A Light Rail, Group Rapid Transit, Personal Rapid Transit Comparison

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ABSTRACT

The existing West Rail Line light rail transit (LRT) deployment in Denver, USA is compared with the results that could reasonably have been expected had the deployment been accomplished using group rapid transit (GRT) or personal rapid transit (PRT) technology that is currently commercially available. In addition, results based on high-speed and capacity PRT (HSCPRT) technology, expected to be available soon, have been evaluated.

All GRT, PRT and HSCPRTsolutions result in shorter trip times and higher ridership than the LRT system. With the PRT and HSCPRT systems the increased fare-box revenue is sufficient to cover operating and maintenance costs as well as amortized capital costs. In addition to attracting additional riders, the higher speeds of the HSCPRT system also result in relatively fewer vehicles being needed. The high capacity aspects of the HCPRT system are probably needed to serve the increased ridership.

INTRODUCTION

The primary purpose of this paper is to compare an existing light rail transit (LRT) deployment with the results that could reasonably have been expected had the deployment been accomplished using group rapid transit (GRT) or personal rapid transit (PRT) technology that is currently commercially available. In addition, results based on high-speed and -capacity PRT technology (HSCPRT), expected to be available soon, have also been estimated.

The light rail deployment used in this analysis is the West Rail Line which opened for service on April 26, 2013 in Denver, Colorado. This line has been selected because it is relatively new and yet has been in operation long enough for trip data to be available. In addition, its routing is such that it only shares three of its 14 stations with other lines.

The GRT system considered here is the 2getthere system that has been in operation in The Netherlands since 1999. This driverless system utilizes 22-passenger vehicles carrying both seated and standing passengers. The analysis is based on the third-generation vehicles currently in production for deployment in the UAE and Singapore. These vehicles have four-wheel steering, are bi-directional and can attain speeds up to 37 mph.

Figure 1. 2getthere GRT Vehicle

The personal rapid transit (PRT) system considered in this paper is the Modutram system under deployment in Mexico. This system utilizes six-passenger driverless vehicles capable of cruising at a top speed of 35 mph.

Figure 2. Modutram PRT Vehicle

HSCPRT is based on six-passenger vehicles utilizing control technology being developed by Transit Control Solutions (Transit Control Solutions, 2016). This technology has been assumed to operate with 70 mph maximum speeds and one-second minimum headways. A feature of this technology is the ability to facilitate slowing on the main guideway, without impacting through traffic, prior to exiting for a station (and accelerating after entering from a station) thus helping reduce the length of station guideways.

Key features of GRT or PRT that are different from LRT include no track switching – the switches are vehicle-mounted – and offline stations – vehicles do not stop at non-destination stations. These differences allow the vehicles to travel within seconds of each other as opposed to minutes for LRT vehicles. They facilitate nonstop travel which increases average speeds and allows the deployment of frequent small stations without the slowing of through traffic.

METHODOLOGY

The methodology used here involves studying the layout, cost and performance of the West Rail Line and utilizing this information to help project the cost and performance of GRT and PRT alternatives. The GRT and PRT solutions are laid out in a way that is believed best capitalizes on the strengths of these technologies. Where alignments differ from those of the West Rail Line, it has been assumed that these alignments could receive public acceptance, possibly with minor adjustments of line and station locations. It is recognized that no public input has been obtained and the alignments represent guideway and station locations that appear reasonable but may not be optimal.

All GRT and PRT solutions result in shorter trip times than the LRT system. The additional ridership generated by the shorter trip times and/or additional stations has been estimated for each alternative solution and used to estimate the rider-dependent costs such as number of vehicles, parking facilities and system operation. Other costs such as elevated and at-grade guideway and station infrastructure (adjusted for demand where necessary) have also been determined. Right-of-way costs (on public space) have been ignored. The GRT and PRT solutions are assumed to fit within the same right-of-way as the West Rail Line and the PRT solution is assumed to be elevated and to fit within existing street rights-of-way where it extends beyond the existing rail corridor. Costs for all alternatives have been compared to the known costs for the West Rail Line using a cost model based on all systems being provided through a public private partnership. Unit costs for GRT and PRT solutions have been based on costs for design-build projects for the particular, and/or similar, systems, increased by a 35% contingency allowance. Revenue estimates are based on RTD fare rates for all systems.

Ridership increases on the GRT and PRT alternatives due to shorter trip times have been based on non-linear demand elasticity by a Logit choice model (Andreasson, 2011).

Non-Linear Demand Elasticity

The transit mode share depends on the utility of transit trips in comparison with those of alternative modes (car, walk etc.). We define disutility as a weighted sum of transit trip time components, transfers and the transit fare. Out-of-vehicle time and Driver-access time are typically perceived as twice as onerous as in-vehicle time. Each transfer is penalized by 5 minutes in addition to the time spent in transfer (waiting and walking). Trip disutility x = In-vehicle minutes + 2 * Out-of-vehicle minutes + 2* Drive-access minutes + 5 mins for each transfer + Mode-penalty + Fare / Value-of-time

Note that LRT, GRT, PRT and HSCPRT solutions have all been assumed to have the same mode penalty even though we believe there may be a general preference for smaller vehicles. Competing modes have similar disutility functions y. The Logit formula for mode share z is defined as

$$z = \exp(-k*x) / (\exp(-k*x) + \exp(-k*y)) \quad (1)$$

where k is a scale factor. As a function of x (for a given y) this formula describes an S-curve decreasing asymptotically from 1 to 0.

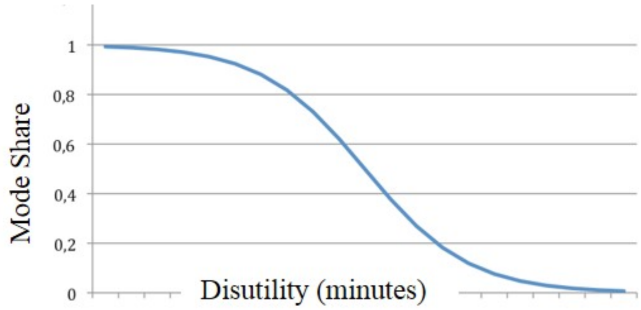

Figure 3. Probability of choosing transit as a function of weighted travel time (disutility)

The effect on the mode share z, of changes in disutility x, can be shown to be independent of other modes as long as the other modes don't change. This means that we can estimate the impact on the mode share of transit improvements without knowing anything about competing modes!

Let x0 and z0 be the initial disutility and mode share respectively. The relative increase in mode share is

$$z/z0 = 1 / (z0 + \exp(k*(x-x0))*(1-z0)) \quad (2)$$

The scale factor k was chosen to be k = -0.035 based on estimates by Liu et al (1998)

WEST RAIL LINE

The 12.1-mile West Rail Line extends from Denver's Union Station to Jefferson County Government Center, traversing through Denver, Lakewood and Golden (RTD 2017). There are 11 stations along the line. An additional three are shared with other lines. The alignment and station locations are shown in Figure 4. The accessibility circles around the stations have one half mile radii representing a maximum walking time of about ten minutes. The service operates on a 15-minute headway for most of the day

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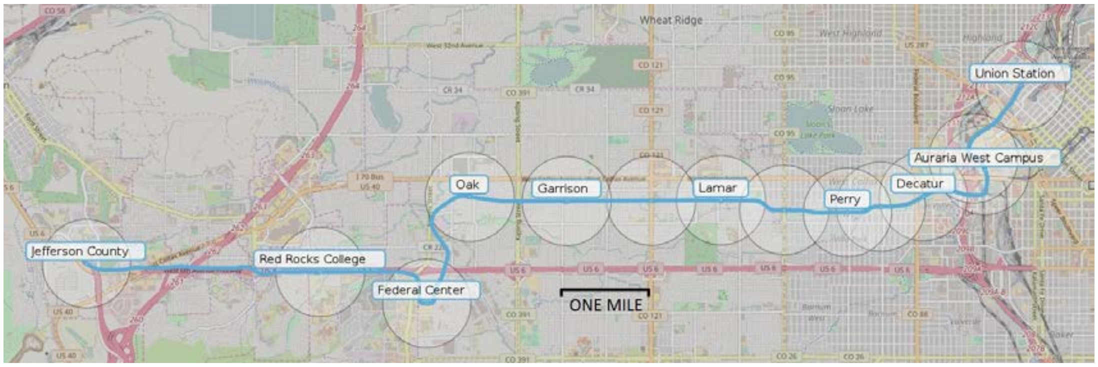

Figure 4. West Rail Line Layout

Construction of the West Rail line, including the above 4,959 parking stalls, cost $707 M (RTD 2012). The line was projected to serve 19,300 riders per weekday but, by early 2016 was only carrying 12,500 (Lakewood Sentinel, 2016)

For comparison with other systems, the cost of parking facilities has been estimated based on $5,000 per surface stall and $25,000 per structured stall. The parking demand for all alternatives has been based on the same rates as planned for the West Rail Line. Riders using the parking facilities are assumed to be generated from the area within three miles of a line, but outside the one-half mile radius around a station.

The following observations and assumptions have been made to better understand the service provided by the West Rail Line and the service area covered as well as to apply these factors to the other modes considered:

- It has been assumed that the amount of parking provided was intended to serve 70% of the projected first year demand
- Since the actual ridership is 65% of projected, it has been assumed only 65% of 70% of stalls are occupied on a weekday. This was found to be approximately correct by observation.
- Each stall has been assumed to generate 2.7 daily rides (i.e. an average vehicle occupancy of 1.35) (DRCOG, 2016)
- Peak hour ridership has been assumed to be 9% of average daily ridership (FDOT, 2013))
- Directional split has been observed to be 55/45

Based on the above assumptions/observations, it has been assumed that the average daily ridership of 12,500 is generated as follows:

- Park & ride – 6,000
- Walk – 5,000
- Bus – 1,250
- Drop-off – 250

The service area for car, bus and drop-off is assumed to be the area within three miles of the rail line but outside the walking service area of the stations. The service area for walking has been assumed to be the area within the one-half mile radius access circles shown in Figure 4.

Assuming an average trip length of 6 miles on the LRT (half the line length), the transit mode share for car, bus and drop-off trips is 0.48 % and the transit mode share for people walking to the station is 2.6%.

The average trip length of 6 miles is the distance from Garrison to Union Station, Federal Center to Knox or Jefferson County to Oak. Table 1 provides the 7:00 AM trip times, including waiting, for light rail, from the RTD Schedule and, for comparison purposes, by car, from Google Maps. The waiting time for LRT was assumed to be half the scheduled headway (time between trains) plus half the assumed maximum walking time of ten minutes (which is about equal to the assumed average driving time for those who park and ride). The waiting/walking time for car was assumed to be 5 minutes to account for parking activities.

Table 1. Trip Time Comparison (Minutes, Unweighted and Weighted)

	Unweighted		Weighted	
	West Rail Line	Car	West Rail Line	Car
Garrison to Union Station	33	26	46	31
Federal Center to Knox	30	16	43	26
Jefferson County to Oak	27	16	40	21
Average	30	21	43	26

The average unweighted LRT trip time is 30 minutes, which is 9 minutes (43%) more than the average car trip time of 21 minutes. However, the average weighted LRT time is 17 minutes (65%) more than the weighted average car time.

Taking direct LRT Operational costs plus a proportionate share of RTD Administrative costs, in 2014 there were 26.4 M light rail boardings at a cost of $74.9 M (RTD 2015). This works out to an average operating cost per rider of $2.84. Approximately 83% of trips on the West Rail Line are at a fare of $2.60 and 17% at $4.50 (RTD, 2017). The average fare will thus be $2.92.

A West Rail Line business case has been developed assuming the rail line was privately funded, constructed and operated in order to provide numbers that can be compared with the other modes considered here. Note that the cost of parking facilities has been reduced commensurate with the 65% of projected ridership that actually materialized. This business case is presented and compared to those of GRT, PRT and HSCPRT in Table 4.

GROUP RAPID TRANSIT (GRT)

This section evaluates a GRT option with similar station locations and mostly constrained to the same alignment as the West Rail Line. 9.1 miles of GRT track are at grade while 18.4 are elevated. It should be noted that, while the West Rail Line is single-tracked from Federal to Golden, the GRT line is double-tracked the entire route to enable a higher frequency of service.

PRT and GRT vehicles are not constrained to schedules or routes. They operate on demand and, after dropping passengers off, can wait in the offline station, continue along the route or, where possible, turn around and go back towards the origin. This flexibility reduces both the number of vehicles needed and the energy used.

The service area of the GRT system has been assumed to match that of the LRT system. It has been assumed to have a top speed of 35 mph with a six-mile trip having one intermediate stop. Waiting times are assumed to be five minutes maximum and

2.5 minutes on average. By applying the Logit choice model in equation (2), we find the GRT system will attract 20,370 weekday riders.

PERSONAL RAPID TRANSIT (PRT)

This section evaluates a PRT option based on the West Rail Line. The alignment, shown in Figure 5, takes advantage of PRT's ability to be laid out as a series of one-way loops rather than being constrained to a corridor. The primary eastbound guideway follows the LRT alignment quite closely, however the primary westbound guideway travels along West 26th Avenue until it reaches I-70 at which point it follows existing streets in a southwesterly direction to the Jefferson County Station. North and southbound guideways connect the east and westbound guideways at intervals of about one half of a mile. All of the guideways away from the LRT route have the cost disadvantage of having to be elevated. However, they have the advantage of increasing the system's walking-distance service area from 9 square miles to 23 square miles. The station accessibility circles shown in Figure 5 have a one-quarter mile radius. Elevated guideways are shown in green while those at grade are orange.

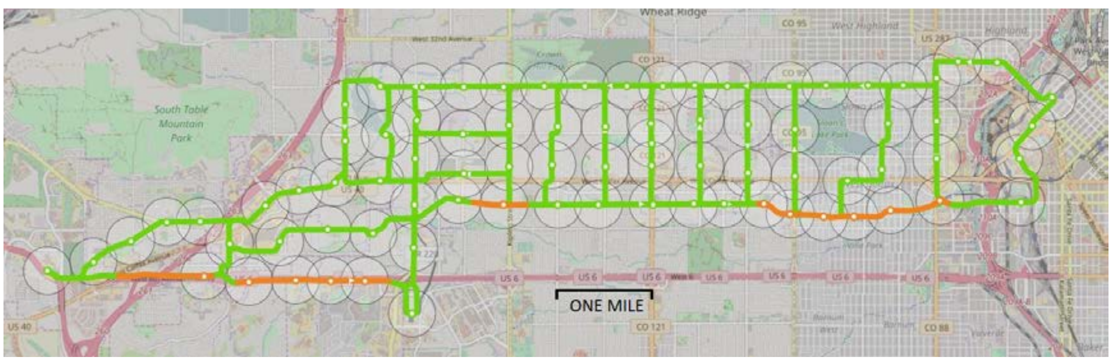

Figure 5. Personal Rapid Transit Layout

There are three factors which increase the ridership on this system over that on the LRT system:

1. The reduced in- and out-of-vehicle times. These have been accounted for using the Logit choice model.
2. The increased areas within one-quarter and one-half a mile of a station. These increase the walking-area service populations
3. The six-fold increase from 14 to 82 stations and the two-and-a-half- fold increase in service area from 9 to 23 square miles. Any system that provides a choice of 81 destinations from any one station as opposed to only 13 will likely greatly increase its mode share. This accessibility increase is thought to be in the range of two to five times. An accessibility factor of two times has been used here. This is considered conservative in that the observed 55:45 directional split implies a fairly uniform distribution of trip generators throughout the system. Figure 4 shows how key results vary by accessibility factor.

HIGH SPEED & CAPACITY PERSONAL RAPID TRANSIT (HSCPRT)

This alternative is based on a PRT system with a maximum speed of 70 mph and minimum headways of one second as under development by Transit Control Solutions (TCS, 2016). However, no changes to the previous alignment have been made and average line speed for a six-mile trip has been assumed to be 50 mph.

The only factor increasing ridership is the reduction of in-vehicle times. This has been accounted for using the Logit choice model.

It is important to note that this alternative has similar annualized capital plus operating costs to the PRT alternative because the higher speeds allow each vehicle to undertake more round trips per hour, thus reducing the number of vehicles required despite the increase in ridership.

COMPARISON OF ALTERNATIVES

This section compares findings for the four different alternatives.

Trip Times

Total trip times are typically comprised of four components:

1. Station access time from the trip origin
2. Wait time at the origin station
3. Travel time in the vehicle
4. Destination access time from the destination station

For the purposes of applying the Logit choice model, estimates of factors 1 through 3 above have been made for each mode and for the primary means of access. Factor 4 has been ignored here on the assumption that a trip would not be made unless the destination was within some reasonable time of the destination station. The fact that some modes have more destination stations has been accounted for separately.

Access times for those driving, or being driven, to stations was assumed to be five minutes while bus times were assumed to be ten minutes. However, these assumptions remained constant across the modes and therefore have no impact on the resulting ridership.

Table 2 shows the resulting total trip times for trips averaging six miles on each mode.

Table 2. Total Trip Times by Mode

	LRT	GRT	PRT	HSCPRT
Riders who park				
Drive access time	5.0	5.0	5.0	5.0
Wait time	7.5	2.5	0.5	0.5
In-vehicle time	18.0	14.0	13.0	7.5
Weighted totals	**43.0**	**29.0**	**24.0**	**18.5**
Riders who walk (1/4 mile)				
Walk time	2.5	2.5	2.5	2.5
Wait time	7.5	2.5	0.5	0.5
In-vehicle time	18.0	14.0	13.0	7.5
Weighted totals	**38.0**	**24.0**	**19.0**	**13.5**
Riders who walk (1/2 mile)				
Walk time	7.5	7.5	7.5	7.5
Wait time	7.5	2.5	0.5	0.5
In- vehicle time	18.0	13.3	13.0	7.5
Weighted totals	**48.0**	**33.3**	**29.0**	**23.5**
Riders dropped off				
Drive access time	5.0	5.0	5.0	5.0
Wait time	7.5	2.5	0.5	0.5
In-vehicle time	18.0	14.0	13.0	7.5
Weighted totals	**43.0**	**29.0**	**24.0**	**18.5**
Riders who bus				
Bus access time	10.0	10.0	10.0	10.0
Wait time	7.5	2.5	0.5	0.5
In-vehicle time	18.0	14.0	13.0	7.5
Weighted totals	**53.0**	**39.0**	**34.0**	**28.5**

It should be noted that the average six-mile car trip in the study area (based on Google maps) is 21 minutes including a 5-minute allowance for finding a parking space and walking, totaling 31 weighted minutes.

Based on the weighted trip times shown in Table 2 and the other factors previously discussed, the weekday ridership has been projected for each mode and the results are provided in Table 3 below.

Table 3. Average Weekday Ridership per Mode

	LRT	GRT	PRT	HSCPRT
Riders who park	6,000	9,764	23,229	28,104
Riders who walk (1/4 mile)	1,450	2,329	56,026	67,214
Riders who walk (1/2 mile)	3,550	5,836	19,061	22,868
Riders dropped off	250	407	968	1,171
Riders who bus	1,250	2,034	4,839	5,855
Totals	**12,500**	**20,370**	**104,123**	**125,213**

An analysis of the business case was undertaken for each mode. For this analysis, the capital cost of capacity-related light rail elements (the parking facilities) was reduced commensurate with the fact that only 65% of the projected ridership materialized. Table 4 presents the results of the business case analyses for each mode.

Table 4. Modal Business Case Analyses

		West Rail Line		GRT		PRT		HSCPRT	
Item	**Unit**	**Quantity**	**Cost (M)**	**Quantity**	**Cost (M)**	**Quantity**	**Cost (M)**	**Quantity**	**Cost (M)**
CAPITAL									
Track	Miles	20		28		54		54	
Stations	No.	14		14		82		82	
Vehicles	No.	?		29		499		369	
VMSF	LS	?		1		1		1	
		Subtotal	**$620**	**Subtotal**	**$326**	**Subtotal**	**$671**	**Subtotal**	**642.1**
Parking Facilities			57		92		220		266
Contingencies					147		312		318
	Total Capital Cost		**$677**		**$565**		**$1,203**		**1,226**
FUNDING									
Equity (15%)			102		85		180		184
Debt			575		481		1,023		1,042
	Total Funding		**$677**		**$565**		**$1,203**		**$1,226**
ANNUALIZED COSTS									
Financing (@4% for 25 years)			36		30		65		66
O&M			11		6		23		23
	Total Annual Cost		**$47**		**$37**		**$88**		**$88**
	Total Annual Revenue		**$12**		**$19**		**$97**		**$117**
	Net Annual Revenue		**($35)**		**($17)**		**$9**		**$29**
	ROI %		**-35%**		**-21%**		**5%**		**16%**
	Annual Passengers (M)		**4.0**		**6.5**		**33.3**		**40.1**
	Total Cost Per Passenger		**$11.77**		**$5.60**		**$2.65**		**$2.21**

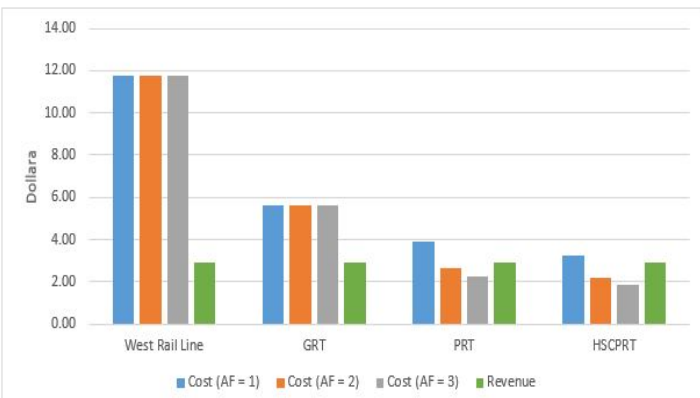

Figure 4 graphically depicts the total revenue per passenger (based on RTD's current fare rates) and cost per passenger (annual operating plus annualized capital costs) compared to the assumed accessibility factor based on the significant increase in number of stations.

Figure 4. Cost (by Accessibility Factor (AF)) & Revenue per Passenger

CONCLUSIONS

The West Rail Line has considerably higher (seventeen minutes) average total weighted trip times than those experienced by commuters who drive. Table 2 shows that each alternative mode evaluated (GRT, PRT and HSCPRT) has progressively lower weighted trip times such that the weighted trip time by car is bettered by all HSCPRT trips regardless of access mode. Considering only those who walk to stations, the mode shares are 2.6% for LRT, 4.2% for GRT, 15.6% for PRT and 18.7% for HSCPRT.

The GRT mode has improved weighted trip times compared to LRT. It experiences quite a significant increase in ridership due to the decrease in total trip time. The lower capital and operating costs combined with the increased fare-box revenues result in an improved business case compared to LRT and the cost per passenger is about half. While it would more than cover its own operating and maintenance costs from fare-box revenues, capital costs would require subsidy.

The PRT mode approximately matches, or improves upon, weighted trip times by car for all of its passengers except for those trips accessed by bus. The very significant increase in projected ridership results from these reduced times and the improved level of service provide by the increase from 14 LRT stations to 82 PRT stations. A significant aspect of this level of service improvement is that over 50% of riders are within a ¼ mile of a station as opposed to less than 12% for the LRT system. The other significant factor (called the accessibility factor here) is the six-fold increase in destinations from any one station (from 13 to 81). Even with an accessibility factor of 1 (no increased ridership due to improved accessibility), the PRT and HSCPRT solutions have costs per passenger of less than $4.00.

While the PRT ridership is estimated to be 12.5 times higher than the LRT ridership, the PRT capital cost is only expected to be 2.1 times, and the operating and maintenance cost (O&M) 3.2 times, higher than that of the LRT system. This results in a much more favorable business case wherein fare-box revenues cover both operating and capital costs and there is a positive return on the equity investment. This high increase in transit ridership resulting from a fairly widespread PRT deployment has also been found by other researchers as summarized in Figure 5.

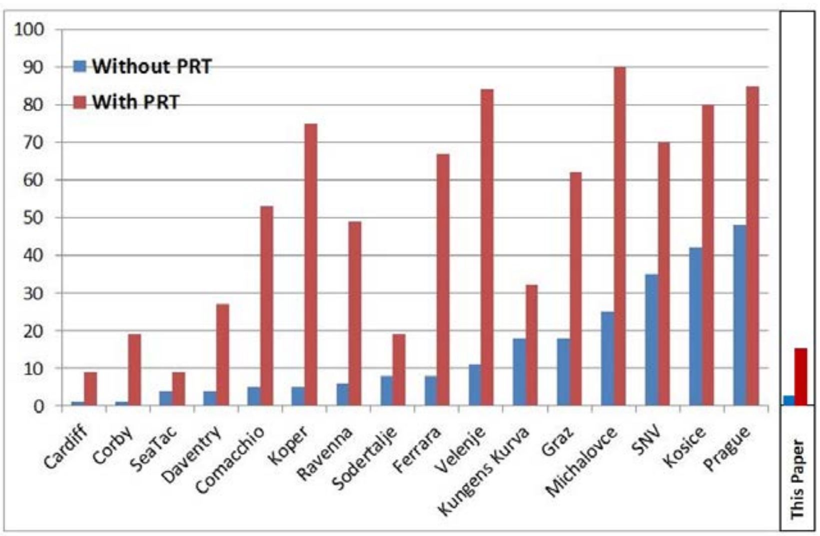

Figure 5. Transit Mode Share Percentage
Source: Studies in the named cities

The HSCPRT mode is significantly faster than the car – up to one half the weighted total trip time. This increase in speed increases the ridership by 20% over the PRT mode.

The average density of vehicles in the PRT system is fourteen per mile – a spacing of 377 feet. At 35 mph, this is a headway of 7.3 seconds – almost double the available minimum headway of about four seconds. Thus, the PRT system has the capacity to accommodate the projected ridership demand.

The average density of vehicles in the HCPRT alternative is ten per mile – a spacing of 528 feet. At 70 mph this is a headway of 5.1 seconds – far higher than the projected minimum headway of one second but, since it is an average, probably not attainable without the "high capacity" aspects.

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