Decisions on Physical Configuration for Light Rail Vehicles

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This paper examines the physical configuration of light rail vehicles (LRV) from the standpoint of the individual car and how it relates to the transportation system. The major decision to be made for double-end bidirectional operation or single-end with turning loops is explored. The advantages and disadvantages of each concept are also reviewed. Whether to specify articulation is evaluated in light of its relationship to fleet size and economic trade-offs as well as the operational benefits and problems that may result from its use. Results of three major LRV procurements that treated articulation as an option are explained. Selection of the patterns for door openings, the interface between doors and platforms, whether to use folding steps, and types of door action available are described. The relationship of seating to aisle needs, door openings, car width capability, and passenger flow is considered. Multiple-unit operation is analyzed as an option, with a review of its effects on throughput capacity and labor productivity. The question of whether to run new cars in trains with an existing fleet is explored. The conclusion is developed that selection of car options must be a result of system design. The LRV should not be allowed to dictate the system and car-wayside interfaces, whether the fleet be for a new line or for replacement. Goals of equipment standardization should not inhibit choices of configuration that will be best suited to the particular light rail operation.

The major factors to consider in selecting a configuration for a light rail vehicle (LRV) are determined by the characteristics of the transportation system itself—physical constraints, distance and volume of trips (average and extremes), desired average speed, dwell time, throughput volumes, station spacing, and upper and lower limits of station loadings. Compatibility with an existing fleet of earlier LRVs must also be considered because of the question of whether the entire fleet is to be replaced in one purchase. The light rail system should dictate the LRV configuration; the existence of an off-the-shelf car configuration designed for some other system should not be allowed to place unnecessary restraints on the choice. Several examples could be cited of light rail operations that have not realized their full potential because an inadequate and unduly restrictive vehicle, such as the "standardized" PCC streetcar, was used. Cleveland and Newark would have benefited from larger, higher-performance cars.

Five fundamental decisions that must be made in the selection of the configuration of a new LRV are as follows:

- Should the car be double-end or single-end?
- Should articulation be used, and, if so, how many sections?
- Where should the doors be located and where should they be in relation to seating patterns?
- What are the platform height options? Should loading be single level or variable height?
- Should multiple-unit operation be used? Should new LRVs be run in trains with older cars?

DOUBLE-END OR SINGLE-END

Perhaps the most fundamental of all LRV choices is that of single- or double-end cars. A vehicle with a cab at each end is more versatile in all operating situations—normal and emergency. Double-end cars can reverse direction easily anywhere in the network. Any station can thus serve as a short-turn point; a crossover on a double-track line is all that is needed. A system with all double-end LRVs has no need for turning loops or wyes at terminals, reducing the need for real estate at what are likely to be costly locations. Double-end cars have further advantages in that special track for turning single-end cars is frequently the locale of the most restrictive wayside clearances. Von Rohr points out that the use of city-center tunnels for light rail in Europe dictates the choice of double-end to avoid high-cost excavations for loops.[1]

In emergencies double-end cars can reverse direction and proceed to the nearest crossover to avoid a blockage. Furthermore, a double-end car while going in the non-normal direction through an emergency single-track operation has a set of doors on the off-side to match the boarding areas at stations. Single-end cars characteristically have fewer doors and, in most models, on one side only. (The resulting added seating capacity is a great advantage of single-end cars.) When single-tracking in the off-direction, such cars must load and unload in the space between tracks. This is not significant in street running or other situations where track is paved to the top of the rail, but it is quite important where track is in ballast and platforms are provided. Many light rail systems depend on low platforms of approximately curb height.

Double-end cars have certain advantages because they do not need a small turning radius in many light rail systems, particularly where there is no tight street running. With no need for loops, such cars need only the minimum radius the route imposes. A large minimum radius permits the use of wider-diameter articulation units, with the interior passage reaching nearly the full interior width of the car, thus giving a feeling of spaciousness and blending the body sections better. Furthermore, the greater the turning radius, the longer the truck center that can be used without excessive overhang. This provides opportunity to utilize longer cars, with their greater economies and passenger capacity. The large turning radius makes some contribution to greater minimum car width, although wayside clearances usually govern that characteristic. Flexibility of track alignment must be balanced with this desire to maximize the radius.

With all these advantages to a double-end LRV, one may wonder why single-end cars are ever selected. The obvious factor in two recent decisions for single-end LRVs—i.e., Philadelphia and Toronto—is the need to phase new equipment into existing systems that employ single-end streetcars. However, the reason for the past single-end choice is still valid. Von Rohr notes that many early streetcar systems used double-end cars, although single-end clearly won out in the latter days of street railways.[1] Only a small number of the thousands of PCC cars were provided in the double-end design.

Single-end cars came to be preferred in cities with many lines because a track network with lines joining and crossing provided ample opportunities for loops and wyes using the street pattern. The two major surviving streetcar systems use single-end PCCs, and there is no valid reason now to prefer double-end cars in Philadelphia and Toronto. (An exception in the Philadelphia situation is the purchase of 29 double-end cars for two suburban light rail lines that have no turning loops or wyes at the outer ends.)

The biggest advantage to a single-end LRV, other than the obvious lower first cost, is the greater seating capacity available in a given body size. Space that would have been consumed by a cab at one end and the offside door openings (and stepwells if low-platform) can be used for additional seating. Each door opening not needed adds four seats, while elimination of the second cab adds another four. Maximum seating in a wide-bodied PCC of the standard length is 60, while a double-end PCC the same size with a

normal component of doors seats a maximum of 48. Gray explains that, when the objective is to carry maximum capacity, single-end cars have lower costs for the initial fleet purchase and for operation and maintenance that can be traded off against the cost of turnback loops.[2] The Boeing LRV has maximum seating of 68, and a single-end version was proposed to seat 84. This range of about one-fourth gain in seating capacity will hold true for most single-end LRV designs except where doors are provided on the offside.

A related advantage of single-end cars is that most or all seats can face forward. This capability can only be acquired in double-end rolling stock by using flipover seats, which require somewhat greater spacing because each "back" is padded. Furthermore, a car with all seats facing one direction can usually be laid out to have an extra row of seats compared with a car where some face each direction.

The higher seating capacity available in a single-end LRV becomes important when the trip characteristics are somewhat like a commuter railroad. In such a line, the average trip would be fairly long, 6.2 miles or more. There would not be a lot of "local" on-off traffic, so aisle spacing and door openings would not be as important as in high-density city cars. There is no new or recently re-equipped light rail system in North America that has those "commuter" characteristics to the extent that the other advantages of double-end cars were overruled.

An advantage of single-end cars that may no longer be important is the ability to tow trailers without the need to run around and recouple to the other end. As will be explained later, the use of articulation tends to make trailers obsolete.

It is interesting to note that the single-end articulated LRVs being provided for Rio de Janeiro have the door pattern and seating arrangement of a typical double-end car.[3] Elimination of the second cab adds 5 seats in its place and undoubtedly lowers the initial cost. In the rear section, all other seats face the rear end of the car. There is a semi-permanent drawbar instead of the normal coupler at the back end. It appears that this car is not intended to be used singly as a normal rule but will operate in trains with an even number of cars. This approach is an economical way to achieve the advantage of double-end cars on a high-density light rail system when it is known that minimum passenger loads will justify more than one car per train.

It is likely that nearly all future LRVs in North America, except for some 4-axle cars used in cities with surviving street railway networks, will be double-end. In Europe, where operation with trailers is still used, new single-end cars may continue to be built. Any single-end car being built now should have a "hostler" control in the back, to permit operating at low speed from the rear of the car, a necessary feature for satisfactory yard handling.

ARTICULATED VERSUS RIGID

The second major component of LRV configuration is the choice between an articulated car and a rigid one. If articulation is selected, then the question is how many "joints" to provide in the total car. LRVs with two articulations are the exception, but they are not unusual in Europe.[1] Articulation ideally should lead to a higher number of seats or other unit of capacity per truck, as was the case with early modern passenger trains, but that is often not the case, as has been observed by Gray.[2] Considerations other than linear capacity usually govern in selecting articulation.

The most common reason for introducing articulation is the attempt to achieve greater labor productivity within the physical constraints of the system governing the distance between truck centers. It is believed that one crew member can handle an articulated car regardless of its length, especially where prepaid or honor fare systems are used.[1] This was not the case with the motor car and trailer car combination widely used in Europe.

Articulated cars do not pose difficulties in passing between the sections, in contrast to end doors in trains. Because so many light rail systems have small curve radii and uneven track, LRVs with end doors have always been a rarity. Use of such doors was considered inherently unsafe.

In trains of LRVs, the inability to pass between cars promotes uneven passenger loading. Articulation helps to minimize this problem by making each "envelope" larger. Lengthening the design of a rigid car soon runs into two system constraints: horizontal clearances on curves and maximum axle loads allowable for the track structure. Articulation gets around this problem by enabling cars to "bend in the middle" and by usually distributing the weight of body and passengers among more axles. However, there have been conversions to articulation that decreased tare weight of trains and incidentally increased axle loads. An example is the 1929 reconstruction of pairs of 4-axle Milwaukee suburban cars to 6-axle articulateds.

As mentioned in the discussion of double-end versus single-end cars, a larger turning radius permits a broader articulation section, providing more of an integration between the car bodies. In fact, some recent articulation sections that are nearly full width contain 4 single passenger seats.

Articulated cars bear several fundamental disadvantages that must be weighed against the gains in labor productivity and passenger flow.[5] It is often more difficult to rerail an articulated car, particularly when the truck under the articulation is involved. The articulation section can be easily damaged in such a derailment. Articulated cars can have adhesion problems when the truck under an articulation is unpowered, as is usually the case. Very good slip-slide control becomes essential to keep from lifting the center section off in turnouts and sharp curves. Furthermore, having some unpowered trucks in the vehicle compels the motors to be especially large if performance is not to suffer.

Articulated cars are more difficult to lift in the shops. It is not possible simply to lift one end, roll the truck out, and roll another in; the entire car must be elevated evenly. Because cars have to be positioned exactly for lifting, shop design becomes a limiting factor.

A major disadvantage of the extra-large articulated car is that the unit could well be much too large for economical use at slack times.[4,5] Extra energy is consumed, and excess wear occurs in hauling around a big car. One solution is to have a small fleet of 4-axle cars for low-volume periods. Often in an existing system this fleet would be the best of some older cars from the days before articulation became widely adopted.

This approach of having some smaller cars opens up the possibility of using 8-axle vehicles with two articulations for the busy periods. The system's acceleration requirements and maximum uphill grades must not be high, or every truck will have to be powered. Such a car can attain a favorable ratio of passengers to axles and a moderate cost per seat. Labor productivity in double-articulated cars is very high with an honor fare system.

The decision whether to adopt articulation can be looked on as an economic trade-off, and therefore bids might be taken allowing a range of choices. There is a risk here in that the car selected might be very different from the optimum for the system. The Cleveland LRV procurement was historic in being very open-ended; merely specifying that 4000 seats were required within a range of 47 to 68 double-end cars, having 3 doors per side if seating capacity exceeded 60.[6] All seating had to be transverse, with minimum pitch of 737 mm, and no seats were allowed in the articulation.

Bids were received from 10 manufacturers covering rigid cars and 6-axle articulated cars with seating capacities all the way from 60 to 84. Table 1 lists these bids with costs and key dimensions. The winner, a 48-car order with 84 seats, was the highest-capacity conforming unit offered. These numbers matched one other bid, with the

Table 1. Bids on light rail vehicles for Greater Cleveland Regional Transit Authority, May 1977.

Car Builder	Total Cost (dollars)	Cost Per Car (dollars)	Number of Cars	Seats Per Car	Car Length (mm)	Car Width (mm)	Truck Centers (mm)	Articulated
Breda	30 960 000	645 000	48	84	24 354	2821	8 229	Yes
U.T.D.C.[a]	32 764 700	712 561	53	76	19 202	2743	11 201	No
Pullman-Standard	34 353 989	582 271	59	68	19 202	2819	10 973	No
Kawasaki[a]	34 452 810	546 870	63	64	18 085	2699	10 719	No
U.T.D.C.	34 740 026	588 814	59	68	19 202	2743	11 201	No
M.T.S.-DuWag[b]	34 953 210	776 738	45	90	26 900	2700	9 820	Yes
Kawasaki	25 278 320	629 970	56	72	22 555	2699	7 468	Yes
Kawasaki	35 546 850	530 550	67	60	18 085	2699	10 719	No
Hawker-Siddeley[c]	37 265 088	665 448	56	72	19 609	n.a.	n.a.	No
Brugeoise et Nivelles	37 580 280	782 921	48	84	25 178	2700	8 401	Yes
Brugeoise et Nivelles	37 744 210	639 732	59	68	19 040	2700	10 665	No
Hawker-Siddeley	40 226 790	681 810	59	68	19 609	n.a	n.a.	No
Bombardier-DuWag	45 013 760	818 432	55	74	24 295	2692	7 722	Yes
Boeing Vertol	51 330 000	870 000	59	68	21 641	2699	7 010	Yes

Note: Bids are ranked from lowest to highest; reference numbers describe disqualifying features.

[a]Nonconforming bid provided only 2 doors per side. Cars having more than 60 seats were required to have 3 doors per side.

[b]Nonconforming bid contained fewer than minimum number of 47 cars.

[c]Front door pattern was nonconforming, with only 1 lane.

Two manufacturers, Brugeoise et Nivelle and Boeing-Vertol, each submitted two additional bids lower than those listed, containing disqualifying manufacturer-suggested cost reductions that did not affect car configuration.

parameters dictated by the total seating required and range in the quantity of cars allowed.[6] Surprisingly, the rather close second-lowest bid was for 59 four-axle rigid cars seating 68 each. There also were 3 matching cars bid by other manufacturers. Again, the mathematics of the specifications dictated those numbers.

The bid was awarded without regard to articulation but on the basis of total price. In retrospect, this was a hazardous approach because the runner-up would not have had the most suitable configuration. There are many situations in which the larger car will permit a reduced train length. The savings in direct labor will more than offset any net additional life-cycle costs incurred resulting from the fleet's having 144 trucks and 48 articulations, instead of 118 trucks without articulation.

The Philadelphia procurement of single-end LRVs for the trolley subway and double-enders for the suburban light rail lines also allowed articulation as an option, but the required number of cars of each type was specified. There were 8 bids from 6 manufacturers. The articulated cars came in third, sixth, and eighth, and the award went to the lowest-bid 4-axle cars (Table 2). Note that the total bids for articulated cars from the same manufacturers were lower than for their 4-axle versions.

In a similar manner, the specifications for Buffalo's new LRV allowed the articulation option. Two bids were received for 33 four-axle cars and three bids for 25 to 27 six-axle articulated cars. Again the 4-axle car won on the basis of price. Here the articulated cars came in high (Table 3). The Buffalo process was unusual in that the evaluation of bids included add-on amounts estimated for spare parts and some life-cycle costs of maintenance plus travel for on-site inspection. These add-ons are not shown in the table. Consideration was not given to any greater labor productivity to be achieved by cars with more seats, since the operation calls for a train crew of one person regardless of train length.

These three examples show how the articulation decision was not made in advance, a conforming vehicle being selected on the basis of low bid. In Cleveland, a vehicle far more suitable to the system's capabilities than the PCCs being retired was made possible by modifications to terminal layouts.

In Philadelphia, it could be argued that conservatism won out and that the opportunity for improved labor productivity was passed up by not selecting articulation. However, the new cars phase in well with their predecessors. A consideration is that Philadelphia's new LRVs normally will not run in trains except on the 2 suburban lines. A large articulated car could be wasteful on a surface-subway system with 5 branches, none of which alone justifies trains. Furthermore, the car selected is also usable on a separate network of surface streetcar lines, although that is not planned at present.

In conclusion, the decision on articulation must be made with full awareness of the gains to be achieved and the restrictions that will be imposed. Articulation has certainly been popular in recent years, and there is no indication that the trend will change. However, each light rail system must be considered with its own characteristics, not simply accepting an articulated configuration because that is popular or in production. There may still be some potential light rail applications that could make use of a rigid 4-axle car at lower total life-cycle costs and with fewer problems than would be experienced with 6-axle articulated units.

LOCATIONS OF DOOR OPENINGS

There is always a trade-off in an enclosed rail passenger vehicle between door openings and seating capacity. Every lane of opening eliminates at least 2 potential seats. The extreme form of maximized seating was the early "open end" car so often used on elevated railways. This evolved into the typical railroad car with enclosed end vestibules. Such door locations are totally unsuited to either light rail or rapid transit applications.

A few double-end light rail cars are in use that have doors only near the ends of the bodies. They are used on light-duty suburban feeder applications, namely Media and

Table 2. Bids on light rail vehicles for Southeastern Pennsylvania Transportation Authority, December 1978.

Car Builder	Total Cost (dollars)	Cost per Car (dollars)	Number of Cars	Cabs	Articulated
Kawasaki	46 291 400	413 316	112	1	No
	11 447 750	394 750	29	2	No
U.T.D.C	48 115 636	429 604	112	1	No
	13 383 500	461 500	29	2	No
Breda	50 384 400	622 030	81	1	Yes
	14 396 800	654 400	22	2	Yes
Breda	53 691 400	479 388	112	1	No
	14 769 700	509 300	29	2	No
Hawker-Siddeley	61 407 806	548 284	112	1	No
	15 961 948	550 412	29	2	No
Brugeoise et Nivelles	61 719 015	761 963	81	1	Yes
	16 228 256	737 648	22	2	Yes
Brugeoise et Nivelles	64 623 936	576 999	112	1	No
	16 637 387	573 703	29	2	No
Budd Company	64 250 310	793 214	81	1	Yes
	19 797 690	899 895	22	2	Yes

Note: The bids for single-end cars include a quantity add-on option as follows: 112 four-axle cars include 18 add-on; 81 six-axle cars include 12 add-on. The lowest bid cars have these dimensions (in millimeters):

	Single-end	Double-end
Length	15 240	16 160
Width	2 592	2 692
Truck centers	7 620	8 400

Table 3. Bids on light rail vehicles for Niagara Frontier Transportation Authority, November 1980.

Car Builder	Total Cost (dollars)	Cost per Car (dollars)	Number of Cars	Articulated
Tokyu Car	21 833 567	661 623	33	No
U.T.D.C.	22 882 864	693 420	33	No
Siemens/DuWag	25 251 044	935 224	27	Yes
Bombardier	26 438 965	1 057 559	25	Yes
Hawker-Siddeley	30 369 008	1 214 760	25	Yes

Note: The lowest bid car has these key dimensions (in millimeters): length, 20 371; width, 2590; truck centers, 11 024. Costs do not include purchaser's bid evaluation add-ons, which were in a narrow spread from $12 568 100 to $12 946 950. These add-ons provided comparisons of life-cycle maintenance and repair costs and inspector travel expenses.

Sharon Hill lines west of Philadelphia and the Mattapan-Ashmont line outside Boston. The great majority of LRVs has at least one set of double doors somewhere in the mid-area.

The proportion of door openings to total car length depends on trip characteristics and load factors. Where the average trip is short and/or where a considerable part of the outer portion of a system is traveled with the cars lightly loaded, then doors could be maximized. This keeps dwell time short and does not eliminate seats that would otherwise receive long occupancy. Where most patrons travel on the greater part of the line and where stations are spread relatively far apart, doors can be kept to a minimum. However, excessive dwell times must be avoided.

The methods of fare collection dictate whether doors should be located near the operator, who can do double duty as a fare collector. Putting doors up front as well as in the center was a great productivity improvement of the 1920s, permitting "one-man" cars that also had relatively fast loading. The double door across from the operator on a PCC was intended to provide 2-way flow with a pay-enter aisle on the right and departure on the left. For applications that are collective-distributive, with one heavily used central station, a single door opening near the operator will suffice, with double-door openings further back.

If cars are double-end, it is usual to provide symmetry of door openings. This cannot be done at the ends with an offset operator's position, and in some cases a narrow one-lane door is provided back of the operator. Without this door, loading from the offside with operator fare collection is inhibited. For example, having a door on the right only across from the operator (with on-board fare collection) compels right-hand running on double track with outside boarding areas and/or left-hand running on double track with boarding areas between the tracks. Because a narrow door behind the operator "costs" only 2 seats, it should be considered for all double-end cars unless all fares will always be collected off-train. Furthermore, such a door near the end on the offside will help loading and unloading at terminals where everyone has paid or will pay later.

The general North American rule in laying out traverse seats in a double-end rail car is that they should face the nearest door. This practice is not followed in Europe, where pairs of seats facing each other are widely used. Defining the nearest door becomes a problem where loading takes place on both sides, so the rule is often set aside for LRVs by having seats face the nearest cab. In this way, at times of light travel, riders can sit nearer the operator while facing forward. The back half of a 6-axle car can even be closed off at such times to reduce vandalism in a lightly occupied area.

"Excessive" door openings make it more difficult to collect all fares on board without loss. This problem has encouraged the application of prepaid or honor fare systems, removing the inhibitions on doors. A prepaid or postpaid fare system combined with ample doors on both sides and double platforms at terminals permits very fast unloading and reloading. A case can be made for providing doors on the offside on a very busy LRT system with single-end cars, as in the PCCs for Boston's Green Line. These doors are used only in the underground portion where everyone exiting or entering has already paid.

Mexico City uses single-end PCCs modified with door openings on the left side to achieve flexibility of loading areas. In some situations, boarding is from center medians of boulevards with right-hand running. The refitted car is an example of how even old LRVs can be made versatile to fit the system rather than making the system conform to the available car.

A lesson to be learned from experience with various patterns of door openings in the long history of light rail is that seldom will decisionmakers be criticized later for providing too many doors. There was formerly a tendency to provide too few, resulting in "pockets" of slow unloading. A prime example was the back end of certain single-end PCCs that had the center doors exactly amidships to provide a symmetrical body structure for double-end option. This layout resulted in 32 seats being to the rear of these doors. Later models with the center door moved more to the rear have faster unloading at the ends of the line.

SELECTION OF BOARDING LEVEL AND STEPS

Light rail vehicles can be designed to fit any desired level of passenger boarding, from the extremes of pavement at the top of rail up to platforms that match the car floor. It is sometimes believed that a system with high-platform loading is not really light rail, but the definition as applied in recent years is broad enough to include all platform heights.

Versatility of LRVs to adapt to different loading levels is shown by the car in common use at Edmonton, Calgary, and San Diego. The first two are high-platform lines, and the last one has paved platforms at rail top. Steps in the LRV for San Diego are external to the car body, while no steps are needed in the Canadian cities.

Decisions regarding platform height(s) should thus be made on the basis of what works best for the system and should not be dictated by what particular car to buy. It is not within the scope of a paper such as this, concentrating on vehicle configuration, to deal at length with the advantages of various options in platform heights. In brief, a case can be made for keeping steps in the station instead of the vehicle when possible. A system without any stops during street running is certainly a good candidate for high platforms throughout.

Within the same system it is theoretically possible to have 3 different platform heights: a lowest either at rail top or at curb height, an intermediate platform height one step below the car floor or, alternatively, at a level even with a bottom car step, and the highest at car floor level.

Unless steps are suspended on the outside of the car body, a stepwell and the relationship to platforms will inhibit the choice of door action. An outward-folding door is manifestly not suitable to high platforms. An inward-folding door or a blinker door will require cutouts in stepwells. Sliding doors and "plug" doors will adapt to any loading level, but they have drawbacks of their own, such as air-actuated operation.[1]

Outward-folding doors with electric drive have a long record of reliability and are therefore preferred where the system is all low-platform and expected to remain that way indefinitely. Internal steps are safer in cold climates; San Diego's approach to loading with the exposed steps might not work in a snowy city like Rochester, New York. The highly workable foolproof blinker doors once so popular on streetcars and on Chicago's elevated make the doorway lanes very narrow.

Several mechanisms are available for changing the height of one or more steps. External steps can be folded out of the way for high-platform operation, or can fit under a properly cantilevered platform, while internal stepwells can rise to make the well area flush with the remainder of the floor. Von Rohr observes that such devices add complications and therefore maintenance costs.[1] Capability to vary steps and thus utilize 2 platform heights that have more than 1 step height difference must therefore be selected with full awareness that a basic complication has been added to the car. The gain is maximum flexibility for the vehicle to fit any type of station.

The conclusion to be drawn concerning boarding level is that the system, present and future, can dictate the step selection in the vehicle with nearly complete freedom. It must be recognized that the high-platform choice restricts the door action to sliding or plug types but also gives greater freedom of door location with respect to trucks.[4] Platform height selection will have far greater impact on station design and right-of-way appearance than it will have on the vehicle.

A strong point has been made over a period of many years that low-platform lines in major metropolitan areas should be constructed to be convertible later to full-size high-platform lines, and some stations and cars—e.g., Brussels—have been designed accordingly. The conversion may never take place, however. So-called pre-metro customarily stays in that state permanently.[7]

A misunderstanding of just what light rail is can bring forth strange ideas. One urban high-platform line with overhead power and no grade crossings is to undergo rebuilding of the platforms as part of a major station rehabilitation project. It was seriously suggested that the platforms be removed and replaced with low ones at curb height so that the facility would then be a light rail line!

CAPABILITY TO RUN IN TRAINS

One decision for LRV configuration that is nearly a matter of pure economics is whether the cars should be capable of running in trains—i.e., at least 2 cars coupled. Although many streetcars did not have couplers, it almost seems a truism now that if there is no need to operate at least 2-1 car trains in the rush periods, then perhaps a light rail line is not justified at all. The only disadvantages of provision for couplers other than higher initial cost are the slight increase in weight, thus using more energy, and a greater

tendency for the car to yaw and pitch because of the added weight beyond the car ends. These differences are noticeable in two groups of otherwise identical PCC cars acquired by Cleveland, 13 with couplers and 7 in their original state.

Coupling ability increases throughput capacity for peak times, since coupled cars are operating at the equivalent of zero headway. This ability is especially important where there is a bottleneck in the system such as single track. A prime example is the Pittsburgh line on the east bank of Saw Mill Run Valley, where a large fleet of PCCs undergoes rush-hour delays because the cars cannot couple and there is a long stretch of single track, with 4 passing sidings. Serious consideration was given several years ago to converting the best of the fleet to multiple units in order to relieve this problem.

Recovery from a delay can be faster with cars that couple because the single cars in the normal operation can be joined into trains during the delay. This will enable the entire group of cars that were held up to move off faster once the problem has been cleared. Furthermore, a disabled car can be towed or pushed by a car with a mating coupler far more readily than if a towbar must be attached. Even where electrical compatibility is not possible because of different control systems and/or very different weights of two types of vehicles, the capability to couple mechanically should be considered.

Once the decision is made to couple (as will usually be the case), the maximum useful train length should be selected. Control wiring can lose its capability as more and more connections between cars are added. Moreover, the difficulty of isolating a problem to a particular car also goes up rapidly with each added coupler. Where there is street running or crossing in a congested area, long trains can interfere too much with other traffic. Abnormal train length is sometimes a symptom of headways that have been made too long in order to reduce labor costs or for other operating considerations. It must be kept in mind that the objective of a light rail line is to move people, not vehicles. The rail car is only a means to this end. Long headways with correspondingly long trains do a disservice to the rider who cannot easily adapt to an infrequent schedule.

Another factor governing train length is the maximum distance gap expected to occur in the power supply. This is a normal concern on systems that have third-rail power pickup, especially where there are street crossings at grade. Usually a line with overhead wire, as is nearly always the case with light rail, has only minute power gaps to divide the power supply into sections. However, LRVs in trains can be very useful for passing under a break in the wire by virtue of having 2 power pickups on the same train spaced 2 or more car lengths apart.

Where platforms are used, their length should be coordinated with the maximum distance between doors on the longest revenue train, allowing a little extra for inaccurate stopping. It may be desirable to move longer trains in yards, but this has no effect on platform length.

Providing the capability for train operation brings with it the need to decide on an existing system whether new equipment should be operable in trains with older equipment or possibly with unpowered trailers. It is a general practice in the transit industry that newer equipment gets used first, the oldest units being brought into service only for peak times. Similarly, trailers are generally employed only at the busiest periods.

The condition and expected remaining life of older equipment must be considered along with the projected need to use these older cars. Restrictions imposed on newer cars by train-line operation with older cars must be weighed. The following are some of these restrictions:

- Power-to-weight ratios cannot be substantially different.
- Control methods must be compatible.
- Braking characteristics have to be well matched.
- Adhesion characteristics have to be similar.
- Acceleration curves and top speed must be reasonably matched.

It can be seen that these restrictions could inhibit the technology used in a new car order. An aging fleet that will be retired before many years should not compel the selection of options that will make new cars obsolete while they are still fairly young. An extreme example of the lengths taken to avoid this pitfall is the new fleet for the Shaker Heights line: double-end, articulated, high-performance. It will be used concurrently with the slower single-end PCC cars gradually being phased out.

If it is necessary to add peak capacity very economically, then the idea of converting some older cars to unpowered trailers might be worth exploring. This approach is particularly applicable in systems where congestion will not allow full use of high-performance LRVs.

CONCLUSION

This paper has reviewed five major considerations in developing the physical configuration for a new light rail vehicle: choice of one cab or two, whether the car shall be articulated, the pattern of doors and seating arrangement, relationship of car floor and steps to loading areas, and single- or multiple-unit operations. There are no "best" answers, although trends show that certain choices are becoming widely accepted—note, for example, the selection of double-end cars with a single articulation for all new North American light rail lines.

A lesson derived from experience is that a current vehicle specification must consider future requirements as well as present conditions. There can be a trap that later compels that extensions be equipped in an ill-suited way just to fit the restrictions of an existing car fleet. The configuration options available for LRVs are so varied that a custom vehicle need not be considered a luxury. The car ought to bring out the optimum capabilities of the system.

A great deal of effort has been expended in recent years to make one standardized car fit different light rail systems; this has proved largely futile. Two re-equipping projects received a car with only a few different features, while three new North American LRT systems ordered another more or less standard "off-the-shelf" car that has little in common with the first "standard" car except some gross configuration features. A pattern may have been set where new LRVs do not achieve the maximum dimensional and performance potentials of some systems.[4] It is encouraging to note that the next likely new light rail system will use a still different vehicle considered best suited to its needs and adapted from a recent design.

REFERENCES

1. Joachim von Rohr. Foreign Light Rail Vehicle Development. Light Rail Transit, Proceedings of National Conference, Philadelhia, 1975. TRB Special Report 161, 1975, pp. 99-109.
2. A. Ross Gray. Application of Light Rail Transit Vehicles. Light Rail Transit: Planning and Technology, Proceedings of National Conference, Boston, 1977. TRB Special Report 182, 1978, pp. 137-139.
3. Articulated Light Rail Vehicle (operated by the Rio de Janeiro Pre-Metro). Brochure by Bombardier Inc., Mass Transit Division, Boucherville, Quebec, Canada, February 1981, 4 pp.
4. E.S. Diamant et al. Light Rail Vehicles. In Light Rail Transit: State of the Art Review, Chapter 5. U.S. Department of Transportation, Washington, D.C., Spring 1976, pp. 117-127 and 156.

5. Robert J. Landgraf. Preliminary Specifications for New Rapid Transit Cars. Shaker Heights, Ohio, Department of Transportation, General Revision No. 2, March 1972, p. 2B.

6. Specifications for Light Rail Vehicle. Greater Cleveland Regional Transit Authority, Final Edition Amended to May 24, 1977, pp. 2-1 through 2-6, 3-1 through 3-4, and Terms and Conditions Paragraph 21.

7. Robert J. Landgraf. Pre-Metro: Conversion Now or Never. Light Rail Transit: Planning and Technology, Proceedings of National Conference, Boston, 1977. TRB Special Report 182, 1978, pp. 62-67.

Practical Considerations in Vehicle Procurement for San Diego LRT

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On the San Diego Light Rail Transit Project, time considerations required procurement of a standard car with project-necessitated modifications. Selection of the standard car and the resultant modifications are discussed.

For the San Diego Light Rail Transit Project, the product of the design criteria and the operating strategies defined the vehicle and sized the fleet. However, as vehicle procurement was on the project critical path, it became urgent to purchase a standard car, and thereby eliminate time for resolving custom design items.

The project, nonetheless, had some features requiring modifications to the standard car. These modifications were project oriented and were practical considerations in procurement of the vehicle.

THE STANDARD CAR

Among the four standard-car offers received, not one was satisfactory to the project without some modification. As standard cars of their respective manufacturers, all essentially conformed to the California Public Utilities Commission General Order 143 (Rules for the Design, Construction, and Operation of Light Rail Transit Systems Including Streetcar Operations), all could make the round trip within 75 minutes, all provided adequate natural ventilation, all could be multipled up to four cars, and all could be equipped with an acoustically damped railroad wheel.

One of the four car types did not have sufficient passenger-carrying capacity and was of a new and unproven design; it would have been difficult to increase the capacity by another 20 standees (full load, not crush) through a straightforward design modification.

Of the remaining three, two required the use of platforms above top-of-rail, and of these two, one was a single-ended, single-sided car. Neither of the two high-platform cars could be certified by an operator as standard cars for 50 car-years, but the manufacturers were willing to build and demonstrate prototypes configured with proven modules. However, the manufacturer of the single-ended car indicated that the high passenger-carrying capability was essential to its standard car concept and was unwilling to consider the modifications required by the project.

As a result, two candidate cars were available and suited the criteria. On one car, the lowest step to street level could be modified, and the maintainability of the other could be demonstrated by the building of a prototype. The remaining technical considerations were the minimum turning radius and estimated energy consumption.

The car with a high platform could negotiate the 60-foot radius curve; the other car could not. However, both cars could be structurally modified. In the end, the 60-foot minimum radius was relieved, and the criterion for minimum lowest step was changed from 12 inches to 10 inches. This meant that car floor and door design changes would be necessary to both standard cars in the final selection. An off-the-shelf version, without modifications, was not available.

The estimated propulsion energy consumption at empty car weight for the two standard cars in the final selection was 5.2 kWh per car mile and 4.7 kWh per car mile, respectively, in the Centre City portion of the run, and 3.6 kWh per car mile and 2.8 kWh per car mile in the high-speed and wide-station spacing portion of the run. The estimates were compared on equivalent conditions and appeared quite plausible. They approximated the engineer's calculation, and they were within the range for other electric traction transit projects with similar service and equipment.

The slightly higher energy consumption of one of the cars was the consequence of its larger size and higher performance capability. The car was wider and could carry about 12 more full-load passengers. It was capable of higher speeds and was chopper-controlled, which contributed to its weight and higher performance, especially at low speeds.

Thus, among the finalists, two were near-standard cars that reasonably fitted the project requirements. One exceeded the requirements more than the other, and as that difference had commercial significance, the decision was made to award the contract for the Siemens-Duwag U-2 car.

MODIFICATIONS

Once the car was selected, the actual purchase order was prepared to provide for certain modifications necessitated by the project. Actually, it soon became apparent that there was not a standard U-2. The manufacturer evolved the design from the Frankfurt U-2 via Edmonton and then Calgary so that San Diego would have its own model (MTDB-1). These evolutions were included in the standard car, whereas the project-necessitated modifications were not.

The seven project-necessitated modifications were as follows:

1. A swing-out footboard was ordered to meet the reduced requirement for the maximum step riser. In this modification, the car builder divided the car floor elevation, just over 38 inches above the top-of-rail, into four equal rises. Two of these are in the door well where structural modifications were minimal. The other two are