Recent Developments in Cable-Drawn Urban Transport Systems

Klaus Hoffmann
Head of Institute
Vienna University of Technology
Institute for Engineering Design
and Logistics Engineering

Cable-drawn transport systems are widely employed as people transportation systems in alpine areas. However, in recent years these transport systems have also been increasingly used in urban areas, and many applications can also be found as transportation systems in airport facilities. In this paper the working principles of cable-drawn passenger transportation systems are discussed. Particular attention is focussed on single- or bicable continuous ropeway systems, funicular railways and inclined lifts. The function and mode of operation as well as advantages and disadvantages of these cable railway systems are described in detail. Several of the solutions at present under construction or already in operation with quite diverse systems are demonstrated. Finally the current fields of application and operational limits of the individual types of construction regarding travel speed, route lengths and carrying capacity are described.

Keywords: *Urban transport, aerial ropeways, funiculars, inclined lifts, cable car, APM system.*

1. INTRODUCTION

A ropeway is a system for the transportation of passengers or goods whereby the passengers or goods are conveyed in different types of cars. The runway is made of ropes (one or two) or rails and concrete carriageways respectively. The hauling function is carried out by means of one or more ropes.

The principle of the cable-drawn transport system was known even in ancient times. As early Chinese historical drawings demonstrate, this principle was already in use at that time for passenger and material transport. Figure 1 shows the earliest known picture of passenger transportation from 250 B.C., South China [1].

In the Middle Ages a monocable aerial ropeway was depicted in a book by Johannes Hartlieb (Figure 2).

During the course of the Industrial Revolution, the invention of the steel cable by the German mining official Albert in 1834 heralded a period of lively development of the various cable-drawn transport systems [1]. While initially development mainly focused on funicular railways such as the Cable Car Line in San Francisco, 1872 (see Figure 3), later interest turned to aerial ropeways, which only came into operation for passenger transport shortly after 1900. A fine example is the reversible aerial ropeway in San Sebastian, Spain opened 1907 (Figure 4).

Various technical systems have evolved over the decades. For example, more recent systems can be classified according to the type of track (carrier) used. Figure 5 shows an overview of the various systems, which are naturally in use with very diverse frequency.

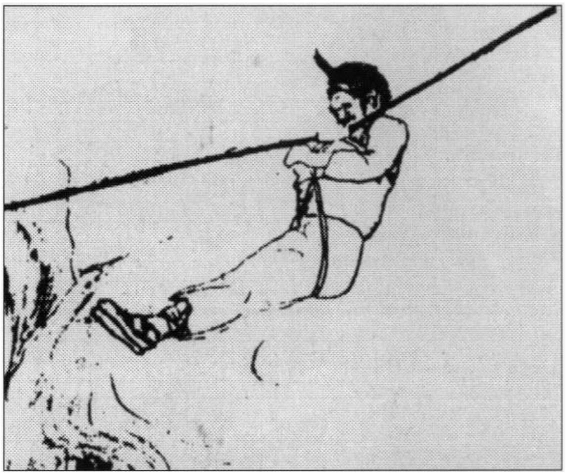


Figure 1. Brush drawing of a Chinese aerial ropeway dated 250 B.C.

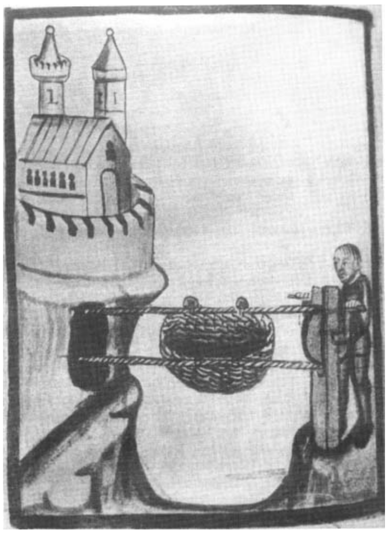


Figure 2. Drawing of a monocable aerial ropeway from A.D. 1411

Received: September 2006, Accepted: December 2006

Correspondence to: Dr Klaus Hoffmann, Ao. Professor
Vienna University of Technology, Institute for Engineering Design and Logistics Engineering
Getreidemarkt 9, 1060 Wien, Austria
E-mail: hoffmann@ikl.tuwien.ac.at

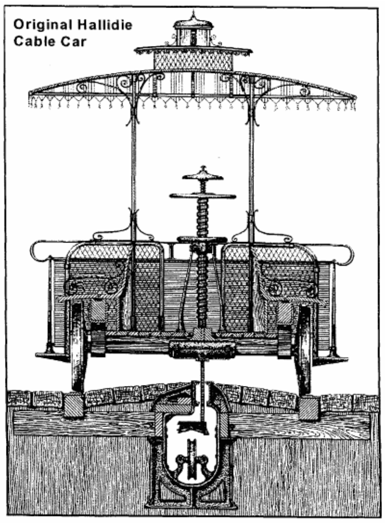


Figure 3. Cable Car, San Francisco, 1872

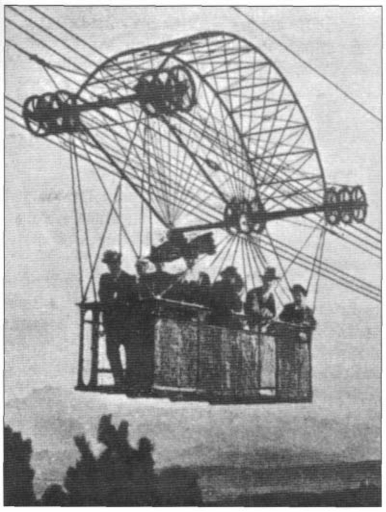


Figure 4. Reversible aerial ropeway in San Sebastian, Spain, 1907

Bicable aerial ropeways and funiculars will subsequently be described in more detail. In addition, inclined lifts are intrinsically a modified form of funicular railway, but are subject to lift regulations [4] and therefore cannot be directly regarded as funiculars [5].

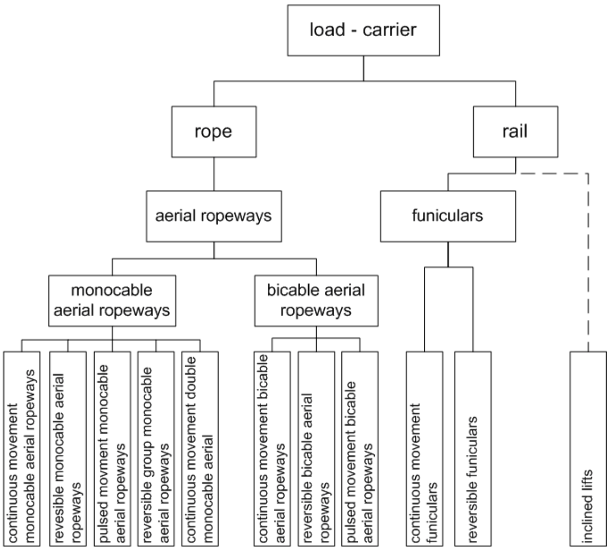


Figure 5. Classification of ropeways

2. AERIAL ROPEWAYS

2.1 Design and mode of operation

The main difference between continuous movement monocable aerial ropeways and bicable aerial ropeways is simply the number of rope systems. While with a monocable ropeway one or two ropes assume the carrying and hauling function (carry-hauling cable), with a bicable aerial ropeway the cars are carried by one or more ropes (track ropes) and moved by a further rope system (haul rope). The continuous movement operation is thus characterised in that moving rope always circulates with uniform speed.

With a detachable continuous movement bicable aerial ropeway the clamping to the haul rope is by means of operationally releasable clamping devices. In the station the cars are separated from the haul rope, decelerated and guided onto an overhead monorail which leads the car at low speed through the embarkation and disembarkation area. Before the station exit the car is accelerated again to the constant haul rope speed and joined to the haul rope by the closure of the clamp. Thus the clamping device fixed to the car can grip the haul rope at any point, so enabling the setting of various sequential intervals between the individual cars.

Outside the station area the ropes are led over line support structures, the track rope on saddles (track rope saddle), the haul rope on support rollers. At the circulating operation there are two track ropes that are permanently anchored at one end of the track, normally the upper end, and maintained under constant tension by weights at the other end. Each of the two track rope sections serve for just one direction and are linked together in the upper and lower stations by the overhead monorails. The haul rope can be tensioned either by a tension weight or a hydraulic tensioning cylinder. Drive for the haul rope is provided by the electric motor-driven drive pulley.

The design and mode of operation of detachable bicable aerial ropeways are as described in Figure 6.

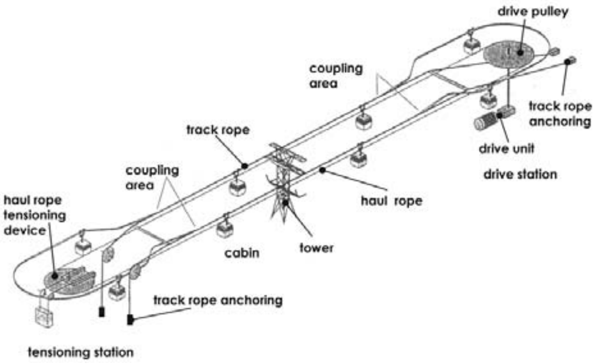


Figure 6. Diagram of a detachable bicable aerial ropeway [9]

2.2 Application area

The advantages of both systems (monocable and bicable aerial ropeways) are: high safety, high carrying capacity, long routes can be implemented (up to approx. 6 km/section), adaptability to the terrain, continuous passenger flows thanks to the constant movement, low space requirement along the route, no overlap with other forms of transportation.

Further advantages of the bicable aerial ropeway are that very long rope spans are feasible (up to approx. 1,500 m), and high wind stability.

Disadvantages of both systems include weather-sensitivity, as safe operation cannot be maintained in the event of high winds, while heated cabins are hardly feasible.

Further disadvantages of the monocable system include low wind stability, and long rope sections can only be implemented with difficulty.

As high carrying capacity is independent of track length and intermediate stations along the route are easy to implement, this ropeway system is admirably suitable for covering long distances in inner urban areas (up to 6 km for a ropeway section).

Where particularly wide distances have to be spanned, two parallel supporting cables are used. This configuration excels with its particularly high wind stability. However, to date it has only been used in mountain regions, but not yet in urban areas. A widely-acclaimed example of this is presented in Section 2.4.

2.3 Example 1: Tung Chung Cable Car

The Tung Chung Cable Car, a detachable continuous movement bicable aerial ropeway, consists of two sections (0.5 m + 5.2 km) with a total length of 5.7 km. Figure 7 shows the alignment of the Tung Chung Cable Car. The first section begins in conjunction with the public transport system from Hong Kong in Tung Chung. From there it crosses Tung Chung Bay to an angle station on Airport Island. The second section leads from Airport Island via a further angle station at Nei Lak Shan to the terminus in Ngong Ping.

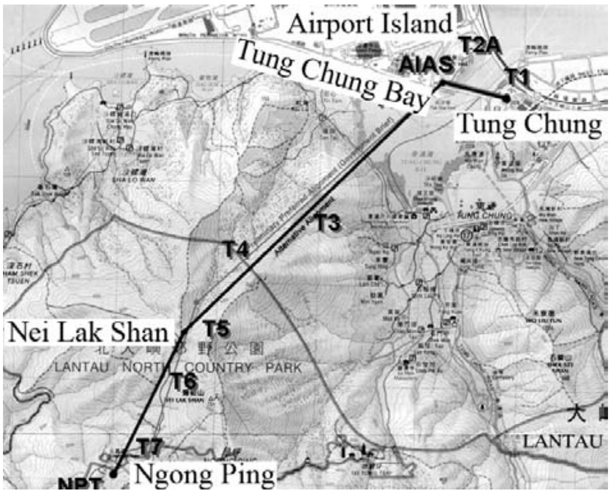


Figure 7. Alignment of the Tung Chung Cable Car [7]

Next to the Ngong Ping Station there will be a themed village leading all the way to the Ngong Ping plateau, where the world's largest seated outdoor bronze Buddha Statue is located. The ropeway will be supported by 8 towers. In total there are 11 comfortable 17-person cars with a carrying capacity of 3,500 passengers per hour. The ropeway journey will offer an attractive 20-minute aerial alternative to the current one-hour journey by Tung Chung Road. In addition to being a new attraction, the ropeway should also provide an appealing interlude for transit passengers at the airport. The Tung Chung Cable Car was opened to the public in September 2006 (Figure 8).

Figure 8. Tung Chung Cable Car [6]

2.4 Example 2: 3S Kitzbühel Aerial Tramway

The 3S Aerial Tramway is a large-scale cabin aerial ropeway which was built to connect the two ski resorts Kitzbühel and Resterhöhe (Figure 9). The mode of operation is similar to that of a detachable bicable aerial ropeway, however the track consists of two carrying ropes. The very large span of 2,500 metres bridges the Saukasergraben with a maximum height above ground of 400 metres. Some 24 cabins with a capacity of 30 persons and a travelling speed of 7.0 m/s give a maximum transport capacity of 4,200 persons in the hour. Figure 10 shows the carrying pulleys and the clamping device which connects the haulage rope with the cabin.

Figure 9. 3S Kitzbühel Aerial Tramway [10]

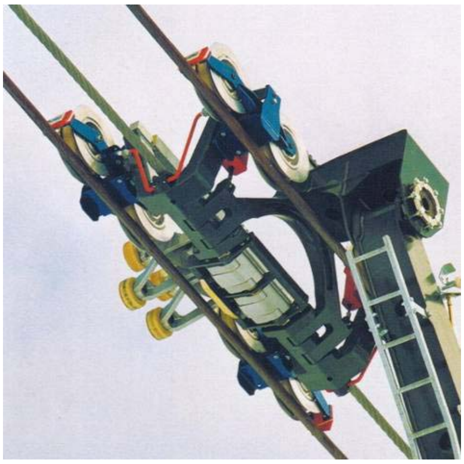


Figure 10. Travel carriage with clamping device [10]

3. REVERSIBLE FUNICULARS

3.1 Design and mode of operation

Figure 11 shows the basic layout of a funicular railway in shuttle operation. Two cars are linked together by a haul rope and this moves them along the route. The cars travel on tracks using steel rollers on rails. The drive unit for the system is housed in one of the stations. Electric motors propel the drive pulley and thus the haul rope via a gearbox. The service brakes act on the flywheel of the fast-moving shaft of the motor, thus braking the entire system (car and haul rope). Passengers embark and disembark when the car is stationary. Funiculars are normally designed as single-track systems. For this reason a passing point is provided in the middle of the route.

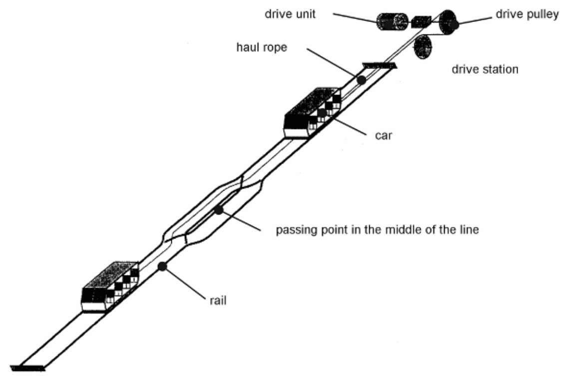


Figure 11. Layout of a reversible funicular

3.2 Application area

This ropeway system is particularly suitable for shorter routes (up to approx. 1.5 km long) in urban areas, where the requirement is for optimum carrying capacities combined with high safety and availability of the system.

Advantages of this system include an environmentally sound, high availability of the system, low maintenance and service requirements, flexible route planning (horizontal and vertical deviations as well as tunnel negotiation possible), optimum travel speed for rope-drawn ropeway systems, operation independent of weather.

Disadvantages are that carrying capacity is heavily dependent on route length and irregular passenger flow due to shuttle operation.

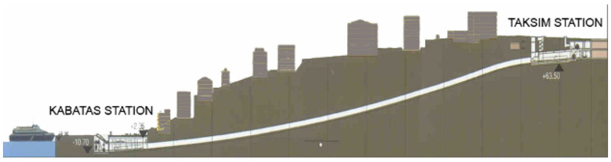
3.3 Example 1: Montjuic funicular, Barcelona

Figure 12 shows the Montjuic funicular in Barcelona, Spain. This fully automatic funicular was built as part of the transportation system serving the competition facilities located on the Montjuic Hill for the 1992 Summer Olympic Games. It is integrated in the city's public suburban transport network and links the underground line with the tourist attractions and leisure facilities of Montjuic. The carrying capacity is 8,000 persons/hour with a route length of 720 m and a travelling speed of 10 m/s, carrying 400 passengers per car.

Figure 12. Montjuic reversible funicular in Barcelona, Spain [6]

3.4 Example 2: Taksim-Kabatas funicular, Istanbul

This very new underground funicular links the sea terminal for the boats to the Asiatic part of Istanbul with the new Taksim – Levent metro line at Taksim Station (Figure 13). This funicular has two cars, each with a capacity of 375 passengers, travelling on a single-track route. The trains can pass each other in the middle of the route by means of an Abt points switch. Due to the relatively low height difference, a ballast rope is used, tensioned with an 18 tonne counterweight. The Doppelmayr Garaventa Group was responsible for the design and installation of the complete funicular. This new funicular was put into service in June 2006.



Rail level at Kabatas station	-11.10	[m.a.s.l.]
Rail level at Taksim station	+63.85	[m.a.s.l.]
Inclined length	640.45	[m]
Maximum slope	22.19	[%]
Vehicle capacity	375	[pass.]
Maximum speed	10	[m/s]
System capacity	7500	[pers./h]

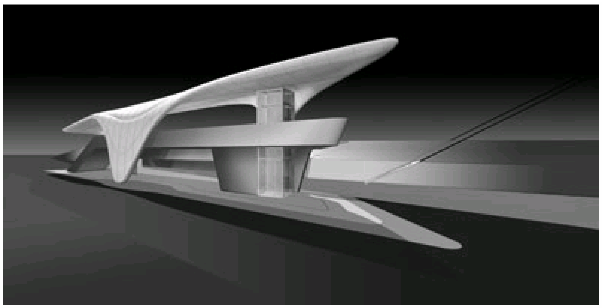
Figure 13. Taksim-Kabatas funicular railway in Istanbul [10]

3.5 Example 3: Hungerburg funicular system, Innsbruck

Renovation work recently commenced on the cable car system linking the centrally-located Congress Centre in the city of Innsbruck with the summit ridge of the Nordkette (Figure 14).

The overall project was subdivided into three sections. For the first section, the Leitner construction company provided a partially-underground funicular railway from the Innsbruck old city via the Löwenhaus and the Alpine Zoo to the Hungerburg. For the two upper sections, the existing cableways were renewed. The architectural designs were drawn up by the world-famous architect Zaha Hadid, who was also responsible for the design of the new Bergisel ski jumping hill. Figure 15 shows the interesting design of the Löwenhaus station building. The layout of the line of the funicular railway starts out almost on the level at the Congress Centre, but ends up very steeply at the Hungerburg (top) station. A special development for this feature was the automatic inclination correction system for funicular carriages with five passenger cabins (see Figure 16). The inclination correction system ensures that passengers can embark and disembark comfortable from a horizontal passenger compartment not only at the lower and upper terminuses, but also at the two intermediate stations. In future, the two carriages of the funicular railway, each with a capacity of 130 persons, will be able to transport up to 1,300 p/h in each direction.

Figure 14. Alignment of the Nordkette ropeways in Innsbruck [6]



Visualisierung der Station Loewenhaus

Figure 15. Station design by star architect Zaha Hadid

Figure 16. Carriage of the Hungerburg funicular railway [11]

3.6 Example 4: Cable liner shuttle

One important alternative for passenger transport over short or medium distances (up to several kilometres) is the cable liner shuttle. This is a train that normally consists of several coupled single cars. This train is moved between the stations on a horizontal route by a haulage rope. The cars normally roll along on steel rails, but there are designs where the cars are supported on air cushions.

A system is currently under construction for Mexico City Airport (Figure 17) which is expected to go into service in 2007. The route is approx. 3 kilometres long. With a maximum speed of 12.5 m/s (= 45 km/h) the journey time between the existing Terminal 1 and the new Terminal 2 at present under construction will be approx 4.5 min. On completion, transport capacity will be some 800 passengers per hour in each direction.

This project is the third airport APM system constructed by Doppelmayr Cable Car GmbH, Austria[10]. The first two projects were successfully implemented at Birmingham and Toronto airports (Figure 18).

Figure 17. International Airport, Mexico City [10]

Figure 18. Airport Link, Pearson International Airport, Toronto [10]

4. INCLINED LIFTS

4.1 Design and mode of operation

The inclined lift is a modified form of the funicular railway in shuttle operation with just one car for transporting passengers over a single-track. But in contrast to a conventional lift, the main difference is that with this transport system the route can be adapted to the terrain. An automatic adjustment device for cabin inclination is also feasible, not only for travelling over a constant inclination, but also a route with varying inclinations. Regardless of the track inclination, the cabin floor remains horizontal. The haul rope is driven by a drum winch or a drive pulley. In the latter case a counterweight travelling between the track bearers balances the car weight.

Designs can differ between inclined lifts with open and covered haul rope loops as shown in Figure 19. In order to increase the driving power of the drive pulley, an additional tensioning device is provided in the other station, thus achieving a closed haul rope loop.

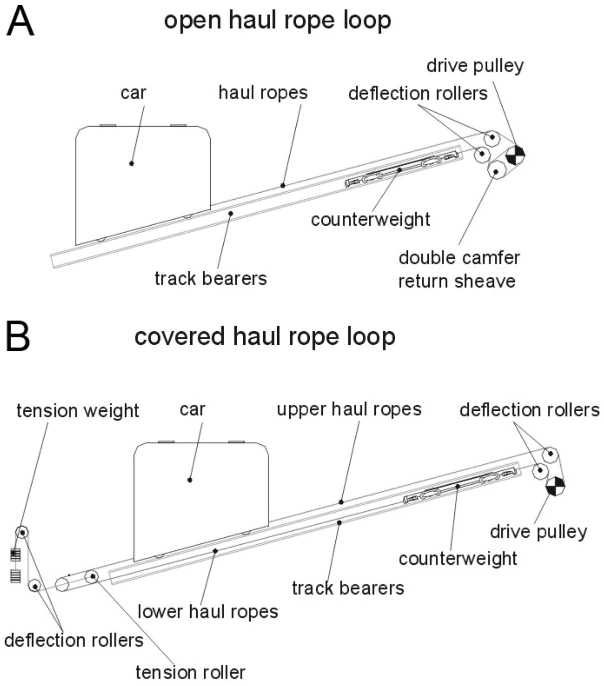


Figure 19. Assemblies of an inclined lift with open haul rope loop (A) and covered haul rope loop (B)

4.2 Application area

This system is widely used particularly in urban areas for ascending short inclines. Thus the inclined lift can easily provide a link between individual hotels, sanatoriums or residential complexes and the main community, parking areas or railway stations. The advantages of inclined lifts are: low space requirement, safe, comfortable, reliable, energy-saving, low-maintenance, quiet in operation, no operator required, extremely resistant to environmental influences, easy transport of wheelchairs or baby carriages, inclinations up to 60° possible, adaptability to existing terrain conditions. A disadvantage is the low carrying capacity of this system.

4.3 Example of an inclined lift, Spa

Figure 20 shows the inclined lift system at Spa, Belgium which consists of two independent, parallel-aligned inclined lifts, each with a cabin capacity of 25 passengers. The maximum route inclination is 32°, and the minimum route inclination 15°. The system links a public parking area with a hotel as well as a public health facility. With a travel speed of 2 m/s and a route length of 160 m, each of the two inclined lifts has a carrying capacity of 250 persons/hour.

Figure 20. Inclined lift, Spa, Belgium [10]

5. CONTINUOUS MOVEMENT FUNICULARS

5.1 Design and mode of operation

In contrast to shuttle operation, a funicular in circular operation requires two completely separate tracks. The cars are coupled to the haulage rope at specific distances by normal releasable clamping devices. Placement of stations along the line is possible without technical limits, according to local service requirements. Figure 21 shows the car of a continuous movement funicular system.

In the stations the cars are automatically detached from the cable and moved by an independent conveyor system, as shown in Figure 22. This is realised with lateral wheels which are moved by inverter-driven motors and form two sections:

- A deceleration sector where the car is slowed down on approaching the parking position.
- A parking and acceleration sector, which has the function of holding the car in the passenger loading area and accelerating it afterwards to the speed of the cable.

At both end stations the cars are rotated through 180 degrees on a rotating platform, so that they can then travel in the opposite direction.

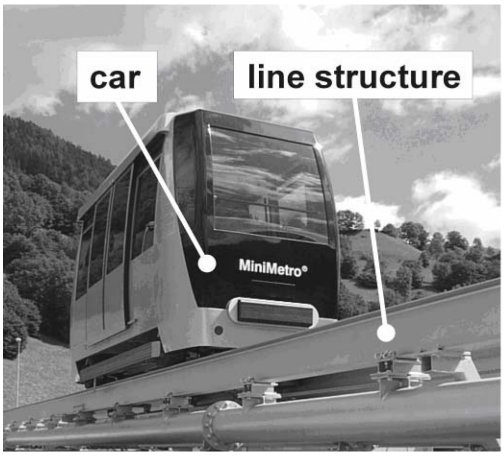


Figure 21. Car of a continuous movement funicular system [6]

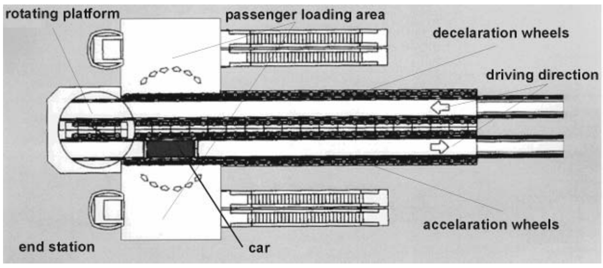


Figure 22. End station of a circulating funicular system [6]

5.2 Range of applications

This ropeway system is particularly suitable as a means of transportation for small and medium sized cities, for connections from public car parks to hospitals, universities or commercial centres, or between centrally-located train or metro stations and peripheral suburbs. It is also known as an automated people mover, or APM system.

The advantages of this system are high availability, environmentally soundness thanks to the central drive unit, fully automatic operation, high carrying capacity, low noise nuisance. Long routes can be implemented, the system is independent of weather, and it is flexibly adaptable to the existing infrastructure.

Disadvantages are high production costs and space requirements.

5.3 Example: Perugia Minimetro

Such a system is under construction in the Italian city of Perugia, linking the Pian di Massiano district with the historic city centre located on a hill [8]. With a difference in elevation of 160 m, the route is 3 km long, of which 1.5 km is on line support structures and more than 1 km passes through tunnels. A planned second section will be implemented at a later point in time. Embarkation can take place at seven stations. A total of 25 cars are in service, each with space for 50 passengers. This system can convey up to 3,000 passengers at a maximum speed of 25 km/h.

Figure 23 shows a part of the track of the lower section of the future system, which will be put into operation in 2007.

In both end stations a rotating platform is installed. Figure 24 shows this platform and the lateral wheels for moving the cars.

Figure 23. Perugia Minimetro – track

Figure 24. Rotating platform in the end station during the construction work [6]

6. LIMITS OF CABLE-DRAWN URBAN TRANSPORT SYSTEMS

An important parameter for the assessment of a transport system is the carrying capacity. To do this with rope-drawn systems, a differentiation must be made between circulating and shuttle operation.

The carrying capacity F_u of circulating aerial ropeways or funiculars in passengers per hour is given by:

$$F_u = 3600 \frac{P}{t} . \tag{1}$$

In equation (1), P is the number of passengers in a car and t the sequence time in seconds. The sequence time is given by the space A between two successive cars and the travelling speed v_F of the system:

$$t = \frac{A}{v_F} . \tag{2}$$

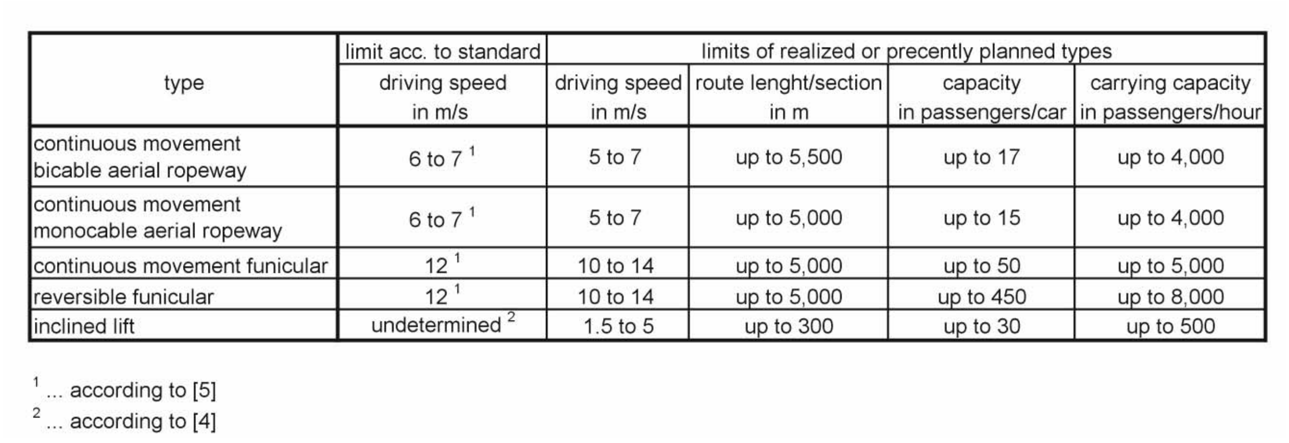
The carrying capacity F_P of shuttle systems results from:

$$F_P = 3600 \frac{P}{t_{ein} + t_b + \frac{L^*_{ges}}{v_F} + t_v + t_{aus}} . \tag{3}$$

With t_{ein} as embarkation time and t_{aus} as disembarkation time of passengers in the stations, t_b the time taken for acceleration of the car on leaving the station and t_v the time taken for deceleration of the car on entering the station, L^*_{ges} the route length over which the car travels at constant speed. From equation (3) it can be seen that the carrying capacity of shuttle systems falls with increasing route length. A larger number of passengers increases the carrying capacity, but also increases the embarkation and disembarkation times [2].

Table 1 provides information on the limits of rope-drawn urban transport systems. The limit values take into account currently valid European standards for cableway systems for passenger traffic and those for inclined lifts take into account the European standards for lifts.

Table 1. Limits of cable-drawn urban transport systems



type	limit acc. to standard	limits of realized or precently planned types			
	driving speed in m/s	driving speed in m/s	route lenght/section in m	capacity in passengers/car	carrying capacity in passengers/hour
continuous movement bicable aerial ropeway	6 to 7 [1]	5 to 7	up to 5,500	up to 17	up to 4,000
continuous movement monocable aerial ropeway	6 to 7 [1]	5 to 7	up to 5,000	up to 15	up to 4,000
continuous movement funicular	12 [1]	10 to 14	up to 5,000	up to 50	up to 5,000
reversible funicular	12 [1]	10 to 14	up to 5,000	up to 450	up to 8,000
inclined lift	undetermined [2]	1.5 to 5	up to 300	up to 30	up to 500

[1] ... according to [5]

[2] ... according to [4]

With continuous movement monocable aerial ropeways and bicable aerial ropeways there are limits to the reduction of the sequence time for increasing the carrying capacity, as there must still be sufficient safety intervals between the uncoupled cars in the station areas.

The achievable travelling speed of funiculars is essentially limited by the route layout and thus the deflection of the haul rope along the route [3].

The implemented or currently planned route lengths are mainly limited due to the current limits in the production of haul ropes.

7. CONCLUSIONS

It has been seen that a wide range of variations on rope-drawn transport systems have been operated since ancient times. Many different technical systems described in this paper have since proven themselves well in urban areas. It can be expected that such systems will increasingly come into service in future, particularly in the further development and more effective realisation of existing passenger transport systems. Reduction of congestion on roads, parking problems, noise and air pollution are the most important arguments which will support the further development of cable drawn transport systems in urban areas.

REFERENCES

[1] Schmoll, H.D.: *Weltseilbahngeschichte*, Band 1 und 2, Steidl Verlag, Eugendorf, 2000.

[2] Charamel, F.: Kapazitätsgrenzen beim Ein- und Ausstieg von Seilbahnen, O.I.T.A.F. Conference, Bozen, Italy, 2001, published in http://www.oitaf.org.

[3] Sehnal, W., Grenzen der Linienführung und Geschwindigkeit bei Standseilbahnen, O.I.T.A.F. Conference, Bozen 2001, published in http://www.oitaf.org.

[4] EN 81-1, Safety rules for the construction and installation of lifts – Part 1: Electric lifts (consolidated version), 2006.

[5] EN 12929-1, Safety requirements for cableway installations designed to carry persons – General requirements – Part 1: Requirements for all installations, pp. 24 ff, 2005.

[6] LEITNER, www.leitner-lifts.com

[7] MTRC, www.mtr.com.hk

[8] Minimetro S.p.A., www.minimetrospa.it

[9] Hoffmann, K., Liehl, R., Cable-drawn urban transport systems, 11th International Conference on Urban Transport and the Environment in the 21st Century, Algarve, Portugal, Vol. 77, pp. 36-52, WIT Press, 2005.

[10] DOPPELMAYR, www.doppelmayr.at

[11] CARVATECH, www.carvatech.com