# EVOLUTION OF GUIDED TRANSPORT SYSTEMS FOR URBAN AND SUBURBAN APPLICATIONS

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The situation of guided urban transport is different from one country to the other, but the number of lines is generally increasing regularly : the improvement of urban public transport networks necessitates the implementation of modern performant systems offering a sufficient capacity.
In France about 100 tramways networks were existing at the beginning of the century, but all of them were dismanteled if we except three lines (one in Lille, one in Marseille, one in Saint-Etienne). After 1960, when the inconvenients of an excessive development of private car traffic became obvious, in France and in some other countries the first reaction was to define and try to develop new modes of urban transport, it means new public transport systems which would be attractive enough to seduce car drivers but without limiting the space offered to car circulation. In spite of some technological successes such as for example VAL system (near many failures of too ambitious systems) this approach was not sufficient, and twenty years ago the reintroduction of the tramway started slowly but regularly, in most of the cases at ground level on reserved lanes. In 2001 eleven French agglomerations are equiped with tramway or light rail, in mosts of the case there is only one line or two.
In Germany the networks were not dismanteled and 55 towns are now equiped with tramway or light rail, often with several lines.

## Technical innovation for three important families of guided transport systems

We will mainly investigate the possible evolution of three important families of urban or suburban guided transport systems which are different but can have similar components and between which we can find some « bridges » :
- fully automated systems usually called *automated guided transport systems* (AGT) or sometimes *automated people movers* (APM) although this last denomination was at the beginning reserved for small and middle sized systems ;
- light guided urban transports, including iron wheel on rail tramways which evolute and pneumatic-tyred guided systems until now often called *intermediate systems* ;
- light railways systems for suburban application : interconnexion tramways (« tram-trains »), regional tramways (« train-trams »), non conventional systems.

It is each time interesting to examine the position of classical iron wheel on rail technique, as regards other types of rolling or suspension.
There are many different types of urban and suburban systems. The objective of a classification with three important families is not to include all of them, but is to point out significant innovations and evolutions, and to identify general tendancies. We are here focussing on technical evolution and its adequation to the context in term of environment, social requirements (for example accessibility for disabled people) and modification of the urbanization. We will not deal with classical metros and classical suburban trains although they currently carry considerable flows of passengers, but these systems are here consired if they evolute towards fully automated versions or new suburban systems.

## Fully automated systems : AGT

Paradoxically when the first researches were carried out 30 years ago, the most sophisticated concepts were envisaged such as PRT or Pesonal Rapid Transit (complex networks with a big amount of small individualized cabins offering a direct origin-destination service), and nowadays we consider more simple solutions such as automatic light metros. Around 1980, intermediate solutions between PRT and automatic light metros were envisaged, such as GRT in USA, C-Bahn in Germany and ARAMIS S in France (this later was abandonned in 1987).
Forgetting the old American classification according to the level of complexity (PRT, GLT, SLT) we will now consider three main sub-families according to the range of applications :
a) AGT for specific urban applications ;
b) AGT for short to middle range applications (including what some specialists usuallly called « hectometric systems », but the denomination was too restrictive) ;
c) AGT for specific suburban applications.

All AGT systems nowadays under operation are of type a or type b. Type c (suburban applications) is nevertheless worth to be mentioned, because of some original technological developments which were carried out, for example with magnetic levitation (see further paragraph suburban systems).

Almost all AGT systems manufactured all around the world have chosen the pneumatic tyres rolling, except a few recent systems : it is the case in all the countries where many developments have been carried out, such as USA, Japan and France. It is an important criteria for an AGT system which has to guarantee short intervalles, which has very often to guarrantee a precise stopping in front of platform doors, and which has sometimes to climb significant slopes, if required with the pushing of a vehicle under failure. A second reason is the reduction of noise and vibrations, in particular for systems which are implemented on aerial guideways .
It is interesting to note that chronologically the first AGT system with wheel on rail technology was the Skyrail in Vancouver (ALRT, Advanced Light Rail Transit built by Bombardier) which is characterized by a linear motor traction, that means that there is no adhesion constraint. Nowadays there is a small number of AGT systems with wheel on rail technology. Besides two other applications for the above mentioned ALRT with linear motor there are now also recent systems with rotating motors :
- the relatively recent implementation of the automatic light metro in Copenhagen, built by Ansaldo ;
- the AXONIS system built by ALSTOM Transport which will be in operation in Singapour in 2002 on the Nord East Line and a few years later on the Marina Line. This system is equiped with platform doors (as other systems like VAL for example), which was not the case of above mentioned Skyrail/ALRT.

The fully automation of classical systems which has been envisaged in Germany (light rail in Frankfurt, metro in Berlin, S-Bahn in Dresde) could in case of achievement increase the number of lines with iron wheel on rail technology : studies have been carried out but the decision of construction has not yet been taken. We are here at the transition with classical systems and we can point out an evolution. At the beginning the objective ot developing AGT systems was to create new systems completely different from existing systems.  There was then automatic light metros like VAL, Skytrain or Japanese systems. Later on MAGGALY in Lyon and METEOR in Paris represented the realization of a new line inside an existing network, with a fully automated vehicle built on the same basis than other vehicles circulating on non automated lines of the same network. A further step would be the fully automation of existing lines which were at the beginning conceived for human driving.

For all these systems an important advantage of the fully automation is a better operation flexibility (adaptation of the vehicle offer to the passenger demand) and a higher frequency during off-peak hours.

## Short to middle range systems

Most of the short to middle range AGTs have been built in airports or other big complexes (universities, exhibition parks…), some of them have been implemented in urban networks. The former AEG Westinghouse system (now Adtranz/Bombardier) has found about 20 applications around the world. It is characterized by a « classical » technology, with rotating motors and pneumatic tyres.

Among short to middle range AGTs the cable hauled POMA-OTIS system is characterized by the proposal of three different solutions for rolling or suspension : pneumatic tyres, air cushion or iron wheel on rail. This last solution was until now not used, but it has been recently tested on a prototype. We can here also note that mechanical active guideway suppresses adhesion constraints and facilitates the choice of air cushion as well as of iron wheel on rail technology even in case of important slopes. This system can be envisaged as an airport people mover (there are a few projects around the world) or as an automatic minimetro.

Another interesting case of short to middle range AGT is SK system which has successively chosen three different types of rolling during the development, following the increase of vehicle weight and performances :

- wheels with polyurethan coating for the first generation SK ;
- wheels with rubber coating for the second generation ;
- pneumatic tyres for the third generation SK which has been dismanteled in Roissy/Charles de Gaulle airport because of excessively  severe specifications, but is now in operation with a good availability level in Changaï (China) in a more simple configuration.

SK is an original system with small vehicles and short intervalles (30s or less) which is well adapted to short distances, for example up to 2km. The diffusion of this system was delayed by the failure of the former manufacturer, but since this year 2001 the manufacturing is assumed by another company : SNC Lavalin.

These examples are given in order to show that for guided transport there are many different technical solutions that are more or lesss adapted to specific cases, according to different parameters such as line length, capacity, etc. Lower speed and shorter intevalles are compatible with short lines.

# Light guided urban transport

As regards the technical component for rolling and guidance the general evolution is opposite to that of AGT systems. Until now all tramways and light rail systems utilize classical iron wheel on rail technique, but recent researches have been carried out in order to developp new guided systems on pneumatic tyres. These systems used to be called « intermediate systems » (intermediate between bus or trolley and tramway), but this denomination is ambiguous as the concept « intermediate » could be considered on three different points of view :

- intermediate as regards capacity ;
- intermediate as regards costs ;
- intermediate as regards technical solution (a vehicle which is rolling on pneumatic tyres as a bus, but which is guided as a tramway).

A few years ago these three concepts were often considered combined, in order to qualify the emerging new systems which are guided and on pneumatic tyres. But nowadays it appears important to dissociate these three ideas, especially for two reasons :

- manufacturers of classical tramways announce weight reductions and cost reductions for their future vehicles and systems. In France, with the help of national programme PREDIT , Alstom Transport launched researches concerning an intermediate system on iron wheels : STIF (« Système de Transport Intermediaire sur Fer ») ;
- there are various solutions to realize guided systems on pneumatic tyres. For some developments the capacity is really intermediate, for other ones it is comparable to that of articulated busses or trolleybusses, and for other ones the capacity is larger and comparable to that of classical tramways.

## Guided systems on pneumatic tyres

At the beginning (until the end of the 90 years), urban light guided transport on pneumatic tyres was only represented by guided bus or guided trolleybus such as O-Bahn in Essen (Germany) and Adelaide (Australia) or such as similar developments in Japan and England. A few lines are being operated around the world for a few years. The functionning is generally judged satisfactorily, but the development of this solution is limited for different reasons, among which :

- guidance rails are above the rolling surface level. It means that the site cannot be crossed ;
- small cuves are not possible, we must consider curve radius higher than a value which is about 60m ;
- the guideway is not significantly cheaper than that of a tramway, for a capacity that is lower. Cost savings by means of guidance bimodality (it means partial equipment of the site with guidance infrastructure) is only possible for specific configurations.

Most of the recent developments of guided systems on pneumatic tyres have been carried out in France (with some exceptions such as the development of a system with electronic guidance in Holland : « Phileas » foreseen in Eindhoven), in order to obtain improved functionnal characteristics compared to that of guided busses, for example as regards the possibility of crossing the site. There are three different technical developpments.

TRANSLOHR conceived by LOHR Industrie as well as TVR conceived by Bombardier are guided by a central rail which is laid under the rolling surface level. But there are some technical differences. For each TVR axle the wheels are oriented by a mechanical device including two vertical rollers, and for Translohr each whole axle is oriented by a mechanical device including two pairs of oblique rollers (« guidance in V »).
CIVIS conceived by MATRA Transport and IRISBUS is developped on the basis of an articulated bus or trolleybus, with an optical guidance (on board cameras following a painted reference on the track), which is if necessary completed by mechanical stops (kerbs) on some parts of the line where the width ot the track has to be reduced and where the speed has to be higher than a determined value (for example 40 km/h). For the three first CIVIS projects (Rouen, Clermont-Ferrand and Las Vegas) no kerb will be built and in a first stage the optical guidance will be implemented discontinuously (not all along the track) with a priority for station areas for accessibility purpose.

Besides technical differences it is important to point out the differences concerning the general concept of the systems, and we will therefore consider three levels of guidance bimodality :

a) for CIVIS as well as for TVR in Nancy there is a total guidance bimodality, it means that during normal operation some parts of he line are guided and other ones are not guided.

b) for TVR under construction in Caen there is an exceptional bimodality, it means that the vehicle is always guided during normal operation, but the guidance is avoided for the link with the depot/workshop and eventually in some cases of specific disturbed operation ;

c) for TRANSLOHR STE (which represents nowadays the basis version of the TRANSLOHR system) there is no guidance bimodality, it means that the vehicle is always guided. As a consequence of this choice the vehicle is not limited to 24m according to road regulation (according to he French regulation « code de la route » the maximal length is 18m but in specific cases derogations can be obtained until 24,50m). This explains two characteristics of the TRANSLOHR STE :
   - the narrow gauge (2,20m) chosen to facilitate insertion and to reduce axle load (the capacity reduction can be compensated by an increased vehicle length) ;
   - the length modularity according to the number of car bodies chosen (for example 25m for STE3 with three bodies, 39m for STE5…).

Contrarily to other guided systems on pneumatic tyres the TRANSLOHR STE has functional characteristics which are comparable to that of modern tramways in terms of capacity and reversibility. The development of a specific switch was required (it is not necessary for a bimodal vehicle which can leave the rail), but this switch can be relatively simple because of the single rail (instead of two rails for railways vehicles).

## General comparizon between pneumatic and iron wheels rolling

A detailled comparizon is always difficult for the following reasons :

a) The type of rolling cannot be juged alone, we must consider the interference with the whole system. There is until now a very big amount of guided systems with iron wheels and only a few guided systems on pneumatic tyres. If we consider more specifically the case of the real « tramway on pneumatic tyres » it is its first experimentation.

b) Iron wheel on rail rolling has well known advantages such as higher limits for speed and axle load, but they are not useful inside the field of application of light urban guided systems.

c) Pneumatic tyre rolling has a well known advantage in term of adhesion. This advantage cannot always be fully utilized. This advantage becomes obvious for lines with significant slopes. The maximal slope is often considered to be 13%, it could be much more but the limitation is due to the confort criterion for standing passengers. Even if some old small iron wheels tramways used to climb slopes up to 13%, we must now consider lower values for modern tramways with low floor and they can only reach 10% in specific configurations if all axles are motorized (for example in Würzburg). The higher adhesion of pneumatic tyres allows higher deceleration rates, but for guided vehicles (contrarily to bus) the maximum emergency value is limited in order to avoid the falling of standing passengers : the maximal value is for example 2,5 m /s2 for metros or AGTs and about 4 m/s2 for tramways.

d) Another advantage of pneumatic tyre rolling is a better adaptibility to short curve radius, but as far as possible these curves have to be avoided in tramway lines in order to keep a satisfying commercial speed.

e) An important expected advantage is infrastructure cost reduction due especially to better insertion capabilities, but it is too early to confirm a detailled economical comparizon.

As a conclusion an important challenge for the tramway on pneumatic tyres could be the reduction of noise and vibrations. Many experts (Jäcker-Cüppers 2001) consider that the main difficulty due to the expected increased development of tramway (or light rail) is the noise level. There are of course different technical improvements which can be implemented in order to reduce noise of tramways with iron wheels, but the rolling on pneumatic tyres could be another solution to go further in this direction.

## Common characteristics and traction equipment

It is possible to find elements which are comparable between classical tramways on iron wheels and new guided systems on pneumatic tyres.
A common general tendancy is the importance of the accessibility criterion, which induces the realization of low floors and which can influence the choice of technical components. The evolution of power electronics with the generalization of IGBT inverters contributes to size reduction of traction equipment and has a favourable impact.
For guided systems on pneumatic tyres it is relatively easy to realize a low floor on 100% of the length of the passenger units. For tramways on iron wheels, a low floor

on about 70% of the length of the vehicle was until now a good compromise, but many technical solutions have been studied in order to realize 100% low floors, it means in order to solve the problem of the conception of the traction bogies at the two ends of the vehicles. Several solutions have been experimented with the so-called « wheel-motor ». In most of the cases it is not a real wheel-motor directly coupled on the wheel but there is « one motor per wheel » using a reduction gear. These seductive solutions have nevertheless some inconvenients on the technical and economical point of view and they will not be generalized. We can give here the example of two recent 100% low floor tramways which have chosen different configurations :
- the motor bogie of the German tramway COMBINO (Siemens) utilizes two « half-motors » mounted longitudinally on each side of the bogie ;
- the new motor bogie for the 100% low floor of the French CITADIS (Alstom Transport) utilizes two transversal motors, and the axles are reconstructed in a lower position by means of gearings.

But the solution of « wheel-motor » has found applications for other vehicles than tramways. The recent version of the automatic light metro VAL (the « VAL 208 ») is equiped with synchronous wheel motors (excitation by means of permanent magnets). Wheel-motors have been experimented for buses equiped with an electrical drive for example in Germany, but we will here focus on a development which has repercussions on a guided system on pneumatic tyres. A new electrical drive has been developped in France with an asynchronous Alstom wheel-motor and a Michelin extra-large pneumatic tyre, in order to equip a range of low floor IRISBUS vehicles : a future bus with electrical drive, the new trolleybus VEG (now called Cristallis with a first application in Lyon) and the already mentioned CIVIS system with optical guidance. In comparizon with other vehicles the avantage of this solution is not to realize a low floor (which is already possible with other configurations) but is to realize a 100% low floor with a larger passage between the rear wheels.

# Suburban systems

According to the general tendancy called « periurbanization » (the polulation increases more in the surroundings of the big towns than in the centers of the cities) urban public transport networks must have a good connection with suburban areas in order to be attractive. Among envisageable solutions we will retain (excluding here land use strategies which are fundamental but do not belong to the scope of this paper) :

a) intermodality with individual transport (car and bicycle). This solution presupposes above all arrangements and parking policies measures. There is only a marginal impact on the conception of the vehicles : the improvement of the accessibility in order to accept rolling chairs can also facilitate the transport of bicycles during off-peak hours (even if we consider that the intermodality between public transport and bicycle can be achieved mainly by parking strategies around the stations) ;

b) intermodality between urban networks and suburban lines (trains and buses) : development of interchange stations, time tables compatibility, payment facilities (for example electronic ticketing)… The improvement of urban networks by the implementation of modern and efficient guided systems (AGTs, tramways or lightrail, guided systems on pneumatic tyres) can facilitate the intermodality by a better attractiveness… but passenger transfer is still necessary ;

c) interconnexion between urban networks and suburban lines, which permits the suppression of the tranfer, by means of a system which can circulate as well on urban network as on suburban lines : the interconnexion tramway which is called in France « tram-train » and in Germany « two systems vehicle » or « Karlsruhe model » according to the first implementation of this solution.

On a technical point of view this system supposes :

- a wheel profile which is compatible with the two types of rails ;
- additional equipment in order to circulate under two different electrical supply systems, for example 750V DC and 25000V AC ;
- additional devices (for example moving plates) in order to solve the problem of accessibility between two types of platform with different heigths and different gauges ;
- a specific safety approach in order to allow the circulation of light vehicles with a reduced longitudinal strength (60 or 80t) on lines where there is a « cohabitation » with heavy trains. A parameter to be considerd is a high level of active safety due to higher emergency deceleration rates (comparable to that of an urban tramway) and possibly to signalization.

This concept was born in Germany and there are now a few interconnexion tram projects in France. One of the first realizations is foreseen in Parisian suburbs. In Europe, after an important network in Karlsruhe there is another realization under operation : the line Saarbrücken-Sarreguemines which is mostly in Germany, the French part is less than one kilometer. A similar concept has been realized in Manchester (England).

d) Development of new types of specific suburban systems. The interconnexion tramway is the most efficient solution when the context is favourable. But for many other suburban lines there is the possibilty to implement guided systems on rails having all the characteristics of the interconnexion tramway (acceleration and deceleration, frequency, etc.) without the netwoks interconnexion. Various solutions have been studied in Germany or other countries. In France this concept is called regional tramway or « train-tram ».

During the last decades researches have been carried out in order to conceive specific suburban systems with magnetic levitation. An important challenge was noise reduction, as already mentionned in another context for light urban guided transport. If we consider high speed transport (between 300 and 400 km/h) aerodynamic noise becomes predominant and noise reduction is relatively small. But if we consider speed ranges well adapted to rapid suburban transport (for example 150 km/h) the impact of rolling noise on global noise is important. Between 1986 and 1989 the technical and economical feasability of the STARLIM system was studied in the frame of the DEUFRAKO French-German cooperation. A first realization was envisaged between Aix and Marseille (South of France) but could not be achieved because of financial and strategic difficulties. The HSST conceived in Japan for a comparable range of applications could no more find a commercial success. The German TRANSRAPID originally conceived for high speeds is sometimes envisaged for suburban applications, for example for « point to point » connexions without intermediate stations.

## System insertion

The compatibility of the system with its environment is a criterion which becomes more and more important. Guided systems have a favourable impact on environment because of many well known arguments that we will not develop here (low energy consumption, clean energy sources such as electicity, space savings…). We will focus here on the difficult acceptance of visual intrusion due to system infrastructures, and on technical solutions which could improve the situation.

First the refusal (with some exceptions) of aerial guideway in European towns is one of the main reasons which explains the lack of success of middle sized AGTs. The construction of a tunnel is expensive for a middle-capacity system. In France and in some other countries the development of fully automated transport was a success for relatively large capacities (automated metros and automated light metro such asVAL) and to a certain extent for short to middle range systems, but not for intermediate systems. This justifies the development of intermediates systems at ground level with human driving, as already mentionned for pneumatic tyred guided systems or light tramways.

Second a strong severity towards visual intrusion can in some towns, especially in France and Italy, lead to a refusal of the overhead lines (which are currently used for the electric supply of guided systems), at least in some areas such as historic centers, in spite of the fact that the aesthetical integration of these lines can nowadays be improved.

In case of success, long term researches which are carried out on fuel cells could in the future contribute to solve this problem, but for the short and middle term we can consider two types of solutions :

a) current pick-up at ground level (Khatir 2000). A conducting rail or plate is embeded in the roadway. It is realized as a succession of segments which are isolated from each other ; for safety reasons a specific device must guarrantee that only segments under the vehicle can be connected with the supply voltage. Three technical solutions are under development :

- mechanical connecting device for STREAM system (Système de Transport Electrique à Attraction Magnétique) built by ANSALDO in Italy ;
- electical connecting device with contactors for INNORAIL system experimented in France by SPIE Enertrans (this system has been envisaged for the future tramway in Bordeaux) ;
- electrical connecting device with IGBT transistors for ALISS system under development in France by ALSTOM Transport.

b) energy bimodality by means of an on–board storage equipment which permits the partial suppression of the overhead lines (Soulas 2000). There are three technical possibilities according to the requirements and the date of application : various types of batteries (lead-acid, nickel-cadmium or new electrochemical couples for example with lithium), flywheel, or supercondensators :

- the feasability of energy bimodality by means of batteries has been tested twenty years ago on bimodal trolleybusses. The new guided systems on pneumatic tyres TVR and TRANSLOHR have experimented lead-acid batteries. With the financial

help of PREDIT the French program SIVTHEC investigates the possibilities of various battery types ;
- flywheels are being operated for several years on trolleybuses in Basel (Switzerland), and have recently demonstrated their performances for other types of application (for example last year Siemens installed a MagnetMotor flywheel in a tramway substation in Köln, in order to improve energy recovery). In order to demonstrate the faisability of energy bimodality on a tramway by means of a flywheel, Alstom Transport has made a demonstration test with a first generation equipment, on a test track in La Rochelle (France) ;
- with the financial help of PREDIT, the French program THALES investigates the possibilities offered by supercondensators to realize an energy bimodality on an interconnexion tramway, with quick recharge in station. Experiments will be carried out with a prototype. The partners are Connex (Eurolum), SNCF, Alstom Transport, INRETS and EDF, in order to associate operators, a manufacturer and research or technical organizations. Contrarily to first generation batteries and flywheels, supercondensators are not ready for an immediate application but could have a higher potential in the next years.

We could consider too the solution of the hybridation which reduces the pollution of a thermic engine (coupled to an electic drive) by suppression of transitory running (Dr Wolf 1999). It is rather relevant for specific suburban systems where the low frequency does not justify an electrification. It can be realized with similar components to those used for energy bimodality : batteries, flywheels or supercondensators. Two German projects have chosen the flywheel : ULEV-TAP as a prototype of interconnexion tramway in Karlsruhe, and LIREX (Light Innovative Regional Express Train) built by Alstom LHB.

# Conclusion

In the field of urban/suburban guided transport there is a big variety of technical innovations which permitts an evolution and a better adaptation to social, environmental and geographical requirements. We made a general survey of many reseaches and developments carried out to improve components and transport systems, without pretending to be exhaustive.

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