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A STUDY ON COOPERATION OF URBAN TRANSPORT MEANS: PRT AND LIGHT RAIL

Summary. It is difficult to organize urban transport in the city center. Existing buildings, narrow streets and working infrastructure make it difficult to use the old-fashion transport means such as trams or buses. The new idea consists in elevation of the transport in the very city above ground level (typical PRT systems cover rare areas like airport or fairgrounds). The study analyzes the hierarchical, layered system consisting of a ring light rail and PRT (Personal Rapid Transit) serving as commuter network. It is shown in the case of an exemplary city that the proposed solution is possible and reasonable. Ridership and vehicle mileage of the entire system are calculated for the light rail analytically, and in the case PRT by simulation.

1. INTRODUCTION

Typical transportation problems of Polish towns include the following:

- dense built-up area in old towns, typically with private vehicles prohibition and no possibility to allow tram or bus traffic and
- a ring-road around old town and the very city itself, wide enough to accept the traffic (perhaps except of rush hours) but with effective travel velocity much below the speed limit because of many traffic-lights or roundabout operated crossroads.

It seems that a good way to overcome these problems is to elevate the transportation above the ground, over the pedestrian and car traffic. Fast elevated transport means (like light rail) require streets with sufficient width and smooth bends. A ring road typically has such characteristic. Narrow and winding roads in the very center allow for construction of PRT elevated network, with much slower traffic than light rail.

The combination of light rail with PRT as a commuter network allows the following:

- to speed up the transport (as it does not cross with existing means, and thus does not disturb existing transport) and
- to place the stations upstairs, directly in offices, schools and shops.

Several analyses of cooperation of PRT as a commuter network with other transport means have been described [1-4]. The proposed solution consists of two transport means: fast ring light rail and PRT (personal rapid transit) network serving as side roads. PRT network consists of unidirectional tracks that allow carrying of passengers from their final destinations to light rail and vice versa. These two transportation means form a three-layered system:

- higher layer – bidirectional light railway following the ring road – for fast transit around the very city,
- medium layer – unidirectional PRT highways (with no stations), faster than ordinary PRT net, and
- lower layer – slower PRT commuter network composed of ordinary PRT tracks.

Several other solutions of presented transportation problem are possible [5], but the purpose of this paper is to examine the proposed above cooperation of light rail and PRT as a proposal for Polish cities.

The analysis of several Polish town centers confirms the described communication structure of ring road (or a part of it) within the dense cities, consisting of old town and the very city itself (we have not shown the names, as are not important in the analysis):

- A: unclosed, elongate ring with larger diameter of 7.7 km and smaller diameter of 5.3 km, surrounding the whole city,
- B: full ring with diameter of 1.5 km, surrounding the city, partially following narrower streets,
- C: very elongate ring, with larger diameter of 10 km and smaller diameter of 4 km, surrounding the whole city,
- D: misshapen, very elongate ring, larger diameter of 2.5 km, smaller diameter of 1 km, partially following narrower streets, surrounding the whole city,
- E: misshapen, very elongate ring: larger diameter 3.7 km, smaller diameter 2.2 km, surrounding the whole city,
- F: elongate ring with larger diameter 10.3 km and smaller diameter 5 km, surrounding the whole city and some suburbs, partially following narrower streets,
- G: misshapen, elongate ring: larger diameter 2 km, smaller diameter 600m, surrounding a part of the city,
- H: elongate ring: larger diameter 2 km, smaller diameter 900m, surrounding a part of the city and some suburbs,
- I: misshapen, very elongate ring: larger diameter 7.1 km, smaller diameter 2.4 km, surrounding a half of the city and some suburbs, partially following narrower streets,
- J: the ring with larger diameter 4.5 km, smaller diameter 3.2 km, surrounding the city and some suburbs, partially following narrower streets,
- K: the ring (or rather the square) with the side of 2.5 km, following the streets and railroad areas, surrounding the city.

The town K was chosen for the analysis. The ring has the length of 10.08 km. A schematic view of the two-layer transportation system is presented in Fig. 1. Bold oval line represents light rail, rounded boxes represent PRT highway and their dashed interior represents the areas to be covered by side tracks.

The paper analyzes the operation of each of the two systems and their cooperation. The two methods of calculations are presented: analytical for light rail and simulation based for PRT. Analytical calculations are typical for not complicated transport systems, like single rail line [6]. There are some attempts to study complicated systems analytically, but this concerns selected aspects of a structure and traffic [7, 8]. Simulation methods allow treating a transport system as a whole and showing the operation depending on various conditions [9-14].

2. DEMAND ESTIMATION

PRT system is a network covering a given commuter area. In the covered region, stations should be placed in appropriate points, and then connected by track segments.

The territory chosen to cover is the upper rounded box in Fig. 1, i.e. the northern part of the area surrounded by light rail ring. The total area of commuter territory is 4.2 km^2.

The average population density for a typical urban area is about 2000 persons/km^2 [15]. For the central area, we have assumed arbitrarily the value triple as big, i.e. 6000 people/km^2.

Specification of demand is not an easy problem, because no real PRT system is used for urban transport (only in airports, exhibition areas, etc., in fact the experimental solutions [16-18]). Of course, the most important is demand during rush hours, since the transport system should be designed for the worst-case scenario. Only because of the lack of relevant data, we based our estimation on the analogous city tram transport, which is a real existing mass service system.

Based on Polish Statistical Yearbook 2010 [15], tram transit request ratio during rush hours per thousand inhabitants in Warsaw is 20 requests/h and in Łódź 14 requests/h. For a typical town, the lower value of 14 requests/h for thousand people has been assumed. For the whole territory, this gives 352.11 requests/h. For 4-seat PRT vehicles, uniform distribution of passenger group cardinality has been assumed, so the mean value is 2.5 persons for one trip, giving group transit demand of 140.84 groups/h during rush hours.

There may be four types of demand for a trip: rail only, PRT only, rail+PRT, and rail+two PRT trips. For simplicity of calculations, we assume that every demand is for a rail+PRT trip. The territory of the whole light rail system is about double the area of PRT, which gives 704.22 single-passenger requests per hour for light rail.

3. ANALYSIS OF LIGHT RAIL

The main parameter of light rail is effectiveness [6]:

$$E = \frac{R * ATD}{S} \quad , \tag{1}$$

where E – effectiveness [passengers*km/vehicles*km], R – ridership [passengers/time unit], ATD – average travel distance [km], S – service [vehicles*km/time unit].

Best Japan monorails have effectiveness from 69 to 93 [passenger_km/vehicle_km]. American light rails have effectiveness from 15 (San Jose) to 36 (Los Angeles). Metro has effectiveness of 15-22 (metro has lower effectiveness because light rail is more flexible) [6].

Generally, average travel distance (*ATD*) is hard to specify, as it has the following:

- urban component (what areas the trains pass, structure of a city/suburbia, possibility to transfer to other transport facilities),
- social component (distance to job/shopping accepted), and
- technical component (higher velocity causes longer trips).

For example, consider changes in Atlanta between years 1979 and 1996. The train velocity rose from 21.6 km/h to 40 km/h, and this together with suburbization processes gives enlargement of *ATD* from 9.2 km to 15.8 km [6]. Metro has a typically longer *ATD* than light rail because metro achieves higher velocities.

For calculations, the distance is the dominating component since the ring is rather small (assumed to be about 10 km) and the location is assumed in rather uniform area (as it follows the ring road around the old town). As the ring is expected to serve the people to skip over the old town, a good assumption for *ATD* is 4 km (the opposite point in a ring is distant for 5km of the rail track); for a trip of 6km, it is better to choose 4-km trip in opposite direction. The number of stations assumed is 17, and for simplicity, the distance of passenger trips may be divided into 5 partitions, with integer value of kilometers each (1, 2, 3, 4, 5 [km]). The arbitrarily taken distribution of probability of taking particular trip distance is presented in Table 1.

Note that in (1) maximum ridership R gives maximum effectiveness E. This is true during rush hours, when full load occurs. But there are periods when the load is lower (for example at night). It is assumed that rush hours last for 5 hours a day, normal movement 11 hours (1/3 of rush hours movement) and 8 hours at night (1/10 of rush hours movement). This gives 53% of whole day movement during rush hours, and it is near 50% for rush hours assumed in [6].

Assuming maximum velocity of 16 m/s, acceleration and deceleration of 2 m/s^2, and 17 stations in the ring (therefore, 17 segments of track in the ring), an average segment of 593m is passed in 45s. Assuming also 60s stay time at a station for boarding and alighting, the total time of passing the ring is about 30 minutes. Therefore, the effective velocity for the light rail is 20 km/h. Additional assumptions are (for rush hours) as follows:

- train capacity 64 passengers,
- 6 trains: every train passing the ring 2 times per hour; three of them travelling clockwise and the other three counterclockwise.

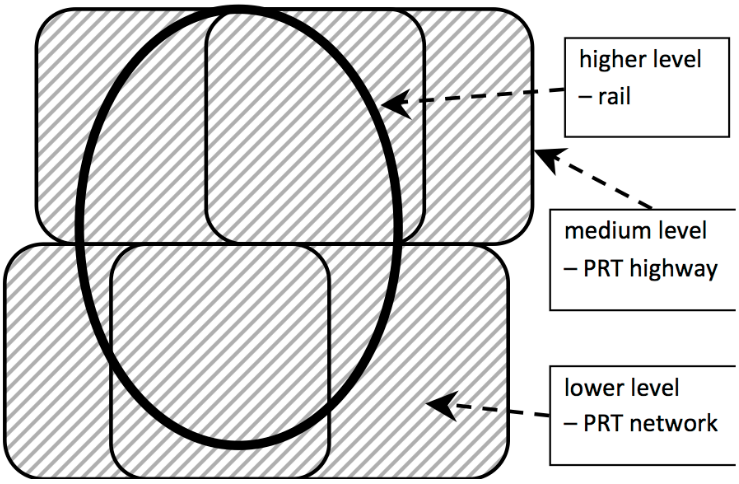


Fig. 1. A schematic of light rail ring (oval) and PRT commuter network (rounded boxes)

Table 1

The distribution of probability of trip distance

distance [km]	Probability
5	0.35
4	0.45
3	0.10
2	0.05
1	0.05
total	**1.00**
4	**mean value**

For 64 passengers, Table 2 shows for every distance (1…5 [km]) the number of passengers taking the trip (for calculations the value need not be integer) and number of times the distance fits in the ring length (10.08 km). This gives total number of passengers transported in one pass of the ring of 187.6, for 1 hour (two ring passes) of 375.2, and for 6 trains during 1 hour of 2251.5. This is the maximum ridership for light rail for the assumed demand structure.

Table 2

Numbers of passengers travelling for individual distance and total

Distance [km]	**Probability**	**Number of passengers** (assuming 64 passengers in a train)	**Number of trips** of this length in full ring	**Number of passengers** passed in ring
5	0.35	22.4	2.016	45.16
4	0.45	28.8	2.520	72.58
3	0.10	6.4	3.360	21.50
2	0.05	3.2	5.040	16.13
1	0.05	3.2	10.080	32.26
Total				**187.6**

A train passing the ring travels the distance of 10.08 km, during an hour (two ring passes) 20.16 km, and with six trains 120.96 km.

The maximum effectiveness for rush hours is 74.5 (=2251.5*4/120.96). Note that the ridership of 2251.5 passengers per hour is over three times greater than the demand estimated for the whole rail area. The effectiveness counted for demand 704.22 requests per hour equals 23.35 (=704.22*4/120.96).

Note that rush hours traffic constitutes 53% of daily traffic. Therefore, the all-day effectiveness is equal to 12.3. This value is rather small compared to the value of light rails in the USA (from 15 to 36). Yet the demand taken from an analogy to tram demand in other cities may be estimated with significant error, for example it does not take into account the bus traffic, taxi traffic, fast urban train, and metro in Warsaw. If the demand is greater twice (40 requests/1000 people during rush hour), the effectiveness would rise twice as well (to 24.6). Also, the density of population may be underestimated. The maximum ridership of 2251.5 passengers/hour gives enough safety margin for underestimation of real demand.

For the demand 704.22/h, rush-hours demand (5h) is 3521.1/h, and assuming daily demand being twice that for the rush hours, it gives 6643.6 passengers/day. For the demand in rush hours equal to maximum ridership of the rail (2251.5/h), rush-hours demand is 11257.5/h and daily demand is 21240.6/h. The annual ridership is assumed 300 "weekday equivalents" [6], therefore it is equal to 1.99 million passengers in the first, and 6.37 million in the second case.

The following is assumed:

- 6 trains run during rush hours (5 hours a day),
- 3 trains run during normal hours (11 hours a day),
- 1 train runs at night (8 hours a day),
- there are 7 trains in total (6 for rush ours and one spare), and
- all trains are used evenly.

Rush-hour mileage for one train is 100.8km (five hours, two ring passes an hour) and 604.8km for 6 trains. Normal-hours mileage for one train is 221.76km (11 hours) and 665.28km for 3 trains. Night-hours mileage for the only train running is 161.28km (8 hours). This gives total mileage of 1431.4km a day, and 204.48km for every one of seven equally exploited (in average) trains. Annual mileage for one train is 61.3 thousand km, and for all trains 429.4 thousand km. During ten years (assumed lifetime of the trains), mileage for one train is 613 thousand km, and for all trains, 4.29 million km.

4. ANALYSIS OF PRT

The analysis was performed for the half of the territory of light rail ring, as mentioned in the introduction. It is the northern part of old town and surrounding districts. Stations in PRT network are placed to obtain walking distance not farther than 300m in straight line.

The PRT highway (bold black line in Fig. 2, assumed maximum velocity 15 m/s) embraces the territory with three loops. No stations are planned on the highway not to disturb the traffic. The highway is guided along main streets forming the ring-road around old town, assuming that the architectural conditions allow it (smooth arcs and mild elevations). The stations (shown as small circles) located directly near light rail stations (greater circles) are transfer ones, while the other stations are ordinary ones.

For ordinary stations (there are 22 of them), assumed average passenger group input is 4/h. For transfer stations (there are 6), assumed input is 10 groups/h (the higher input is natural for transfer stations). The total input is 148 groups/h, which is close to the value of 140.84 groups/h estimated in section 2.

The Origin-Destination Matrix is planned in such a way that the probability of transit orders from every ordinary station to some other ordinary station is uniform and 6 times lower than probability of transit orders to the nearest transfer station. There are no orders to other transfer stations than the nearest one because it is more convenient to travel by light rail. The probability of orders from transfer stations to ordinary stations is also six times higher than probability of orders between ordinary stations.

5. TRAFFIC SIMULATION OF PRT SYSTEM

The traffic in the case of light rail was analyzed analytically, but it is impossible to make such calculations for PRT network. Therefore, the analysis has been completed using simulations in Feniks 4.0 environment [12, 13, 19]. The simulator was prepared under Eco-Mobility project, among several simulation-based analyses of PRT [12, 13, 20-22].

The following parameters have been assumed:

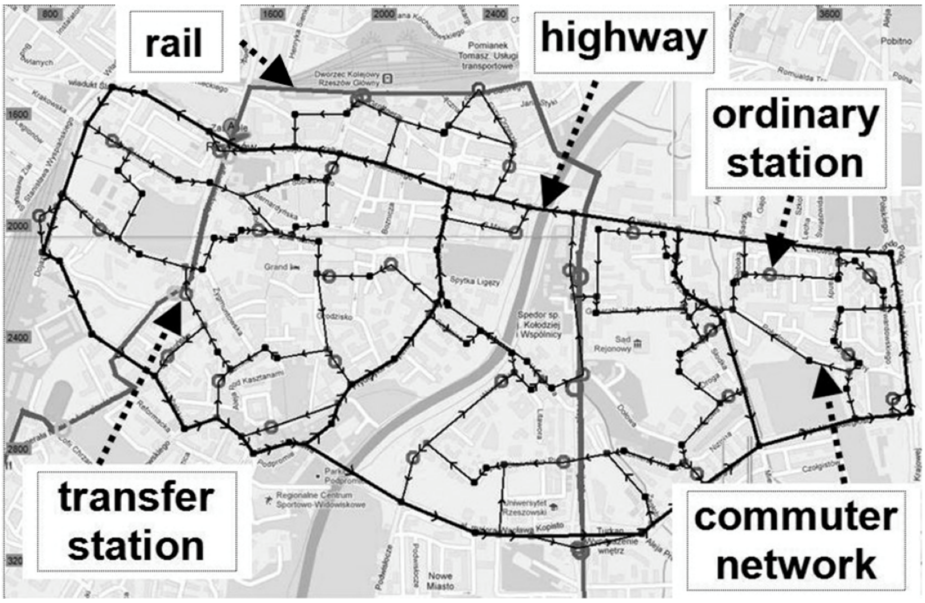
- acceleration and deceleration 2 m/s^2,
- maximum velocity: highway 15 m/s, commuter segments 10 m/s,
- static separation 10 m,

- boarding/alighting: triangle distribution (10, 20, 30) [s],
- transfer stations: 8 stub-berths,
- ordinary stations: in-line with 2 parking positions line (alighting and boarding positions established in the sequence).
- experiments: 12 h.

For the PRT network, an experiment with maximal input [12] has been performed.

This experiment consists in setting unbounded number of passengers at every station. As every vehicle arriving at the station is immediately taken by next group of passengers, the experiment shows the maximum number of trips that can be performed by the network, i.e. maximum ridership, denoted $RSmax$ [1/h]. The experiment was performed for 35 vehicles and for 45 vehicles. The results are as follows:

- 35 vehicles – 385.7 trips/h,
- 45 vehicles – 493.3 trips/h.



Map Data ©Google

Fig. 2. PRT network cooperating with light rail ring

Obviously enough, $RSmax$ sets the absolute limit of network's equilibrium. Let λ (groups/hour) be the demand value, and safety margin m be the ratio $RSmax/\lambda$. As λ is growing, so are the waiting queues as well as average waiting time. The effect is especially dramatic for λ close to $RSmax$ (ρ close to 1). For $\lambda \leq RSmax$ ($m \leq 1$), the network is no longer in the state of equilibrium, and the queues grow infinitely. Moreover, in practice,

- the demand is not uniform among the stations,
- the Origin-Destination matrix is not uniform,
- the structure of the network is usually not symmetric, resulting in an irregularity of the traffic on various segments, and
- input rates and Origin-Destination matrix may change in time.

Therefore, in order to provide the safe, "normal" working conditions that would allow for analyzing properly the role of algorithm parameters, we assumed that in all variants of the model the input rate λ does not exceed 0.5 $RSmax$ (m should be >2).

As the ridership for 35 vehicles exceeds the expected demand over twice (the safety margin m=2.61), the conclusion is that 35 vehicles is enough to serve the PRT network for the half of the light rail ring (during rush hours).

After the preliminary identification of maximal input, an experiment for regular operation of PRT network was performed (column 1 in Table 3), with the following results:

- average trip time is about 5 minutes,
- effective velocity about 38 km/h (maximum velocity 54 km/h on highway and 38.5 km/h on commuter segments: this means than traffic jams do not occur),

- average queue length is 0.15 (less than every sixth passenger group even waits!), and
- average squared delay (square root of sum of relative delays in [%] divided by number of trips, see later in this section) is 21%.

For delay analysis (delay occurs when trip time is longer than free path ride), a synthetic parameter called average squared delay has been introduced [13]. This parameter reflects average relative delay (in [%]), but it is significantly enlarged when single delays are large.

The results show that the PRT network works reasonably, and the amount of only 35 vehicles is enough to carry the traffic.

In the next experiment, the input rate was increased twice (column 2 in Table 3, extreme conditions for the network). Now, the safety margin is only 1.35 (grey background; recommended at least 2 [12, 13]). Indeed, the network works poorly, as the increase of input rate causes average queue length to rise four times (from 0.15 to 0.60, grey background). In such a case, the network does not work in equilibrium. The remedy is to increase also the number of vehicles, provided that it does not cause traffic jams.

Table 3

The distribution of probability of trip distance

Experiment	**1**	**2**	**3**
Safety margin *m*	2.61	**1.35**	1.73
Vehicles	35	35	45
Input [groups/h]	148	296	296
Full trips /12h	1730	3361	3365
Empty trips /12h	1489	2065	**2701**
Avg. trip time [s]	280 (~5 min)	279 (~5 min)	280 (~5 min)
Avg. velocity [km/h]	38.5	38.5	38.5
Avg. waiting time [s]	111 (~2 min)	219 (>3 min)	119 (~2 min)
Avg. queue length	0.15	**0.60**	0.32
Average squared delay [%]	21	21	21

The third experiment (column 3 in Table 3) was performed for the same (larger) input rate but with also larger number of vehicles (45). The results show that it is safe, because traffic jams still do not occur (average squared delay is the same: 21%). Yet the problem has been solved: now the average queue length is 0.32 instead of 0.6. This experiment shows that the extraordinary growth of input requires more vehicles to serve.

The service for the higher demand is performed for the cost of more empty trips to deliver vehicles for the passengers (2701 trips for the 45 vehicles fleet – grey background). An analysis of empty vehicle management is given in [12, 13].

Next output parameters observed concern daily and annual mileage. A vehicle travels 17.7 km in an hour, 88.5 km during rush hours, and 167 km a day (rush hours give 53% of daily traffic). Assuming a year equal to 300 weekday equivalence, this gives 50 thousand kilometers a year. This value well corresponds to estimated mileage for taxis. According to data from several Internet sources, the daily mileage of an average taxi is about 100 to 350 km and annual mileage about 50 thousand km, which confirms the analysis.

A question arises: how many vehicles may efficiently travel in the network? If there are a small number of vehicles, they do not disturb each other. But if many vehicles travel, they concur at the join-type intersections, and they wait before entering a station while passengers embark/alight. The Average Squared Delay parameter (ASD [19]) shows this synthetically:

$$ASD = \sqrt{\frac{\sum_{full\,trips} \Delta_{ft}^2}{number\ of\,full\ trips}} \tag{2}$$

(square root of sum of squared relative delays of full trips (Δ_{ft}) divided by number of full trips). The delay Δ_{ft} (in [%]) is counted as actual trip time divided by nominal trip time (with maximal allowed velocity). When the vehicles do not interfere, in typical PRT network ASD is about 20% (for maximum velocity of 10m/s on ordinary tracks, 15m/s for on highways, $2m/s^2$ acceleration and deceleration, and several km of typical inter-station distance).

Fig. 3 shows the value of ASD for various numbers of vehicles (from 40 to 200) in the network shown in Fig 2. It shows to what extent the vehicle fleet may be safety enlarged: a designer may designate a threshold of average squared delay over which the network is assumed to be jammed. In our example, having the basis of ATD=20%, we may define that the network is jammed if ATD rises by half, i.e. to 30%. This is reached at the number of vehicles of about 185. The number of vehicles used in the experiments was 35 and 45, far less than this threshold.

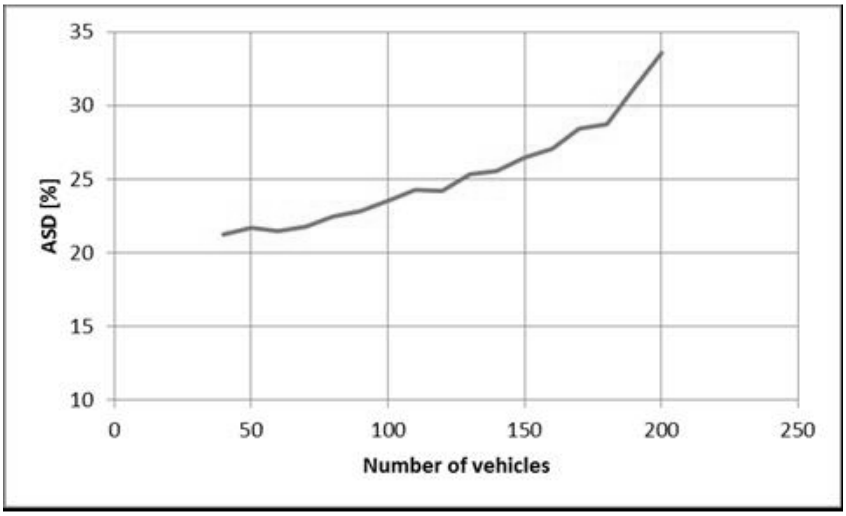


Fig. 3. Average Squared Delay versus a number of vehicles

6. CONCLUSIONS

The analysis of a transportation system consisting in light rail, supported by PRT network, is possible and reasonable. Ring rail plays the role of efficient ring road, and PRT allows to place tracks in hardly accessible areas of old town. Rising above the ground allows it to coexist with other means of transport and pedestrian movement. The main operating parameters are reasonable and both cover everyday demand and give a margin for extraordinary traffic. Also, a comparison of mileage with existing means of transport validates the analysis positively.

The solution may be used in other cities, but they should be analyzed in similar ways. Also, cooperation with existing transportation means (bus, tram, metro, and water transport) should be examined.

The results show that simulation is a good mode of analysis of PRT transport, in which case analytical methods do not suffice. The Feniks simulator proved to be a good environment for such calculations.

Main operating parameters of the two transport systems are collected in Table 4. The comparison shows that having the two transport systems together, rail stations may be placed less densely, which would enlarge the effective velocity of light rail. On the other hand, narrow and sinuous streets in the old town may reduce the theoretical effective velocity of PRT.

Table 4

Comparison of main operating parameters of light rail and PRT

Transport system	**Light rail**	**PRT**
Effective velocity [km/h]	20	38.5
Ridership [thousand passengers/day]	6.5	6.5
Maximum ridership [thousand passengers/day]	21.2	14.4[a]

[a] Assuming that maximum input not causing unbounded growth of passenger queues is 0.8 *RSmax*

There are several PRT systems working, including Masdar, Heathrow Ultra and Suncheon Bay Project in South Korea [16-18]. Yet, several later projects were canceled or discontinued, like SkyTran for Tel Aviv [23], Ultra for Taiwan [24] and Greenville in South Carolina, USA [25]. For this reason, new ideas are much needed for PRT further development.

Such a concept is the subject of a new research in ICS, WUT, where dual-mode PRT is the next step of Feniks simulator evolution. In dual-mode PRT, vehicles travel on a track separated from ordinary traffic, but they may leave the track and travel just like cars, but sill in driverless mode. This results in greater flexibility of the transport and limits walking distance nearly to 0. Moreover, stations are unnecessary in PRT network because vehicles must be able to be embarked/alighted just as taxis (but the stations may be preserved for battery charging or other maintenance purposes). Of course, the vehicles speed must be limited when travelling outside separated track.

7. ACKNOWLEDGMENT

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