high floor vehicle should only use third rail power supply while on the joint operation metro / LRT.
- ✓ A low floor vehicle plus necessary overhead line should not pose problems to the existing gauging envelope.

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3 Fundamental vehicle concepts

In this chapter the two fundamental vehicle concepts will be summarised and compared to each other. A preliminary evaluation will take place, which will be revised at the end of phase 2 of the project.

To gain a better overview TTK has carried out some interviews with main industrial LRV manufacturers: Siemens, Alstom, Bombardier and Stadler. For these interviews experts from these companies personally known to TTK have been contacted. Therefore their statements represent not the „official opinion", but can be seen as an indicator, what will be possible or not. For confidentiality reasons TTK will not provide the received information from each company separately. The industry views were directly integrated in the discussions in chapter 2. The following list repeats the main issues raised by the industry:

- Bogie: A low or high floor bogie of 1,522 mm will be technically feasible. But this can lead to additional cost, if the 1,435 mm state of the art bogie must be heavily adapted. If this is the case new structure tests must be carried out leading to higher cost. But all manufacturers were optimistic that this adaptation will not be so complex. In general the adaptation of the low floor bogie is a greater challenge.
- Wheel profile: The discussed Helsinki metro wheel profile should not be a problem, neither for low floor nor for high floor LRV.
- Buffer load: Up to 850 kN buffer load will create problems for LRV, especially for low floor vehicles. Larger structural adaptations are required. For high floor LRV this task would be easier, but it was highly recommended to stay for high floor LRV within the limit of 600 kN and to add crash elements if required. Additional buffer load will lead to more weight, but it was questioned if this really leads to more safety.

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3.1 Summary of both concepts

The technical criteria and recommended values are discussed in chapter 2 are summarised in the following table:

Criteria	Low foor LRV	High floor LRV
Floor height	300-350 mm	1,000 mm
Power supply	Overhead wire in the metro and on the Jokeri line	Third rail in the metro and overhead wire on the Jokeri line
Wheel profile	Existing metro profile	Existing metro profile
Track gauge	1,522 mm	1,522 mm
Vehicle width	2.65 m	2.65 m
Gap closing device	Moving step at 350 mm level	Cinematic folding step
Structure	400 kN plus crash elements	600 kN plus crash elements

Tab. 1: Feasibility matrix of Low floor- and high floor concept

3.2 Proposed low-floor concept

In general it will be technically feasible to integrate an adapted low floor LRV into the metro operation. For the surface operation on the Jokeri line a standard low floor LRV is for sure a suitable solution, but there are some difficulties which should be considered for the joint operation:

- Floor height should be between 300 and 350 mm, otherwise the surface operation advantages will be lost. But this will result in extensive adaptation of the metro infrastructure at the stops. All stops served by LRV need to have a second level at a length of 60 – 80 m of about 300 mm height.
- Percentage of low floor: To make life much easier it is highly recommended to go for 70 % low floor LRV and not for 100 %. 70 % would allow normal bogies at the ends. This will result in a better ride quality and technically it will be easier to adapt theses bogies to a track gauge of 1,522 mm.
- Power supply: The use of the third rail in the metro area will technically not be possible. Therefore the additional cost for an overhead line in the metro sections must be considered. There are no problems with the overall gauge in the tunnels.

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- Wheel profiles: Technically it will be feasible to use the metro wheel profiles in low floor LRV. This aspect will not cause problems that cannot be solved.
- Track gauge: For the joint operation 1,522 mm is highly recommended to avoid huge investment cost in the metro section. Bogies with 1,522 mm in low floor LRV are technically feasible, but depending on the actual layout of the standard modular LRV (Combino by Siemens, Citadis by Alstom or Flexity Swift by Bombardier) adaptations on the bogie frame and the tramcar body might be required. The problem is, that the available space for adaptations in these modular concepts is very limited.
- Vehicle width: The maximum standard width of 2.65 m is recommended.
- Structure: Low floor LRV normally have a buffer load between 200 and 400 kN. But there are also other examples, e.g. Flexity Swift by Bombardier for Stockholm, with 600 kN. The Helsinki metro requires up to 850 kN. To be on the safe side 400 kN plus additional crash elements are recommended. As discussed at the kick-off-meeting in November 2003 it is up to HKL to set the standards for crashworthiness. It must be kept in mind, that 400 kN mean additional cost compared to a standard modular LRV.

The main differences resulting from the joint operation between an off the shelf standard modular LRV and this Helsinki adapted LRV is the buffer load and the track gauge. If this LRV would serve only the Jokeri line without operating in the metro system a buffer load of max. 400 kN without crash elements would be sufficient and the track gauge would not have to be 1,522 mm (even if 1,522 mm would also in this case allow the use of the metro maintenance facilities, if a link is established).

<u>Examples of existing modern low floor vehicle concepts with a buffer load of up to 600 kN:</u>

Graphic 15: Low floor light rail vehicle Karlsruhe, manufacturer: Siemens TS, buffer load 400 kN

Graphic 16: Low floor light rail vehicle Stockholm, manufacturer: Bombardier, buffer load 600 kN

3.3 Proposed high-floor concept

In comparison to the low floor concept a high floor LRV would technically better fit into the metro environment. But for the surface operation on the Jokeri line high platforms (950 mm) must be taken into account. The following points should considered for the joint operation:

- Floor height should be about 1,000 mm to cope with the height of 1,050 mm of the metro platforms. In this case no adaptations are required in the metro area. The gap of 325 mm between the vehicle and the platform can be closed with a retractable step of a width of about 250 mm.
- Percentage of high floor should be 100 %.
- Power supply: The use of the third rail in the metro area will be technically feasible and would avoid any additional cost for underground overhead wire. There are no problems with the overall gauge in the tunnels.
- Wheel profiles: Technically it will be feasible to use the metro wheel profiles in high floor LRV. This aspect will not cause any problems.
- Track gauge: For the joint operation 1,522 mm is highly recommended to avoid huge investment cost in the metro section. Bogies with 1,522 mm in high floor LRV are technically feasible, but as in the low floor discussion adaptations on the bogie frame and the car body might be required. For any adaptations there is more space available in the car body in comparison to the low floor concept.
- Vehicle width: The maximum standard width of 2.65 m is recommended.

- Structure: High floor LRV normally have a buffer load of 600 kN. The Helsinki metro requires up to 850 kN. To be on the safe side 600 kN plus additional crash elements are recommended. This means only the crash elements must be added.

Examples of existing modern high floor vehicle concepts:

Graphic 17: High floor light rail vehicle Hanover, manufacturer: Alstom LHB

Graphic 18: High floor light rail vehicle Cologne K 5000, manufacturer: Bombardier

Graphic 19: High floor light rail vehicle Stuttgart, manufacturer: Siemens

4 Discussion of impacts of the two vehicle concepts

4.1 Definition of a reference case

For the comparison of the impacts of the joint operation a Jokeri reference case was defined together with the client at the end of December 2003.

- Length of Jokeri line about 27 km from Tapiola to Itäkeskus
- No direct connection to the metro system. In Tapiola the Jokerli line would end underground at the station, but one level abouve the metro. In Itäkeskus the final station is on the surface in front of the metro station
- 28 stops on the Jokeri line
- Basic infrastructure characteristics: 1,435 mm standard gauge, about 60 m lenght of stops (for double traction), about 270 mm platform height, 40 m minimum curve radius, 750 V overhead wire
- Operation of standard low-floor LRV on the Jokeri line
- Basic vehicle characteristics: 30 m long, 2.65 m wide, 300 mm entry height, 750 V overhead, 1,435 mm European standard gauge, 70 % low-floor, 70 km/h Vmax (comparable to the modular concepts of Siemens, Alstom or Bombardier)
- New depot including maintenance facilities, but the metro depot will be used for main larger parts (e.g. bogies, transport with trucks)

For the metro side it was assumed that the extension from Tapiola to Matinkylä will be built anyway (underground or on the surface) and that the proposed additional measures for the joint operation (e.g. longer stops in case of the low-floor LRV) will be already included in the conceptional planning from the beginning on. The cost for the additional measures will be listed in the following chapters of this study.

It is important to realise that all following numbers are representing only the difference (delta) between this reference case and the mixed operation.

4.2 Infrastructure

It is obvious, that the metro infrastructure (existing and planned) and the infrastructure on the Jokeri LRT-line must be adapted to the requirements of the joint operation metro/LRT. But the impacts on the infrastructure are not the same for the low-floor- or the high-floor-solution.

4.2.1 LRT

This refers to the section between Tapiola and Itäkeskus.

Low-floor-solution: In comparison to the reference case there are two differences:

- Due to the difference in the gauge (1435 mm in the reference case) the cost for the roadbed and track are a little bit higher.
- The eastern end in Itäkeskus, see 4.2.4.

High-floor-solution: In comparison to the reference case there are some more differences:

- Connection metro/LRT at Itäkeskus as in the low-floor case
- The height of the platforms on the Jokeri line must be about 950 mm
- The platforms need ramps and therefore more space
- Due to the difference in the gauge (1435 mm in the reference case) the cost for the roadbed and track are a little bit higher.

4.2.2 Metro

This refers to the section between Tapiola and Matinkylä as well as Itäkeskus and Vuosaari.

There is a large difference between the low- and the high floor concept for this point:

Low-floor-solution: One has to distinguish between the existing infrastructure on the eastern side and the new planned extension on the western side:

- The stops between Itäkeskus and Vuosaari must be adapted. Today the length of a platform is about 135 m (a metro train of 6 vehicles can serve this stop). For the future in case of the envisaged automatic operation the frequency will be tighter (up to 4 minutes) and the length of one metro train can be shortened to a 4-vehicle-train-set of about 80 m lenght. Therefore it is planned in case of the low-floor-joint-operation to lower the existing metro platforms on a lenght of about 55 m to a height of 300 mm.
- The stops between Tapiola and Matinkylä (which are not built so far) must be adapted in the same way.Ther overall length of a platform must be about 135 m instead of about 80 m for s pure metro operation.

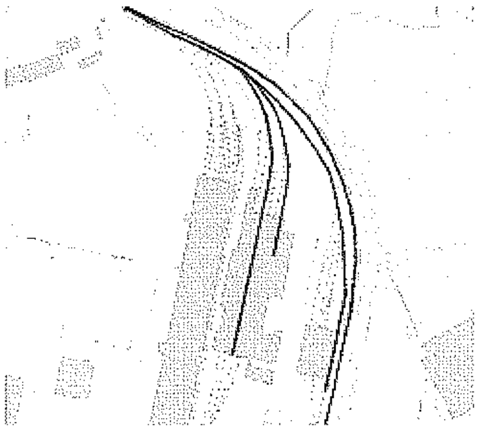
- In the metro area overhead wire (750 V) are required.

High-floor-solution: In this case the metro infrastructure can remain as it is. The LRV is able to stop at the existing stations (to bridge the gap between platform and vehicle, moving gap closing devices will be used) and it will use the third rail power supply.

4.2.3 Depot and maintenance facilities

There is no difference between high- or low-floor LRV.

In case of the joint operation the maintenance of the vehicles can be carried out in the existing metro depot[2]. The following picture from HKL provides an overview of the possible layout of adaption of the metro depot:



Graphic 20: Possible layout of the metro depot including the maintenance facililties (in red) for the LRV of the joint operation (source HKL)

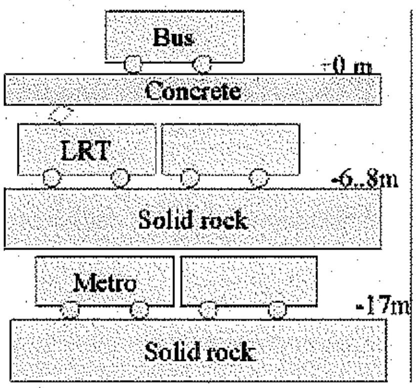
A depot along the Jokeri line is also required in the joint operation case. But this can be reduced by some significant parts (e.g. wheel lathe, hydraulic vehicle jacks), which are required in the reference case.

4.2.4 Connection between LRT and metro

There is no difference between high- or low-floor LRV.

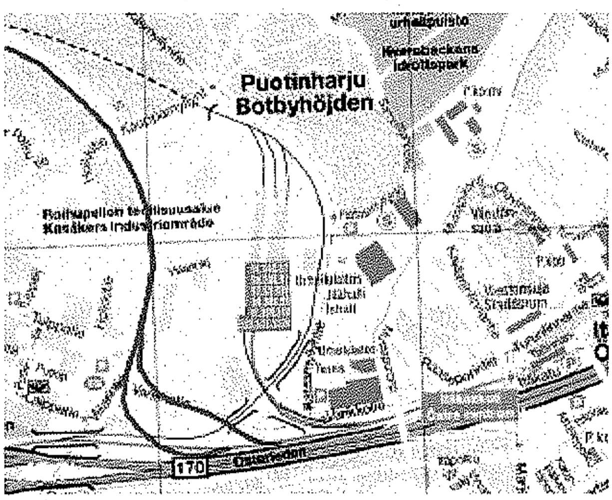
Western end in Tapiola: Direction West the metro and the LRT-system will come to the same level and continue underground or on the surface together on the same rails. See following picture:

[2] Confirmed by Mr. Vesanen, HKL, 22.12.2004 via e-mail



Graphic 21: Possible layout of the Tapiola station (source City of Espoo, M. Kokkinen)

Eastern end in Itäkeskus: In the joint operation case the connection between LRT and metro is planned some 100 m direction west of the metro station (see 4.2.4) and the stop would be inside Itäkeskus station.



Graphic 22: Proposed connection LRT/Metro at Itäkeskus (in red)

4.3 Cost

Changes to any public transport concept always have a direct impact on the related costs. This includes cost changes in the areas of operations, infrastructure, rolling stock procurement and maintenance. To get a complete overview of the cost impacts of a project it is therefore vital to make the different costs comparable. The approach within this study is to first discuss the costs related to operations, infrastructure and rolling stock. Within chapter 5 the estimated costs will then be made comparable by the use of annuities and the estimated overall related annual project costs will be shown.

4.3.1 Operation

For the comparison of operations on the Jokeri line (reference case) and for the mixed operations concepts (high-floor; low-floor) it is important to realise that not only the vehicles but also the line lengths differ considerably.

While operation of the Jokeri line between Tapiola and Itäkeskus means a light rail operation on about 27 km, the mixed operation would have a line length of 35 km between Vuosaari and Matinkylä. As will be shown in chapter 4.3.3 on rolling stock, this already means a higher number of vehicles. It also means that operational, maintenance and personnel costs will be higher for the mixed operations scenarios not only because of the more complex technology on the mixed operation LRV's but also because the line length is more than on the reference case. Higher maintenance cost on the mixed operations vehicles is due to the additional technical equipment such as the gap bridging devices. However, maintenance cost on high-floor vehicles is significantly lower than on low-floor vehicles.

For the calculation of vehicle energy consumption, a price for traction energy of 4 ct/kwh [3] was applied.

Operational cost was estimated in four parts. One for the other operational cost, without maintenance, cost for operations personnel and energy consumption. These were estimated separately. All costs are differences between the reference case and the mixed operations case, given per year. Positive numbers mean higher costs than on the reference case, negative numbers show cost reductions.

Cost type	Low-floor scenario	High-floor scenario
Personnel	420,000 € p.a.	420,000 € p.a.
Maintenance	300,000 € p.a.	60,000 € p.a.
Energy consumption	80,000 € p.a.	80,000 € p.a.
Other operational cost	120,000 € p.a.	60,000 € p.a.
Delta total operational cost:	920.000 € p.a.	620.000 € p.a.

Tab. 2: Operational cost for the two scenarios

[3] E-Mail from Mr. Vesanen, HKL, 14.01.2004

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If the calculation would be focused only on the 27,3 km of the Jokeri line, the differences would be the following[4]:

- The low-floor scenario would lead to additional cost of 60,000 Euro.
- The High-floor scenario would lead to savings of 180,000 Euro.

Additional revenues due to more passengers have not been taken into account at the moment.

4.3.2 Infrastructure

On the infrastructural side, the following points have a cost impact:

- Adaptation of platforms on the proposed metro line between Matinkylä and Tapiola (low-floor concept only)
- Additional overhead power supply on the proposed metro line between Matinkylä and Tapiola (low-floor concept only)
- Adaptation of platforms on the proposed Jokeri light rail line between Tapiola and Itäkeskus (high-floor concept only)
- Adaptation of the roadbed and track due to the difference in the gauge (1435 mm in the reference case)
- Adaptation of platforms on the existing metro line between Itäkeskus and Vuosaari (low-floor concept only)
- Additional overhead power supply on the existing metro line between Itäkeskus and Vuosaari (low-floor concept only)
- Construction of connecting infrastructure between light rail and metro lines in Tapiola and Itäkeskus (both concepts)
- Reduction of the necessary light rail depot in comparison to the reference case (both concepts)

The light rail depot needed for the separate operations of light rail and metro systems can be reduced from a depot also able to do maintenance to a depot only used for vehicle storage and vehicle preparation when mixed operation is introduced.[5]

[4] Without the capital cost for the vehicles. This would increase the additional cost of the low-floor scenario by 560,000 € and would decrease the high-floor scenario by 30,000 €. But the capital cost are discussed in chapter 4.3.3.
[5] In this case some smaller investments in the metro depot have to be made allowing the maintenance of the LRV. According to the information of HKL about 200,000 € are required for this (e-mail from M. Vesanen, 22.12.2003).

However, for the calculation of this cost reduction, it was assumed that even when the two systems are completely separate, big parts such as bogies and complete vehicles etc. will still be put on a truck and taken to the metro depot for major overhaul. Smaller maintenance will be carried out at the light rail depot and additional equipment such as hydraulic vehicle jacks and a wheel lathe will be necessary.

A total cost reduction of **- 4,800,000** € was calculated for the depot along the Jokeri line, when mixed operation is introduced.

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The remaining additional infrastructural costs were estimated as follows:

Line section	Infrastructure	Low-floor scenario	High-floor scenario
Section A Matinkylä – Tapiola Above ground (Scenario 1)	Stops and platforms	450,000 €	No additional cost
	Track and power supply	1,500,000 €	No additional cost
Section A Matinkylä – Tapiola Below ground (Scenario 2)	Stops and platforms	700,000 €	No additional cost
	Track and power supply	1,000,000 €	No additional cost
Section B Jokeri Line Tapiola - Itäkeskus	Stops, platforms and track	1,500,000 €	3,300,000 €
	Connections including power supply	60,000,000 €	60,000,000 €
Section C Itäkeskus - Vuosaari	Stops and platforms	2,000,000 €	No additional cost
	Track and power supply	1,500,000 €	No additional cost
Delta total infrastructural cost Scena. 1*:		**62,150,000 €**	**58,500,000 €**
Delta total infrastructural cost Scena. 2*:		**61,850,000 €**	**58,500,000 €**

*including the cost reduction by the cheaper depot for mixed operations. Scenario 1 is based on tracks above the ground between Matinkylä and Tapiola, Scenario 2 underground.

Tab. 3: Infrastructure cost for the two scenarios

It is necessary to point out, that the adaptation of the existing metro stations to include a low-floor section can hardly be carried out under operations. These means that the sections would have to be temporarily closed for construction. Otherwise the cost for this change would raise into not acceptable areas.

4.3.3 Rolling stock

The costs relating to light rail vehicles are obviously connected to the following issues:

- Number of vehicles (which in term is determined by line length, operating speed and the number of vehicles per train)
- Additional technical features for the mixed operation

Jokeri line		Mixed operation	
No. Of stops	30 stops	No. Of stops	36 stops
Line length	27,3 km	Line length	35 km
operating speed	30 km/h	operating speed	33 km/h
turning time	20 min	turning time	20 min
time of circulation	130 min	time of circulation	150 min
frequency	5 min	frequency	5 min
No. of vehicles	**26 vehicles**	**No. of vehicles**	**30 vehicles**
Incl. reserve	**29 vehicles**	**Incl. reserve**	**33 vehicles**

Tab. 4: Required number of vehicles for Jokeri line (no double traction included, 10 % reserve) and mixed operations

The results of table 4 show that for the operation of 5 minute intervals on the Jokeri line itself, 29 vehicles (including 10% reserve for maintenance and repair) are needed. Double traction was not considered (see chapter 4.4) due to the very high operating frequency and resulting sufficient line capacity during peak hours, even at single traction.

When mixed operation is considered, it is important to realise that increased line length due to the through operation of light rail vehicles on the metro line will also increase the number of vehicles needed. Higher operating speed on the metro line will lower this number.

As can be seen from table 4, the number of required vehicles rises from 29 to 33 for the mixed operation.

Vehicle cost for the mixed operation will be increased due to the following factors:

- Additional crash elements
- Bogies for 1,522 mm track gauge
- Gap closing mechanism

- Signalling (automatic operations) equipment
- Higher fire safety standard[6]
- Additional third rail power pick-up (only for high-floor concept)

For each semi-automatic vehicle, this would amount to additional costs of 330,000 € for the low-floor and 380,000 € for the high-floor vehicle. However, a standard high-floor vehicle is less expensive than a low-floor vehicle.

Fully automatic operation would amount a rough estimation of additional costs of 500,000 € minimum per vehicle not mentioning the necessary investment for infrastructure (compare chapter 4.5.3).

Overall, the difference in cost due to the introduction of the mixed operations in comparison to a standard low-floor LRV (reference case, 1,435 mm track gauge, 70% low-floor) per vehicle are estimated to be:

- 330,000 € additional cost per vehicle for the low-floor concept
- about the same cost for a mixed operations high-floor vehicle as for a standard low floor vehicle (the additional cost are compensated by the lower basic price)

4.4 System dimensioning

The frequency on the Jokeri LRT-line was fixed by the client[7]: 5 minutes during the rush hours otherwise 10 minutes and late in the evening and on Sundays 20 minutes. There is no demand forecast available neither for the Jokeri line nor for the joint operation case.

Normally the system dimensioning is based on the demand during the rush hour and some technical parameters of the system like possible length of stops, possible frequency. The required capacity of the vehicles (seats and standees) and the dimensions (length, width) will be derived from theses values. But this procedure is not possible at the moment.

Therefore the proposed vehicle layout (in the reference case and the joint operation) is based on a standard 30 m length. The width was fixed anyway at 2.65 m (see chapter 2.4). This leads to a LRV of about 90 seats and 110 standees.

[6] Assuming that the new EN 45545 will not cause substantially higher cost for additional fire protection than todays standards.
[7] At the Kick-off-meeting 14 of November 2003 in Helsinki.

In single traction the rush hour capacity[8] of the Jokeri line for each direction is about 1.400 persons in the area of the highest demand. The daily demand for both direction on this cross-section should not be higher than 14.000 persons.

If the demand is higher than expected there are principally two options:

- The LRV will have to operate in double traction or
- Longer LRV up to 40-45 m can be used. This would increase the capacity to about 250 persons (seats and standees). Operation in double traction would not be possible anymore because the lenght of the platforms in the metro area would be too short (in case of a low-floor LRV).

4.5 Safety issues

With any public transport system, the question of high customer safety is a vital part of all discussions. Therefore it is important to ensure, that any new system is always at least as safe as already existing systems. This means at the least that all existing norms and standards are followed and state of the art technology is used.

One of the safety issues which have to be considered when mixed operation is to be introduced is the question of front buffer load. This has already been discussed in chapter 2.5. The conclusions reached in that chapter are of course still valid.

Some other safety relevant aspects will now be discussed.

4.5.1 Safety problems arising from the lower platform height (low-floor concept only)

When mixed operation is considered using a low-floor vehicle concept for the light rail operation, sections of the platforms in the mixed operations area would have to be lowered to accommodate these vehicles. If a high floor metro vehicle would pass this section of a station, the power pick up arms for the third rail of this metro vehicle could be rather easily reached by passengers that are currently on this platform. This would mean that passengers on the platform would be at risk of electric shock from these protruding power pick up arms. Therefore, in the case of such an operation, some way of keeping passengers from this hazard would need to be implemented. This could either be platform doors that allow access to the track area only when a light vehicle has stopped and the vehicle doors are lined up with the plat-

[8] Based on the assumption that the ratio of the rush hour demand is 20 % of the overall demand for each direction.

form doors or doors that keep the complete light rail platform vacated as long as no light rail vehicle is in the station.[9]

Of course this would have to take into account both directions of operation.

Additionally, light rail vehicles must not stop in the metro area, while metro trains cannot be allowed to stop in the lower light rail section.

This safety hazard would not occur, if the operation of high-floor light rail vehicles were used.

4.5.2 Fire safety

A further big issue when introducing the light rail vehicles into the metro tunnels is the question of fire safety.

Standard light rail vehicles normally only have lower fire safety standard than metro vehicles. Higher fire standards of course mean higher vehicle costs. These have been included in the additional cost for the light rail vehicles for the mixed operations concepts.

A new European fire safety standard (EN 45545) is currently under development. However, as this is still in draft status, and especially the materials part is still under hard discussion, it is not possible to predict its exact influences on the system.

However, it can be assumed (and drafts of the standard already available confirm this) that requirements placed on the vehicles will still be higher for vehicles operating on a system which is "defined by tunnel operation" than for vehicles which are mainly used for above ground operations.

4.5.3 Signalling / automatic operation

It is hardly possible to make any estimates for the signalling and operational concepts when it is not yet known, whether the system will be fully automatic and what type of system will be used[10].

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[9] Assuming that for the future automatic metro operation platform doors (or something similar) are required on the whole length of the stops no additional cost were calculated within this study.

[10] According to the information provided by HKL at the kick-off-meeting in November 2003 for this project HKL is planning to submit a tender in 2004/2005 for a full-automatic system with an option of semi-automatic if the full-automatic solution will be too expensive or technically to complex to be realised.

The following discussion in this chapter is not all an evaluation of the HKL-plans for an automatic metro operation. It refers only to the idea to introduce an additional system (here LRT) into an automatic metro environment.

A few points can be made:

- No already existing metro system has ever been changed to automatic operation using existing vehicles while in operation.
- Including a mixed operation scheme into such a completely new system which is not yet existing anywhere would hardly be possible and greatly increase vehicle costs for the light rail vehicles (a very rough estimation would come to at least 500,000 € for each vehicle only for this system; this is equivalent to an increase of the total cost of about 20-25 % for each LRV)
- The main additional technical elements would be the ATC (automatic train control) consiting of ATP (automatic train protection) and ATO (automatic train operation), safety devices at the doors, video cameras on board, additional fire safety devices, automatic couplings.
- The light rail vehicles would use this system only a fraction of the operating time, otherwise it would not be used and additional "conventional" driver – vehicle interfaces would have to be provided

Some lessons can be learnt from the city of Nurnberg. In Nurnberg the operator is upgrading a first line of its metro system to automatic operation[11]:

- From 2006 on the line U3 will operate fully automatic without any drivers, but this line will be newly built.
- The interesting aspect is that in the city center between the stations "Rothenburger Strasse" and "Rathenauplatz" a mixed operation with the conventional line U2 is planned. But in 2007 this line should be converted (under daily operation conditions!) to an automatic mode.
- A detailed feasibility study including economic aspects was carried out before[12]. This study showed that the project makes economically only sense because the older metro vehicles have to be replaced anyway and the demand for a new line is existing and this line has to be built now. Otherwise the project would not have been realised.
- All metro vehicles operating in the future in an automatic mode are new built.
- The additional cost for the whole project is 210 Mio. € (110 for vehicles and 100 for infrastructure)[13]

[11] See: ETR 11, 52 (2003), pages 679-685: Eine automatische U-Bahn – Technische Besonderheiten der AGT-Fahrzeuge für Nürnberg

[12] The acronym for this study was „SMARAGT"; more information is available under www.smaragt.de

[13] The „normal" cost of 300 Mio. € to built the line U3 nust be added to these numbers.

These information from Nurnberg show that under special conditions an upgrade to a fully automatic system may make sense. It is obvious that the conditions in Helsinki are not the same[14] and only the pure metro conversion to automatic operation is a great challenge.

For these reasons, such a full-automatic-system was not included in the LRV price which was basis for the calculations in chapter 4.3.3. Rather, a semi-automatic system was used as a basis for the following reasons:

- Such systems, e.g. LZB systems used in Germany, are already existing (e.g. Düsseldorf) and operational
- It does not make sense, to include a further critical system into an already complicated mixed operations scheme.
- A fully automatic system is normally a "closed box". The introduction of external additional vehicles at some defined points will be technically possible but will lead to additional requirements to guarantee a safe and reliable operation. This will cause additional cost and affect the stability of the whole automatic system.
- The introduction of light rail line of sight operation into the semi-automatic section is possible and has been done.
- The driver of the light rail vehicle would have to stay in the vehicle anyway and therefore it is not a problem for him to control the doors and check the operations of the vehicle
- In this case, the cost per vehicle will only be a fraction of the cost which would need to be assumed for fully automatic operation. This has been included in the calculations in chapter 4.3.3.
- The additional cost for the integration of the LRV into a fully automatic system are very high in comparison to the expected benefits.

✓ **Therefore, one of the conclusions of this study has to be, that if a fully automatic metro system has to be introduced on the metro, mixed operations should not be pursued.**

✓ **The main reasons are: High technical complexity, economical aspects and time constraints**

[14] E.g. in Helsinki all metro cars are already prepared for a future automatic operation. Within the vehicle structure space was reserved from the beginning on for technical equipment required for the automatic operation

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5 Summary and Recommendations

5.1 Summary of economical aspects

In this chapter all estimated numbers will be be made comparable by the use of annuities and the estimated overall related annual project costs will be explained. The following principles were used:

- Vehicles: 5 % interest, lifetime 30 years, 0 % residual value
- Infrastructure: 5 % interest, lifetime 50 years, 50 % residual value[15]

The formula to calculate the annuities g is[16]:

$$g = C_0 \cdot \frac{(1+i)^T \cdot i}{(1+i)^T - 1} \qquad C_0 = \sum_{t=0}^{T} \frac{a_t}{(1+i)^t}$$

With the help of this transformation all numbers have the same annual basis and can be compared. The following table summarises the results[17]:

[15] Calculated back on today's value. Example: For an investment of 1 Mio € today the residual value (a_{50}) is not 0.5 Mio €, but 43,600 Euro. The net present value (C_0) of today is then 1,000,000 – 43,600 = 956,400 Euro.
[16] g = annuities, C_0 = net present value, i = rate of interest, T = lifetime, a_t = cash flow at time t
[17] . Scenario 1 is based on tracks above the ground between Matinkylä and Tapiola, Scenario 2 underground.

		Reference Case	Scenario 1 LF	Scenario 1 HF	Scenario 2 LF	Scenario 2 HF
Section A Matinkylä - Tapiola	stops / platforms	standard metro	24.000 € p.a.	0 € p.a.	37.000 € p.a.	0 € p.a.
	track / power supply	standard metro	81.000 € p.a.	0 € p.a.	52.000 € p.a.	0 € p.a.
Section B Jokeri Line Tapiola - Itäkeskus	stops / platforms / track	low platforms	79.000 € p.a.	174.000 € p.a.	same as scenario 1	
	connections incl. power supply	n.a.	3.137.000 € p.a.	3.137.000 € p.a.		
Section C Itäkeskus-Vuosaari	stops / platforms	standard metro	105.000 € p.a.	0 € p.a.	same as scenario 1	
	track / power supply	standard metro	79.000 € p.a.	0 € p.a.		
	Other operational cost	Operation of Jokeri line 27.3 km line length maintenance on site except for large parts	120.000 € p.a.	60.000 € p.a.	same as scenario 1	
	Personnel		420.000 € p.a.	420.000 € p.a.		
	Maintenance		300.000 € p.a.	60.000 € p.a.		
	Energy consumption		80.000 € p.a.	80.000 € p.a.		
	Vehicles	About 29 vehicles on the Jokeri line	1.281.000 € p.a.	530.000 € p.a.	same as scenario 1	
	Depot and connection to depot	New depot +connection, but using metro depot for maintenance of larger parts (trucked there)	-249.000 € p.a.	-249.000 € p.a.	same as scenario 1	
		Sum:	5.457.000 €p.a.	4.212.000 €p.a.	5.441.000 €p.a.	4.212.000 €p.a.
		Sum without connections:	2.320.000 €p.a.	1.075.000 €p.a.	2.304.000 €p.a.	1.075.000 €p.a.

Tab. 5: Matrix of influence

Some interesting conclusions can be drawn from the table:

- It is easy to see that the additional annual cost for the joint operation is in the range between 4,2 Mio € for the high-floor case and 5,4 Mio € for the low-floor case.
- The major part of these costs results from the connecting constructions, which are the same for both cases.
- Without connections it becomes clearer, that the high-floor case is economically more attractive. The additional annual cost (without connections) is 1,1 Mio € for the high-floor case and 2,3 Mio € for the low-floor case.
- The advantage of the high-floor case is mainly based on the lower procuring and maintenance cost.
- The depot cost can be reduced for both cases in comparison to the reference case.
- Higher revenues or any public funding have not been taken into account.

5.2 Recommendations

The question is now what kind of recommendations can be derived from these numbers and the technical issues:

- The low-floor case is more expensive and from the technical point of view the greater challenge. Platforms in the metro area must be rebuilt what means an interruption of the metro service (or much higher cost). Safety aspects in the metro area play an important role (platform height and passing trains). The advantage is the low level access on the surface.
- The high-floor case is technically easier to realise and cheaper. There are no main safety problems. The metro infrastructure can remain as it is. The disadvantage are the required high platforms on the surface.

✓ **Therefore it is recommended if the joint operation should be realised to go for a high-floor solution in a semi-automatic metro environment**

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But there are some additional aspects which should be taken into account for any future decision:

- The advantages of the joint operation (more passengers!) must be estimated and the revenues calulated to check whether the joint operation can cover at least a part if its cost. Only this data allows a better evaluation of the overall economic situation.
- The demand forecast would also lead to a more precise system dimensioning, which is based on too many assumptions at the moment.
- The connections must be subject to a more detailed planning to take sound decisions.
- The joint operation must be integrated into the plans for the automatic operation of the metro from the early beginning on, otherwise the cost will explode.
- And in case of a fully automatic operation the joint operation should not be realised.
- If the low-floor case (inspite of the arguments and recommendations of this study) is the favourite, safety aspects must play the most important role in all further plannings.

5.3 Additional aspects for an operation on the Jokeri line only

If the joint operation will not be realised, some fundamental questions for the Jokeri line came up during this study:

- If a low-floor LRV is chosen a 70 % low-floor solution with normal bogies should be considered.
- The gauge of 1,435 mm defined in this study as a reference case should be reconsidered (mixed operation heavy rail and LRT (a long term perspective?) and the use of the metro depot would not be possible).
- Infrastructural parameters need to be studied more in detail for any concept that´s chosen; the parameters should be adapted more to light rail than to tram standards (e.g. stop spacing, curve radius, operating speed, signalling etc.).
- Integrated planning of vehicle and infrastructure design is vital for the success of a system (BOT contracts do not necessarily solve this problem!)
- Long-term cost impacts should be give a priority: LCC, form follows function in design (use the technical experience from Germany and take the design from France).

5.4 Key messages of this study

- ✓ **Both a low- and the high-floor-LRV would technically fit into the metro system. But the intergation of a high-floor-LRV is much easier to be realised.**
- ✓ **The overall additional annual cost for a mixed operation is between 4,2 Mio € (high-floor-LRV) and 5,4 Mio € (low-floor-LRV). Major part of these cost come from the connections.**
- ✓ **The joint operation should not be realised in a fully automatic metro environment.**

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