It is difficult to organize urban transport in a city center. Existing buildings, narrow streets and operating infrastructure make it difficult to let old-fashion transport means like tram or bus. In the paper, a raised transport consisting of ring monorail and commuter PRT network are analyzed. The proposed solution consists of fast ring railway called “monorail” and PRT (personal rapid transit) network serving as side roads. These two transportation means form a hierarchically layered system. It is shown on an case of an exemplary city that the proposed solution is possible and reasonable. A ridership of the whole system is obtained: for monorail by analytical calculations and for PRT by simulation.

INTRODUCTION

Typical transportation problems of Polish towns include:

– dense built-up area in old town, typically with private vehicles prohibited and no possibility to allow tram or bus traffic,
– a ring-road around old town, 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. This allows:

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

Several analyses of cooperation of PRT as a commuter network for with other transport means were described [1,2,17,21]. The proposed solution consists of two transport means: fast ring railway called “monorail” and PRT (personal rapid transit) network serving as side roads. These two transportation means form a layered system:

– higher layer – bi-directional light railway ring of 10.08 km – for fast transit around the city
– lower layer – a PRT network consisting of faster, unidirectional tracks (highways, with no stations) distributing passenger streams from monorail to PRT side tracks and slower PRT unidirectional side tracks transferring passengers from/to their final destinations.

Many other solutions of presented transportation problem are possible [13], but the purpose of this paper is to examine the proposed above cooperation of monorail and PRT, as a proposal for Polish cities.

A schematic view of the two-layer transportation system is presented in Fig. 1. Bold oval line represents monorail, rounded

Fig. 1. A schematic of monorail ring (oval) and PRT commuter network (rounded boxes)
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 co-operation. The two methods of calculations are presented: analytical for monorail and simulation-based for PRT. Analytical calculations are typical to not complicated transport systems, like single rail line [13]. There are some attempts to analyze complicated systems analytically, but this concerns selected aspects of a structure and traffic [16,19]. Simulation methods let to treat a transport system as a whole and show the operation depending on various conditions [3,4,7-10].

1. DEMAND ESTIMATION

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

The territory chosen to cover is the upper rounded box in Fig. 1, i.e. the northern part of area surrounded by lightrail ring. The total area of commuter territory is 4.2 km2.

The average population density for a typical urban area is about 2000 persons/km2 [18]. For the central area we have assumed arbitrarily the value triple as big, i.e. 6000 people/km2.

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 [22-24]). Of course, the most important is demand during rush hours, since the transport system should be designed for the worst case. Just because of the lack of relevant data we based our estimation on the analogy to the city tram transport, which is a really existing mass service system.

Basing on Polish Statistical Yearbook 2010 [18], 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 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 transit demand of 140.84 groups/h during rush hours.

There may be four types of demand for a trip: monorail only, PRT only, monorail + PRT, monorail + two PRT trips. For simplicity of calculations, assume that every demand is for a monorail+PRT trip.

The territory of the whole monorail system is about double the area of PRT, which gives 704.22 single-passenger requests per hour for monorail.

2. ANALYSIS OF MONORAIL

The main parameter of monorail is effectiveness [16]:

\[ E = R \times \text{ATD} / S \] (1)

where:

- \( E \) – effectiveness [passengers*km/vehicles*km],
- \( R \) – ridership [passengers/time unit],
- \( \text{ATD} \) – average travel distance [km],
- \( S \) – service [vehicles*km/time unit].

Best Japan monorails have effectiveness from 69 to 93 [passenger_km/vehicle_km]. American lightrails have effectiveness from 15 (San Jose) to 36 (Los Angeles). Metro has effectiveness 15-22 (metro has lower effectiveness because lightrail is more flexible) [16].

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

- 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),
- 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, this together with suburbanization processes gave enlargement of ATD from 9.2 km to 15.8 km [16]. Metro has typically longer ATD than lightrail because metro achieves higher velocities.

For calculations, the distance is the dominating component since the ring is rather small (assumed about 10km) 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 4km (the opposite point in a ring is distant for 5km of the monorail track); for a trip of 6km it is better to choose 4km trip in opposite direction.

It is illustrated in Fig. 2. 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.

![Tab. 1. The distribution of probability of trip distance](image)

![Tab. 2. Numbers of passengers travelling for individual distance and total](image)
Assuming maximum velocity 16 m/s, acceleration and deceleration 2 m/s², 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 lightrail is 20 km/h. Additional assumptions are (for rush hours):

- 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.

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 (10.08km). This gives total number of passengers transported in one pass of the ring 187.6, for 1 hour (two ring passes) 375.2 and for 6 trains during 1 hour 2251.5. This is the maximum ridership for monorail for the assumed demand structure.

A train passing the ring travels the distance of 10.08 km, during an hour (two ring passes) 20.16 km, 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 monorail 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 lightrails 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 monorail (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” [13], therefore it is equal to 1.99 million passengers in the first, and 6.37 million in the second case.

It is assumed that:
- 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),
- all trains are used evenly.

Rush-hours mileage for one train is 100.8 km (five hours, two ring passes) 20.16 km and for 6 trains during 1 hour 2251.5. This is the maximum ridership for monorail for the assumed demand structure.

For ordinary stations (there are 22 of them), a passenger group input is 4/h. For transfer stations (there are 6) assuming input is 10 groups/h (the higher input is natural for transfer stations). The total input is 148 groups/h, close the value 140.84.

3. ANALYSIS OF PRT

The analysis was performed for the half of the territory of monorail ring, as mentioned in the introduction. It is a 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. Fig. 3 shows the coverage of the territory with stations (circles). There are only small areas distant more than 300m from a nearest station.

The PRT highway (bold black line in Fig. 4, 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 monorail 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, close the value 140.84.
groups/h estimated in section 1.

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 a nearest transfer station. There are no orders to other transfer stations than the nearest one because it is more convenient to travel by monorail. The probability of orders from transfer stations to ordinary stations are also six times higher than probability of orders between ordinary stations.

4. TRAFFIC SIMULATION OF PRT SYSTEM

The traffic in the case of monorail 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 [7-11]. The simulator was prepared under Eco-Mobility project, among several simulation-based analyses of PRT [5-9,15]

The following parameters have been assumed:

- acceleration and deceleration 2m/s2,
- maximum velocity: highway 15 m/s, commuter segments 10m/s,
- static separation 10m,
- boarding/alighting: triangle distribution (10,20,30)[s],
- transfer stations: 8 stub-berths,
- ordinary stations: in-line with 2 parking positions.
- experiments: 12h.

The schematics of the two types of stations are presented in Fig. 5 (for picture clarity only 4 berths out of 8 are shown in the case of stub-berths transfer station).

For the PRT network an experiment with maximal input [9] has been performed.

This experiment consist 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:

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

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 monorail ring (during rush hours).

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

| Tab. 3. The distribution of probability of trip distance |
|-----------|-----------|-----------|
| Experiment | 1         | 2         | 3         |
| Safety margin | 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       |

- 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 0.15 (less than every sixth passenger group even waits !),
- average square delay (square root of sum of relative delays in [%] divided by number of trips) 21%.

**Fig. 3. Walking distance to PRT stations (up to 300m in straight line)**
For delay analysis (delay occurs when trip time is longer than free path ride) a synthetic parameter called average square delay has been introduced [10]. 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, 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 [9,10]). 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.

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 square delay is the same: 21%). Yet the problem has been solved: now 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 simulation may show to what extent the vehicle fleet may be safely enlarged: a designer may designate a threshold of average square delay (for instance: 25%) over which the network is assumed to be jammed.

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 [9,10].

Next output parameters observed concern daily and annual mileage. A vehicle travels 17.7 km in an hour, 88.5 km during rush hours, 187 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.

CONCLUSIONS

The analysis of a transportation system consisting in monorail, supported by PRT network, is possible and reasonable. Ring monorail plays role of efficient ring-road, and PRT allows to place tracks in a hardly accessible area of old town. Rising it above the ground allows to coexists 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.

Tab. 4. Comparison of main operating parameters of monorail and PRT

<table>
<thead>
<tr>
<th>Transport system</th>
<th>Monorail</th>
<th>PRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective velocity [km/h]</td>
<td>20</td>
<td>38.5</td>
</tr>
<tr>
<td>Ridership [thousand passengers/day]</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Maximum ridership [thousand passengers/day]</td>
<td>21.2</td>
<td>14.4*</td>
</tr>
</tbody>
</table>

* Assuming that maximum input not causing unbounded growth of passenger queues is 0.8 \( R_{\text{Smax}} \)

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

The results show that simulation is 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 system are collected in Table 4. The comparison shows that having the two transport systems together, monorail stations may be placed less densely, which would enlarge the effective velocity of monorail. On
the other hand, narrow and sinuous streets in the old town may reduce the theoretical effective velocity of PRT

ACKNOWLEDGMENT

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Fig. 5. Types of stations: a) in-line, b) stub-berths

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18. Polish Statistical Yearbook 2010


Studium współpracy sieci PRT z pierścieniową koleją miejską

Zorganizowanie transportu miejskiego w centrum miasta nie jest prostą sprawą. Istniejące budynki, wąske ulice i działająca infrastruktura utrudniają funkcjonowanie tradycyjnych środków transportu jak tramwaj czy autobus. W artykule przeanalizowano użycie transportu wyniesionego powyżej poziomu gruntu, składającego się z szybkiej lekkiej kolei zwanej „monorail” i systemu PRT (Personal Rapid Transit) służącego jako sieć dojazdowa. Te dwa środki transportu tworzą hierarchię warstw systemu. W artykule pokazano na przykładzie typowego miasta że zaproponowane rozwiązanie jest możliwe i sensowne. Wyznaczono przepustowość całego systemu: dla kolei analitycznie a dla PRT przez symulację.

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