WIRELESS ELECTRIC PROPULSION LIGHT RAIL TRANSIT SYSTEMS IN SPAIN

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ABSTRACT

A frequent criticism of new light rail transit systems is the negative visual impact of overhead power lines (catenary). Vehicle manufacturers have recognized this problem and developed systems that allow trams to operate without catenary. There are three main approaches: providing electricity from ground level systems, storing energy on-board the vehicle, and generating power on-board the vehicle.In most cities where alternatives to catenary power lines have been implemented they are only implemented on particularly sensitive sections of the routes. This has been the case in Spain where three of 11new light rail systems have adopted a hybrid electrification system using on-board energy storage. Spain's experience with hybrid electrification provides a good case study of the technology.

This paper summarizes light rail system development in Spain. It focuses on comparing LRT systems that use hybrid electrification versus those that do not. The research confirms, consistent with previous research, that the costs for systems using hybrid electrification are higher than for those using catenarypower lines. The research also shows that increased streetscape redevelopment – often required in places where visual impacts need to be addressed with hybrid electrification – are a key driver of these increased costs.Finally, an interview with the operator managers of the 3 LRT systems that use hybrid electrification was carried out to understand key operational differences between the two systems.

INTRODUCTION

New light rail transit (LRT) systems have been built in 11 Spanish cities since 1994. The wide variety of different urban contextsand needs has led these cities to adopt different designs and operating practices. One important difference is in power supply: three cities have built LRTlines without catenary power lines on at least part of their route.

The traditional approach for providing electric power to light rail vehicles has been with overhead power lines. Overhead power supply is a proven and well understood technology. However, overhead power lines are considered by some to be unsightly and this potential negative impact has been seized upon by opponents of light rail lines as an argument against their construction.

Consequently, many cities considering new LRT lines in recent years have sought solutions for providing power to light rail vehicles without using catenary power lines. Vehicle manufacturers and public transport construction companies recognized this demand and have developed several solutions. These solutions require vehicle manufacturers to work together with the infrastructure providers to ensure that the vehicles can be provided with sufficient power to operate.

There are three main methods for providing power to vehicles without using catenary power lines (1):

1. Ground level power supply (GLPS) – power continuously supplied to the vehicle at ground level via direct contact with a conductor or inductively;
2. Onboard energy storage system (OESS) – power stored on the vehicle, using flywheels, batteries, supercapacitors or a combination thereof, recharged periodically via regenerative braking and contact with a power conductor; and,
3. Onboard power generation system (OPGS)– power continuously generated on the vehicle as required via hydrogen fuel cells, microturbines or diesel engines.

The three Spanish cities that use alternative power distribution all use OESS, more specifically the ACR (Rapid Charge Accumulator) system developed by CAF (Construcciones y Auxiliar de Ferrocarriles) and the Technical Institute of Aragón. All of them have constructed systems with catenary power lines on some sections and without catenary on other, more visually sensitive, sections (this combination of with and without catenary is referred to as hybrid below).

The objective of this paper is to describe the experience of Spanish LRT systems operating without catenarypower supply. Section 2 summarizes LRT systems in Spanish cities. Section 3describes the wireless electric propulsion system used in Spain, lessons learned regarding this system, and briefly discusses a survey designed to better understand neighborhood resistance to new LRT lines (since one reason for choosing OESS is to satisfy people who object to the catenary wires). Finally, Section 4presents conclusionsand recommendations.

LIGHT RAIL TRANSIT SYSTEMS IN SPAIN

Spain has made significant investments in its urban rail networks during the last 25 years. Cities have built new regional rail lines, metros and LRT systems. This section presents a brief description of light rail lines built in 11 cities. It begins by describing LRT in 8 cities that have built systems with catenary power supply and then describes 3 cities where some of the LRT line sections were built without catenary power supply.

Most of Spain's new LRT systems were inauguratedbetween 1999 and 2008 when Spain experienced a period of great economic expansion. This made financial resources (both public and private) available for building new transport infrastructure. Many cities invested in public transport to improve urban transport sustainability. Often, these investments were made in smaller cities or in peripheral areas of large cities, which has caused them to have relatively low demand.

When the economic crisis arrived in 2008 funding was drastically reduced and demand fell, which put many lines in difficult situations (e.g., financial problems in the Parla LRT, construction delays in Granada, suspension of service on the Vélez-Málaga LRT, non-inauguration of the Jaén –Andalucía- LRT). On the other hand, some of the LRT lines were successful despite the difficult economic conditions, and so network extensions are being planned (Vitoria LRT and connection of the two tram networks in Barcelona).

LRT Systems with Catenary

The first of Spain's new generation LRT lines were built with conventional power supply based on overhead lines (catenary). The same electrification system is used for the hybrid LRT systems in those sections that operate with overhead contact system.All the LRT lines installed simple aerial lines (without supporting cables) to reduce the visual impact on the urban environment.

Madrid

Madrid has a population of 3.17 million inhabitants (2). Madrid has three LRT lines (ML1, ML2 and ML3), all of which were opened in 2007. Its three lines are located on the outskirts of the city. These lines serve new urban developments in the case of ML1, and small towns in the cases of ML2 and ML3 (Pozuelo de Alarcón, with 85,000 inhabitants and Boadilla del Monte with 50,000 inhabitants) (2), as well as running through employment areas.

ML1 is a stand-alone line that runs between the metro stations of Pinar de Chamartín and Las Tablas. It provides service to the new neighborhoods of Sanchinarro and Las Tablas. The new lines were designed to help support development of these new neighborhoods, and while a certain amount of development has taken place, the new neighborhoods near the line can still be considered as "low intensity" development, and empty plots still can be found along the line. This limited development has contributed to the low demand for this line (3).

A substantial portion of ML1 was built underground and this led to a quite high investment cost of over 53 million EURO per kilometer (96million USD per mile) compared to an average cost for Spain's new LRT lines of approximately 23 million EURO per kilometer (39.6 millionUSD per mile). This cost could have been reduced given that most of the area involved was being developed simultaneously, and some sections of the LRT could have easily been integrated into the wide roadway infrastructure, instead of building them underground (for example, a 700 m -2,297 feet- underground section along Príncipe Carlos Street, which has a width of 60m -197 feet-) (4).

ML2 runs through the outskirts of Madrid from the subway station of Colonia Jardín (common station with ML3) to the commuter railway station of Aravaca, going through the town of Pozuelo de Alarcón. It has 12 stations. It provides service to office buildings, shopping malls and university campuses. Except for its two ends, ML2 goes through a sparsely populated area with no chances of being urbanized (1). Its high average cost of over 34 million EURO per kilometer (61 millionUSD per mile) can be attributed to the many underpasses and overpasses built to avoid level crossings with area roadways. Again, costs could have been reduced by avoiding unnecessary underpasses and overpasses by changing them by level crossings and installing traffic signal priority systems for the LRT (4).

ML3 runs from the metro station of Colonia Jardín to Boadilla del Monte. It has 16 stations. This interurban radial line provides service to leisure areas, office buildings and university facilities. Like ML2, ML3 runs through sparsely populated areas, apart from both ends (Calvo et al., 2013). The average cost of this line was approximately 22 million EURO per kilometer (39 million USD per mile). This cost could also have been reduced using the same strategies mentioned above for ML2.

Madrid’s three LRT lines have a ridership of over 16 million passengers per year (5). The rolling stock is composed of 35 Alstom Citadis 302 trainsets (8 trainsets for ML1, and 27 trainsets for ML2 and ML3).

Parla

Parla is a suburban city located in the south of Madrid with a population of approximately 125,000 (2). The Parla LRT opened in 2008. It is a circular tramline that runs onthe surface. It has 15 stations, one of them connecting with the suburban rail network of Madrid. The average cost of this line was 17.7 million EURO per kilometer (32million USD per mile).

Parla’s LRT operates mostly through the outskirts of the city although a small portion of the line runs through the city center. The LRT provides service to several industrial areas and the neighborhood of Parla Este. This district is characterized by low intensity building and unbuilt plots. This line has a ridership of 5.4 million annual passengers (6). The rolling stock consists of 9Alstom Citadis 302 trams.

The municipality of Parla was supposed to pay 33% of the LRT’s investment cost which it expected to obtain from the new urban developments in Parla Este. However, the economic crisis meant that the area did become urbanized and many plots remained empty. Therefore, in 2011, the system entered a financial crisis. There was even a temporary service disruption. Finally, the City Council renegotiated the debt and the tram kept operating normally.

Barcelona

Barcelona (1.6 million inhabitants) (2) has two independent LRT networks: Trambaix and Trambesós. The Tambaix network consists of three lines (T1, T2 and T3) located on the west side of Barcelona. It has 29 stations and connects Barcelona with the surrounding cities of L'Hospitalet de Llobregat, Esplugues de Llobregat, Cornellà de Llobregat, Sant Joan Despí, Sant Just Desvern and San Feliú de Llobregat.

The Trambesos network consists of three lines (T4, T5, T6) serving the east side of Barcelona and the satellite towns of Sant Adriá de Besós and Badalona. The Trambesos network includes 27 stations. The tram lines on both networks operate through densely populated areas, so they capture a high demand (26.8 million passengers per year). The first sections were inaugurated in 2003, and last in 2007. The average cost of these lines was approximately 25 million EUR per kilometer (45 millionUSD per mile). The relatively high cost is due to building in a dense urban area where many utilities needed to be relocated.

Barcelona is currently considering the possibility of connecting the two systems with a new 3.8 km line. The new line would have five stations and would double the current demand (7). Both networks use Alstom Citadis 302 trams (23 train units in the Trambaix network and 18 in the Trambesos network).

Bilbao

Bilbao is an industrial city located in northeast Spain. The city's population is 345,000 (2). The Bilbao LRT opened in 2002. The average cost of this line was 9.5 million EURO per kilometer (17.3 million USD per mile).

The LRT of Bilbao helps improve public transport, but the project's main objective was boosting the image of Bilbao, in conjunction with the Guggenheim Museum. The approximately 5.5 km line is runs along Bilbao's river (behind the museum). It consists of 14 stations serving the central city, museum, and metro and commuter rail stations. This line serves a demand of 2.9 million passengers per year (8). The rolling stock consists of 8 CAF Urbos I trams.

Tenerife

Tenerife is an island located off the coast of Moroco (Africa). It is part of Spain and a very popular tourist destination. The LRT network of Tenerife has two connected lines (the first opened in 2007), serving the cities of de Santa Cruz de Tenerife (204,000 inhabitants) and San Cristóbal de la Laguna (153,000 inhabitants) (2).

Both LRT lines traverse heavily populated zones and provide service to hospitals, museums, university centers and interchange stations. There are 21 stations in Line 1 and 6 stations in Line 2. They attract an annual demand of 13.5 million passengers (9). The relatively high unit cost of Tenerife's LRT (approximately 23.5 million EUR per kilometer) is mostly due mostly to the complicated topography of the area where Line 1 was constructed (2). The rolling stock consists of 26 Alstom Citadis 302 trams.

Vitoria-Gasteiz

Vitoria – Gasteiz is the capital city of the Basque Autonomous Community, located in northern Spain. The city has a population of 245,000 (2). The LRT of Vitoria-Gasteiz opened in 2008.

The LRT connects the city center with two branches leading to suburban neighborhoods and forms a Y shape network with 18 stations. The line was built as part of a coordinated urban transportation strategy that included bus network re-planning, facilities for active transport (e.g., comprehensive bike lane network) and urban design. This transport strategy was one reason Vitoria-Gasteiz was named European Environmental Capital during the year 2012. In 2015 this LRT was used by 7.7 million travelers (10).The LRT rolling stock consists of 11 CAF Urbos II trams.

Murcia

Murcia is a city of 441,003 population in the southeast portion of Spain. The LRT of Murcia began service in 2011.

The Murcia LRT has 28 stations andservesmostly low-density areas, such as university, industrial areas, football stadium, shopping centers, sparsely populated areas and neighborhoods of single family houses. The line serves an annual demand of 4.3 million travelers (11). The rolling stock consists of 11 Alstom Citadis 302 trams.

Valencia

Valencia is a city of 790,000 population (2) located on the Mediterranean Sea south of Barcelona. Valencia’s LRT was opened in May 1994 and was the first modern tram line in Spain. Some of these lines come from the transformation of former narrow-gauge suburban railways.

Currently, Valencia’s LRT network consists of Line 4 (opened in 1994 and expanded in 2005), and Lines 6 and 8 (both opened in 2007). Line 4 (21 stations) connects Valencia’s metroto areas of high demand such as university centers and Malvarrosa Beach. Line 6 (19 stations) aims to circumnavigate Valencia (although only the first section has been built). Line 8 (4 stations) connects Line 6 with lines 5 and 7 of Valencia’s Metro System, and with the port of Valencia.The three lines amount to a total of 20 km, all running on surface. They have an annual ridership demand of over 9 million passengers per year (12). The system uses 25 Siemens and 19 Bombardier Flexity Outlook Cityrunnertrams.

Hybrid LRT Systems

Hybrid LRT systems use a combination of fixed overhead wires and onboard power supply to provide electricity to trams. This section describes the hybrid LRT lines in three Spanish cities.

Sevilla (Seville)

Seville is a city of approximately 691,000 (2) population in the southwest portion of Spain. Seville’s LRT opened in 2007, and was expanded in 2011.

Seville’s LRT consists of a single short line running from the historic city center to San Bernardo, where commuter and metropolitan bus stations are located. The LRT has relatively high ridership (4.1 million passengers in 2015). (8)

The LRT runs through some of the most scenic streets in Seville's historic center. It travels at a very low speed so tourists can use it to see the area comfortably. While the line runs entirely on the surface, its operation through historic areas, which are very important for tourism and urban development, led to relatively high costs (27.5 million EUR per kilometer, 50 million USD per mile). (4)

Initially Seville's LRT was built with overhead wires, but in 2011 it was adapted to operate without wires in the central historic area to minimize the system's visual impact.The rolling stock consists of 4 CAF Urbos III trams with the ACR system.The ACR system is recharged at the stops by means of a rigid catenary section integrated in the marquee of the stops.

Zaragoza

Zaragoza is the capital of northeastern Spain's Aragon region. It has a population of approximately 660,000 (2). The LRT line of Zaragoza was opened in 2011 and cost 35 million EUR per kilometer(64 million USD per kilometer). The project included comprehensive redevelopment from façade-to-façade and pedestrianizing of the streets it runs upon.

In 2015 the LRT transported 28 million passengers (8). This high demand is generated because the line links the city's historic center with the two main suburban nodes (Valdespartera and Parque Goya).The route runs the most part in double track with reserved right-of-way and is 12.8km long (8 miles).

The LRT route runs through the historic center without catenary for approximately two kilometers to reduce its visual impact. This is the longest wirelessLRT section in Spain.The rolling stock consists of 21 CAF Urbos III trams with the ACR system.The ACR system is recharged by third rail at stops.

Granada

Granada is a city in southern Spain's Andalusia region. The city has a population of approximately 235,000 (2). The Granada LRT line began construction in 2007 and was inaugurated in 2017 (the period of works ended up being double of the planned one).

The Granada LRT has 26 stops (three of them underground), and it connects Granada with the main cities of its metropolitan area: Albolote, Maracenaand Armilla. Due to its metropolitan nature (the regional population is approximately 530,000) (2), the line provides service to important regional destinations including the bus and train stations, industrial parks, administrative, sports, hospital and university centers, as well as connecting with a new urban development zone (13). The LRT line is 16 km long. The system has an estimated demand of 12.9 million riders per year (14).The Granada LRT project included comprehensive redevelopment from façade-to-façade of the streets it runs upon. The route is mostly double-tracked with an exclusiveright-of-way, except for a 528-meter section on Calle Real de Armilla, where it is a single track. There is priority for the LRT at intersections with road traffic.

The catenary line is of a tram type when it runs on surface, while in the underground sections rigid catenary has been installed. The Granada LRT has four wireless sections of length: 1,016, 1,250, 870 and 1,560 m (15). Its rolling stock consists of 15 Urbos III trams with the ACR system.

WIRELESS LRT SYSTEM EXPERIENCE IN SPAIN

This section summarizes key information and experience about the implementation and operation of wireless LRT systems in Spain. It begins by outlining the main reasons for using wireless systems. Next it describes the wireless power distribution system used in Spain. Finally, it describes several aspects of operating experience.

Why wireless power distribution?

There is a great deal of general resistance to rail-based public transport operating on surface streets in Spain. This resistance is often justified by the visual impact – people say they do not want the overhead power distribution system – but thereal reason is often resistance to a new mode of transport reducing space for private vehicles.For example, a recent survey in Andalusia found that approximately 33% of residents disagree with reducing the space available for cars to give it to public transport (16). Furthermore, many (45.4%) residents consider LRT to be an inappropriate means of transport for their region (17).

One of the main strategies used by cities to address resistance generated by negative visual impactis constructing wireless power distribution systems. This was especially important in cities where the trams operate in historic areas such as Seville and Zaragoza. Here the economic benefits of tourism were used to justify wireless systems.

In Seville, moreover, the overhead system had to be disassembled every year for the passage of the Easter week processions. In Zaragoza, the public authorities promoting the LRT systemdemanded from the tendering process that the LRT operate without cables through the historic center.

Today, the practice of using wireless power systems is extending beyond the historical centers. For example, in Granada, the wireless sections are outside the center. In thesecases the reason for installing wireless sections was mainly to silence the protests of the neighbors regarding construction ofthe LRT linein general and the presence of the cables in particular.

Furthermore, the Granada LRT was also built underground along 2.74 kmto satisfy neighborhood concernsalthough the street is wide enough for surface running (30 m / 98 feet wide). In fact, a multi-criteria analysis studyabout surface or underground layout alternatives using a hierarchical analytical process concluded the surface layout was the best alternative (18).

Wireless LRT Electric Power Distribution in Spain

As outlined above, there are three main types of wireless power distribution systems used for LRT systems today: ground level power supply, on-board energy storage systems, and on-board power generation systems. These three technologies are fully described in (1) and (19).

All three tram lines that operate wireless sections in Spain today use the OESS approach. More specifically they use the Urbos III ACR (Acumulador de Carga Rápida –fast charge accumulator-)rolling stock. The ACR system uses ultracapacitors to store and deliver energy. The trams charge the ultracapacitors along the catenary sections, or at stops (the charge cycle lasts between 20 and 30 seconds).The energy stored is then used to power the vehicle as it travels between stops. The vehicles can travel between 1,000 and 2,000 meters between charging, depending on the characteristics of the route, the required performance and installed capacity (20).It is possible to add the ACR system to existing LRT rolling stock and infrastructure.

The ACR system also allows trams to recover the energy produced during braking and store it in the ultracapacitors. This helps the ACR system improve energy efficiency of the LRT systemscompared to conventional trams. In conventional trains, braking energy can only be recovered when another vehicle in the vicinity can use it. This can save up to 20% of energy (21). In addition, the system offers autonomy to the vehicle when the power supply fails.

The ultracapacitors store and deliver energyusing a purely physical process. They can store large amounts of energy and provide high power levels almost instantaneously. There are no chemical reactions in its operation. The ACR system durability is around fifteen years, which means that they need to be replaced approximately half-way through the normal useful tram life of twenty-five or thirty years (22).

The operation of a tram equipped with the ACR system is as follows (23): (1) the tram departs the stop with theACR equipment fully charged; (2) when circulating on a wireless section, the motors and the auxiliary equipment are fed with the accumulated energy; (3) during the braking process, the kinetic energy is fully recovered and stored in the ACR, thereby initiating its recharging process; (4) at the stop, and after the rise of the pantograph, the charge of the ACR equipment is completed to start a new cycle.

Although all LRTs with a hybrid electrification system in Spain use the ACR system, each of them has a different way of charging the ultracapacitors. In the case of Granada, the ACR recharges directly from the catenary, before passing to the sections without catenary. In the case of Zaragoza, there are no overhead wires at the stops. The ultracapacitors get recharged by means of a skid that makes contact with a short third rail section at the intermediate stops of the wireless section. The third rail is located in the ground. Two beacons, one located on the ground and another on the tram, determine that the vehicleis stopped in the proper position to recharge, and only then the third rail is electrified and the skid descends. The ultracapacitors can be fully rechargedduring the normal commercial stopping time. Finally, in the case of Seville, the trains recharge the energy through a short section of rigid catenary installed in the stands of the stops.

Spanish Experience with Wireless LRT Systems

This section outlines several key lessons from the construction and operation of wireless LRT lines in Spain.

Total Project Cost

Table 1 shows the costs of LRT systems in Spain (updated to 2016). As shown in Table 1, the unit investment cost for hybrid systems is significantly higher than for systems with overhead contact systems (23.23 million Euro/km versus 33.36 million Euro/km -39.57 million USD/mile versus 64.44 USD/mile). Furthermore, because there is almost twice as much underground construction in the systems with overhead contact systems, these costs likely underestimate the increased cost of hybrid systems.

Interestingly, the capital costs associated with avoiding construction of the overhead systems should result in savings (the Aalborg Denmark LRT project had capital costs (updated to 2016) between 0.77 to 0.95 million EURO/km; 1.39 to 1.71 USD/mile (24)). Thus, the installation of sections without catenary should reduce the initial investment (as well as reduce the maintenance costs associated with the catenary).

The higher construction costs are likely due to the greater extent of the redevelopment carried out in the area along the LRT lines that use hybrid operations. More specifically, in cases where public administrations were more conscious of the aesthetic effect of LRT power cables, or where population was against the LRT, they also took greatest actions to improve the urban environment along the LRT line.

For example, in the cases of Zaragoza and Seville where the LRT lines pass through the historic center, significant activitieswere carried out to improve the urban environment andenhance its attractiveness to tourists. Moreover, in Zaragoza, the implementation of the LRT included comprehensive redevelopment from façade-to-façade throughout the entire route. Finally, in the case of Granada,an integral redevelopment from facade to facade of all the streets through which the LRT passes has been carried out as well (including the installation of movement and crack gauges in all houses to measure possible damage to buildings), even though this line does not pass through the historic center.

In contrast, in the cities where only overhead contact systems were used for power supply, the LRT systems generally run through less central and / or less urbanized areas. In most of these cases there was much less redevelopment done as part of the LRT construction (good examples include Parla, Tenerife and Murcia).

TABLE 1 Main Characteristics of Spanish LRT Systems

Sources: (4), (25), (15)

LIGTH RAIL SYSTEM	Total investment (M€)	Total investment (M USD)	Length (km)	Length (miles)	Unit investment (M€/km)	Unit investment (M USD/mile)	Underground (%)	Wireless (km)	Wireless (%)
OVERHEAD CONTACT SYSTEMS									
Bilbao	53.50	59.92	5.57	3.46	9.61	17.31	0.00		
Vitoria	108.65	121.69	8.20	5.10	13.25	23.88	0.00		
Madrid ML1	287.54	322.04	5.40	3.36	53.25	95.98	67.00		
Madrid ML2	294.33	329.65	8.70	5.41	33.83	60.98	31.50		
Madrid ML3	296.60	332.19	13.70	8.51	21.65	39.02	10.40		
Parla	145.13	162.55	8.20	5.10	17.70	31.90	0.00		
Barcelona Trambaix	378.00	423.36	15.10	9.38	25.03	45.12	0.00		
Barcelona Trambesos	344.52	385.86	14.10	8.76	24.43	44.04	11.00		
Tenerife	371.61	416.20	15.90	9.88	23.37	42.13	0.00		
Murcia	272.44	305.13	18.00	11.18	15.14	27.28	0.00		
Valencia	364.43	408.16	20.00	12.43	18.22	32.84	0.00		
AVERAGE (A)	**265.16**	296.98	**12.08**	7.51	**23.23**	39.57	**10.90**		
HYBRID SYSTEMS									
Granada	592.04	663.08	15.92	9.89	37.19	67.03	17.20	4.70	29.50
Sevilla	60.54	67.80	2.20	1.37	27.52	49.60	0.00	1.40	63.64
Zaragoza	452.82	507.16	12.80	7.95	35.38	63.77	0.00	2.20	17.19
AVERAGE (B)	**368.47**	412.68	**10.31**	6.40	**33.36**	64.44	**5.73**	**2.77**	**36.77**
(B)/(A) (%)	**139.0**		**85.3**		**143.6**		**52.6**		

Rolling Stock Costs

The second reason for higher costs is rolling stock. Spain provides an interesting opportunity to compare the costs of rolling stock with and without the wireless system. More specifically, Urbos III trams from CAF are used in both the wireless systems and in the Malaga Metro. The Malaga Metro is a grade-separated 12.9 km long tram system with approximately 80% of underground construction. The rolling stock costs are(cost updated to 2016):

- Granada –Urbos III ACR cost was 3.55 million EURO (3.98 million USD) (15).
- Malaga Metro – Urbos III cost was 3.12 million EURO (3,49 million USD) (26).

This comparison shows that the rolling stock cost increases about 13.8% for the wireless system.

In addition to the extra capital cost for the trams, the ultracapacitors have an estimated useful life of about 15 years. When the required performance is very high (many charge and discharge cycles) the ultracapacitors must be replaced more often than when it is low. In the case of very hot areas – such as Spain – where air conditioners require a lot of energy, the ultracapacitors may need to be replaced more often. For example, in Seville, the replacement cycle has been estimated to be every 7-8 years (19). On the other hand, the higher initial investment in rolling stock associated with wireless LRT systems can be compensated by the energy savings resulting from the greater use of the energy generated in the braking of the trains.

Operator's opinions

As part of this research a survey of operators was conducted to obtain more information on the actual operations of the three hybrid LRT systems. More specifically, senior managers at each of the operators were asked to compare operations in the wireless and wired sections, as well as some more general questions. The survey results are summarized in Table 2.

TABLE 2 LRT operators' interviews summary

Source: own source.

Question	Metropolitano de Granada	Tranvía de Zaragoza	Metrocentro de Sevilla
Availability	No differences between conventional/ACR.	No differences between conventional/ACR.	No differences between conventional/ACR.
Maintenance	Rolling stock: More maintenance required with ACR. Infrastructure: Wire sections: less maintenance. Off-wire sections: ACR beacons required.	Infrastructure: Wire sections: less maintenance. Off-wire sections: third rail charging system required.	Infrastructure: Greased catenary cables required.
Special requirements	Ground beacons required for automatic pantograph upload/download. 3,000 kg crane needed to handle energy storage coffers.	Ground charge system must have a safety certificate (SIL-4 (Safety Integrity Level)). Two charging points per stop and directions (availability and coupled trainsets).	Upper charging system by means of rigid catenary (integrated in stop shelter). Ground beacons required for automatic pantograph upload/download. Copper-zirconium collecting shoe (instead of graphite) for speeding up charging process.
Aspects of special attention	Design and implementation: ACR system (capacity) must be adjusted according to line (sections length and slope) and service requirements (speed, air conditioning, minimum charge level for determiningmaximum time at stops). Minimum operating charging level affects accumulator's life cycle.	Design and implementation: ACR system (capacity) must be adjusted according to line (sections length and slope) and service requirements (speed, air conditioned, minimum charge level for complying maximum time at stops). Third rail system: trainset must be perfectly positioned to start the power charging process. Safety: ground charge	Design and implementation: adjustments to comply with maximum time at stops. Safety: training courses for personnel, firefighters, etc., to avoid accidents with energy accumulators on the roof of trams.

	Safety: training courses for personnel, firefighters, etc., to avoid accidents with energy accumulators on the roof of trams.	system must be switched off when there is no train at the stop; the system must be not flooded.	
Benefits	Minimize visual impacts. Reduce energy use.	Minimize visual impacts. It guarantees the service when the catenary does not work. Reduce energy use.	Minimize visual impacts.
Disadvantages/ problems	Problems at design and implementation stage. ACR system is very expensive. Little experience relating to accumulators' life cycle. Safety issues related to energy accumulators on the roof.	Towing and operation problems when a train fails in the off-wire section (energy charge level in the shunting/towing train).	Limited energy availability.
Improvements	Longer useful life. Largerenergy storage capacity. Reduce energy storage size and weight.		Larger energy storage capacity. Decrease the price.
Costs	The higher cost of trains can be partially offset by energy savings. Cheaper infrastructure in off-wire sections. Energy savings.	Energy savings.	Energy savings.
Preferred system	ACR system positively valued because it makes possible to establish LRT lines along city areas otherwise (with catenary) it would have not be permitted.	Operator's point of view: overhead system preferred (less complex; easier and faster troubleshooting/failure repair). Public image/system's acceptance: better for off-wire system (no visual impact).	Overhead system for peripheral streets: less visual impact and higher power required (higher circulating speed). Off-wire system for city center historic areas: less visual impact and less power required (low speed).
Future projects	Off-wire system for crossing the historic center.	Line 2 feasibility study considers the possibility of some off-wire sections.	Future extensions (circular line) may include some off-wire sections

			near city center.
Citizens' opinion	Protests during the works. Highly rated for its lower visual impact.	Protests during the works. Off-wire sections: highly rated (façade-to-façade redevelopment). Overhead sections: good opinion.	Historic center Overhead system era: protests. Off-wire: high rated. Outside historic center (overhead system): Overhead system: no protests.
Other aspects you would like to emphasize	ACR benefits.	No safety problems related to the ground charging system have occurred. Success of the LRT passing through the city center (it was a difficult political decision).	Nothing.

The main findings of this survey were:

- Two of the Spanish wireless systems require special infrastructure (i.e., third rail sections in Zaragoza and rigid catenary in Seville) that add capital costs, although these costs need to be balanced against the reduction in costs for less catenary. These special elements also need specific maintenance (ACR beacons, third rail, catenary greasing).
- All operators mention the savings in maintenance related to sections without catenary and that regenerative braking leads to energy savings;
- Increased safety concerns – the operators have increased concerns regarding ACR train safety (due to energy storage in the roof), this entails special design and training (e.g., for first responders);
- More complicated design – the wireless sections need to be designed more carefully than traditional catenary systems (to ensure the correct operation of the service);
- Long-term maintenance issues are not yet certain (e.g., how long will the on-vehicle systems last). Energy storage should have more capacity; and,
- Off-wire system for passing through the center and historical zones and catenary for the rest of the route. Much improved public perception (reduction in visual impacts).

Perhaps the most important finding from the survey is that all the operators are considering wireless sections in their future extension plans. In other words, they believe the benefits of wireless systems outweigh the disadvantages. It can also be pointed out that many of the disadvantages will be reduced in the future as they become more common, manufacturer improves the ACR system, and as operators gain more experience.

CONCLUSIONS

Spain has built new tram lines in many cities in the last 25 years. This provides an interesting opportunity to study the integration of new technologies into LRT systems and to compare the characteristics of different systems. This paper summarizes new LRT systems in 11 Spanish cities, then focuses on the use of wireless operation in three cities. The paper then describes the costs and operating experience for the three cities using (partly) wireless operations.

All three of these systems use the ACR system for OESS (using ultracapacitors).They are all hybrid, in other words, they circulate without overhead cables only during some parts of their route. The length of the off-wire sections ranges between 0.87 and 2.0 km.

The main reasons that led to the installation of sections without catenary in the Spanish LRT systems have been the elimination of the visual impact of wires in historic areas and the rejection of the population to rail transport on surface in the city. Thus, to reduce public opposition, the cities decided to remove the catenary

While it is difficult to directly compare total costs (infrastructure plus rolling stock) of conventional and hybrid LRT systems, in general theSpanish LRT projects with a hybrid electrification have been more expensive than those using overhead power distribution only.

Two reasonsSpanish LRT systems with wireless operations are more expensive are the greater extent of redevelopment done as part of these systemsand the higher cost of the rolling stock.In terms of rolling stock, the research shows thattrams with the ACR wireless technology system are approximately 14% more expensive than conventional trams. This increased cost is consistent with previous research (19)(27), and it can be attributed to the greater complexity of trams with OESS technology compared to conventional trams (1).

Regarding to the experience in the use of the ACR system by the Spanish operators, they emphasize that the inclusion of the ACR system does not reduce the availability of the trains, the savings in maintenance related to sections without catenary, the special maintenance needs of specific elements (ACR beacons, third rail, catenary greasing), the need to guarantee safety (energy accumulator boxes and the third rail) and the importance of the adjustments during system implementation.

According to the operators, the main advantages of wireless LRT are the reduction of visual impact and the reduction of energy consumption. As disadvantages, the operators mention above all the inherent dangers of energy storage in the roof. Regarding system improvements, they cite above all the increase of energy storage capacity. In general, they prefer the system without catenary for passing through the center and historical zones and the conventional system for peripheral zones. City residents value very positively the elimination of the catenary in the historical zones, while no protests have been taken place by its presence in the peripheral streets. Finally, all the operators are considering wireless sections in their future extension plans.

Recommendations for further research include completing a more detailed analysis of the additional costs to LRT systems of redevelopment activities (and wireless sections) needed to overcome public resistance to new LRT lines. This information would be important for policy makers who want to understand just how much these non-essential (from a transport system perspective) costs add to the total project cost.

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