

Elasticity Model for Easing Peak Hour Demand for Metrorail Transport System

P. K. Sarkar, Amit Kumar Jain

Abstract—The demand for Urban transportation is characterised by a large scale temporal and spatial variations which causes heavy congestion inside metro trains in peak hours near Centre Business District (CBD) of the city. The conventional approach to address peak hour congestion, metro trains has been to increase the supply by way of introduction of more trains, increasing the length of the trains, optimising the time table to increase the capacity of the system. However, there is a limitation of supply side measures determined by the design capacity of the systems beyond which any addition in the capacity requires huge capital investments. The demand side interventions are essentially required to actually spread the demand across the time and space. In this study, an attempt has been made to identify the potential Transport Demand Management tools applicable to Urban Rail Transportation systems with a special focus on differential pricing. A conceptual price elasticity model has been developed to analyse the effect of various combinations of peak and nonpeak hours/fares on demands. The elasticity values for peak hour, nonpeak hour and cross elasticity have been assumed from the relevant literature available in the field. The conceptual price elasticity model so developed is based on assumptions which need to be validated with actual values of elasticities for different segments of passengers. Once validated, the model can be used to determine the peak and nonpeak hour fares with an objective to increase overall ridership, revenue, demand levelling and optimal utilisation of assets.

Keywords—Congestion, differential pricing, elasticity, transport demand management, urban transportation.

I. INTRODUCTION

THE demand of urban transport has been ever growing due to rapid urbanisation and the increase in the socio-economic activities in the cities. Urban transportation is characterised by a large scale temporal and spatial variations in demand patterns [1]. The demand during the morning and the evening hours are high due to office timings, similarly, the traffic demand near CBD of the city is considerably higher due to various economic activities than that in the outskirts. As a result, the demand in peak hours (usually morning and evening) near CBD is exceptionally higher than the demand during lean hours. The trains remain highly congested during peak hours especially near CBD. Conventionally the peak hour congestion inside metro trains is addressed by increasing the supply by way of introduction of more trains, increasing the length of the trains (cars/train), optimising the time table to increase the capacity of the system etc. In the short term, this approach has helped in addressing the problem but to a limited

extent. The efficacy of the supply side measures is limited by the design capacity of the systems beyond which any addition in the capacity requires huge capital investments. A part of the solution may lie in demand side interventions to actually spread the demand across time and space. This study is an attempt to develop an Elasticity Model for Examination of Differential Pricing system for Metro trains.

II. VARIATION IN URBAN TRANSPORT DEMAND

The travel demand varies hourly, daily, weekly, monthly, seasonally and annually. On a weekday, the travel demand is high in the morning and evening hours owing to the office timings. The demand remains comparatively lower in non-office/school/college hours. The demand curve for yellow line (Jhangeripuri to Hudacity Centre) of Delhi Metro, India throughout the day is shown in Fig. 1.

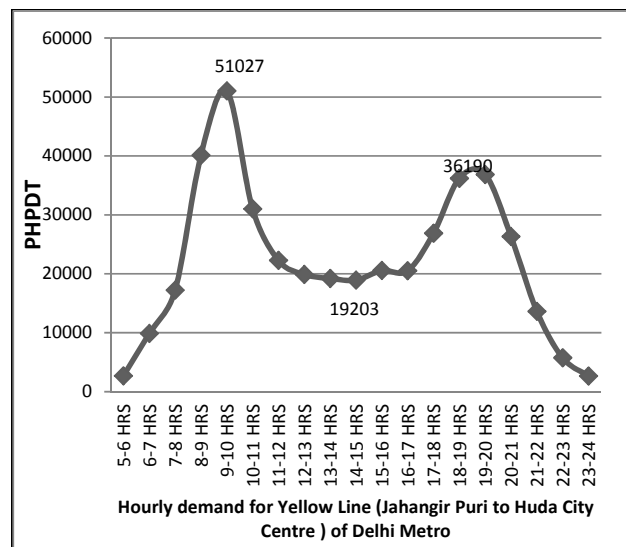


Fig. 1 Hourly variation in demand in yellow line of DMRC, Mar 2014 (DMRC pers. comm April, 2014) [2]

Generally, there are two peaks of demand in a day: Morning peak and evening peak. The demand is high during morning 07.00-10.00 AM as commuters have to reach their work places in the morning and similarly, the demand in evening 05.00-08.00 PM is high when commuters leave for their home.

III. WHY DEMAND SIDE MANAGEMENT IN URT?

The traditional approach to increase the supply to ease peak hour congestion inside metro trains has its limitations. Beyond

P K Sarkar is with the School of Planning and Architecture, New Delhi, 4-Block-B, Indraprastha Estate, New Delhi 110002, Mob no 919810469985, (e-mail: spatphod@gmail.com)

Amit Kumar Jain is with Northern Railway, Delhi, DRM Office, State Entry Road, New Delhi 110001, (e-mail: jainakirts@yahoo.co.in)

a certain capacity, there would be need of additional track, significant improvement in the train control (signalling) system which involves huge capital investment. Further, the supply side solutions may address the problem of overcrowding in peak hours by substantial investment but this additional capacity shall remain underutilised during the non-peak hours. A system designed for peak hour demand will always result in suboptimal utilisation of infrastructure during non-peak hours.

Demand side management [1] of variable demand is more relevant and logical in URT systems due to their cost characteristics. The URT systems are characterised by very high fixed cost and relatively low variable cost. The fixed costs of URT systems are disproportionately high as compared to road based transport systems largely due to heavy investment involved in laying of track, installation of signalling system & traction system and procurement of rolling stock [3]. The variable cost of operation of the URT system is relatively low due to low friction between wheel of train and the steel tracks, high capacity (Passengers/train) of the system and automation in train operations. The relationship of various types of the costs associated in the in the demand and supply analysis is shown as below:

$$TC = FC + VC;$$

TC- Total Cost, FC- Fixed Cost, VC- Variable cost. The average per unit total cost for Q unit of supply (occupancy in trains):

$$TC/Q = FC/Q + VC/Q$$

$$ATC = AFC + AVC;$$

ATC- Average Total Cost per unit, AFC- Average Fixed Cost per unit, AVC- Average Variable cost per unit. Since VC is significantly less as compared to FC, the ATC predominantly depends upon AFC i.e. lower the AFC, lower the ATC. The AFC is inversely proportional to Q (FC being constant over short term), more is the Q, lesser is the AFC.

Since, variable cost is minimal, the key to minimising the unit cost (average total cost) is to reduce the average fixed cost (AFC). The AFC is determined largely by the design capacity of the system. If design capacity is high, the average cost per unit is also going to be high. The AFC for a URT system designed to cater to the peak demand is likely to be high due large variation in demand. The AFC for the system designed for average demand will be relatively less, such a system would result in low level of service (overcrowding) during the peak hours. The optimal design of the system is possible if demand is constant throughout the day and system is designed for this constant demand but demand is highly variable. The flatter is the demand curve; the optimal is the design of the system. Unfortunately, the real life demand curves for URT systems show wide variation in maxima and minima. The key to optimisation of design is to reduce the gap between maxima and minima by adopting demand side management tools.

Further, AFC can also be reduced by increasing supply (Q). However, any increase in Q (number of trains) in nonpeak hours will not serve any purpose to the commuters and will only lead to wastage of resources and consequent rise in cost of operation. The transport management tools are essential to address the congestion in peak hours in URT system.

IV. TRANSPORT DEMAND MANAGEMENT TOOLS

The demand management in URT systems is not only required for mitigation of overcrowding but also for optimal utilisation of fixed assets. The following Transport Demand Management Tools may be employed to level out the demand and for optimal utilisation of the assets [4]:

A. Differential Pricing [5]-[7]

It entails higher fares during peak hours and lower fares during non peak hours. The differential pricing system discourages commuters to travel in the peak hours and encourages non peak hour travelling and thereby may help in levelling the peak hour demand.

The focus of this paper is on adopting Differential Pricing for demand levelling in peak hours by offering higher Fares in peak hours and lower fares in non peak hours.

B. Parking Policies

The higher parking rates during peak hours may deter the passengers from using Metro rail in the peak hours and lower parking rates in non-peak hours will encourage passengers to use Metro rail in non-peak hours. The differential parking rates for peak and non peak hours may be helpful in demand levelling to some extent.

C. Land Use Planning- Mix Land Use

Mix land use ensures multiple economic and social activities in a region thereby reducing the need of long distance transport for going to work, market, schools etc. Mix land use planning may greatly help in minimising the overall transport demand.

D. Integrated Fares

The integrated fares with other modes of transport encourage hassle free and economical use of multiple transport options. The transport demand is optimally distributed among different modes of transport in the regime of integrated fares. The MORE Card launched by MOUD recently, if adopted by all modes of transport across the country, can bring a revolution in the field of integrated fares.

E. Polycentric City

The city with multiple CBDs helps in evenly spreading of transport demand across the city. Unlike a city with one CBD where a predominant transport demand is concentrated to/from CBD, the polycentric city helps in spatial levelling of the demand.

F. Staggered Office/School Timings

Most of the offices in the capital work from 9-9:30 to 1730-1800. The same office hours results into very high

concentrated demand in morning peak and evening peak hours. If we may stagger the timings of the offices in two slots of 9.00-17.30 and 10.00 to 18.30, the transport demand during peak hours can be levelled out considerably.

G. Work from Home

These days the concept of 'work from home' is gaining momentum with the help of reliable, advanced IT systems available and the convenience to the employee as well as employers. In many cities (Hong Kong, Singapore) the office space is so costly that the employer encourages the employees to work from home. These policies may help in further reduction of transport demand.

H. Network Design-Radial to Circular

In the early stages, the Metro rail networks in a city are designed radially to connect the high demand corridors with the CBD. The radial network forces everybody to move to the centre of the city even if one has to travel from one radial line to other radial line resulting in heavy concentration of the demand towards the CBD. The conversion of radial network to circular helps in re-distributing the demand over circular lines and reducing the peak hour demand towards CBD.

I. Transport Oriented Development

Transit Oriented Development (TOD) refers to residential and Commercial Centres designed to maximize access by Transit and Non-motorized transportation, and with other features to Encourage Transit Ridership. A typical TOD has a rail or bus station at its centre, surrounded by relatively high-density development, with progressively lower-density spreading outwards, which represents pedestrian scale distances. Transit Stops and Stations that are convenient, comfortable and secure, with features such as comfortable waiting areas, vendors selling refreshments and periodicals, washrooms, Wayfinding and Multi-Modal Navigation Tools. Integrated development of residential and Commercial Centres, mixed land use, encouraging NMTs and walk based trips help in controlling the demand for transport.

J. Encouraging Non-Peak Hour Travel by Offering Special Facilities

The customers may be encouraged to travel in the non peak hours by offering some promotional schemes like Incentives for Singapore commuters (INSINC) scheme, special facilities for Senior Citizens, differentially abled etc.

K. Cycling

The use of bicycle can substitute both public and private transport trips and thereby reduce the overall demand. However, a conducive environment is required to be created to promote the use of bicycles such as separate lanes, cycle stands, cycle on rent schemes, permitting transport of cycles in public transport etc.

V. SUPPLY SIDE MANAGEMENT TOOLS FOR URT

Similar to the Road transport sector, the supply management tools in URT focus on increasing the capacity of

the system to cater to the increasing demand. The supply management tools [3] are applied incrementally to match the increasing demand over the time. The supply management tools deployed in URT are shown in Fig. 2.

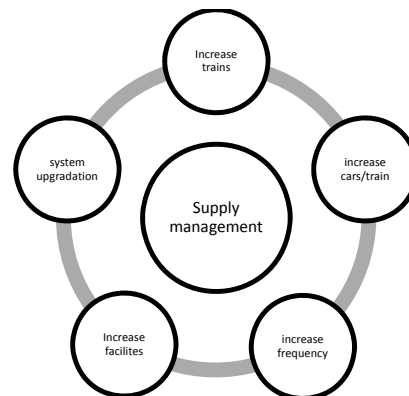


Fig. 2 Supply side measures to ease congestion in URT

A. Increase in Trains

The carrying capacity of a URT system is determined by passenger capacity of the trains passing through a point in an hour. The carrying capacity can be simply increased by introducing more trains in an hour if system permits.

B. Increase in Cars per Train

The carrying capacity can also be increased by adding more cars per train even without increasing the number of trains provided system permits addition of more cars. DMRC has progressively increased the number of cars per train from 4 cars to 8 Cars now at Line 2 and Line 3/4.

C. Increase in Frequency of Trains

The number of trains per hour (frequency) can also be improved by removing the bottlenecks in the system like reducing the terminal reversal time, increase in speed of the trains, minimisation of dwell time at stations, optimisation in time tabling.

D. Increase in Parking Space, AFC Gates, DFMD

The capacity of the station to manage the increasing demand may be increased by adding facilities like Automatic Fare Collection Gates, DFMDs, Lifts, and Escalators, reorganisation of the passenger flows and also by increasing the available parking space.

E. Signalling System up Gradation

The Signalling System may be upgraded to allow the trains at closure headways. The Paris Metro, London Underground have adopted the most modern Communication Based Train Control Systems (CBTC) with driverless Train Operations to improve the frequency of the trains and to increase the capacity of the system.

F. Station Capacity Enhancement

The stations especially those near CBD may not be able to cater to the ever growing traffic demand. The capacity of the

station can be increased by adding more area to the station building, relocating some of the activities outside the station like ticketing activities etc.

VI. LIMITATIONS OF SUPPLY MANAGEMENT TOOLS

The supply side solutions can be adopted only to the extent of capacity of the infrastructure [7]. For example, the length of the platforms of the BG lines of DMRC can accommodate 8cars only as the maximum length of the train. Further, any addition beyond capacity needs improvement in track, signaling, rolling stock, manpower which involves huge capital investment. The supply side solutions always results into suboptimal utilisation of the assets as demand during non-peak hours remain below the capacity of the system.

VII. DIFFERENTIAL PRICING AS DEMAND MANAGEMENT TOOL FOR URT

Differential pricing as a demand side management tool has mostly been used in road sector to control the peak hour demand in the congested sections. One of the main reasons for adopting congestion pricing for road sector is to deter the commuters from using already congested roads and push them to public transport. The congestion pricing model cannot be straight forwardly adopted for URT systems as promotion of public transport is also equally important for sustainable development of a city. For URT systems, the differential pricing scheme is to be used as a pull measure to attract passengers during non peak hour rather than pushing them out of URT system. There is a need of offering reasonable concessions in fare in non peak hours/ non working days so as to shift some peak hour demand to non peak hours and also to attract more passengers to use URT system. With the advent of modern Automatic Fare collection (AFC) system which allows charging of fares as per time of the day and distance travelled, the differential pricing have been increasingly adopted by metro rail systems also as a Transport Demand Management tool. UK, Australia, US, and most recently in Singapore are some of the example of successful implementation of Differential pricing model [5], [6].

VIII. MOTIVATION BEHIND ADOPTING DIFFERENTIAL PRICING STRATEGY [8]

The differential pricing not only helps in easing peak hour congestion but also promotes ridership in off peak hours and over all revenue of the metro rail operator. The key motivations for cities to adopt differential pricing are as under:

A. Manage Peak Hour Travel Demands

The differential fare pricing strategy would allow optimal utilisation of the capacity of the metro rail system by shifting peak hour passengers to off peak hours. The spare capacity available in the off peak hour will be efficiently utilised and the congestion in the peak hour will be eased.

B. Reflect the Appropriate Service Costs

The unit and marginal cost of providing services in peak hours is more than that in off peak hours due to the higher

staffing and overhead costs of accommodating rush hour loads. For example, studies in the US and Europe have consistently shown that the marginal cost of peak services is about three times that of off-peak services [8].

C. Increase Fare Box Revenue and Off-Peak Ridership

The peak hour commuters are in general less sensitive to fare hike as their travel demand is in line with their work schedule. Higher fares for peak hour travel could therefore increase fare revenue. On the other hand, offering concessional services in off peak hours can potentially boost ridership because most off-peak commuters tend to be highly price-elastic.

D. Maintain Social Equity

The differential pricing strategy may also help in eliminating socially regressive aspects of transit fare policies such as those that result from flat fare regimes where off-peak users cross-subsidise the rush hour commuters. Here commuters who tend to enjoy higher incomes than off-peak users and who travel longer distances are subsidised by off peak travellers who tend to have lower incomes and travel shorter distances. Further, differential pricing strategy may also boost non fare revenue from commercial development activities at the stations due to enhanced ridership in off peak hours.

IX. PRICE ELASTICITY OF TRAFFIC DEMAND FOR URT

The elasticity model of differential pricing for URT is based on elasticity of demand with respect to price. As per basic economic principle of demand and supply, the demand of any commodity or services decreases if price is increased. The Price Elasticity of traffic demand is defined as percentage change in quantity (demand in our case) for 1% change in the price of the product/services. So if 10% increase in fares results in 5% reduction in the transport demand, the elasticity of transport demand is -0.5. The elasticity of the transport demand in a city is generally low due to essential nature of the transport demand. So small variations in prices do not really affect the demand of transportation. Further, the elasticity of transport demand depends on various factors in a city such as availability of alternate modes of transports, demographic profile of the city, socio economic characteristics of the city, the population of the city etc. The larger the population, the lower is the elasticity as people are more dependent on public transport in more populated cities.

Mayworm et al. [9] has estimated the elasticities for different sizes of the US cities as shown in Table I.

TABLE I
ELASTICITIES OF TRAVEL DEMAND FOR DIFFERENT SIZES OF US CITY [9]

Central City Population	Mean	Standard Deviation	Cases
Greater than 1 million	-0.24	±0.10	19
500,000-1 million	-0.30	±0.12	11
Less than 500,000	-0.35	±0.12	14

Kaushik Deb, Massimo Filippini, [10] have estimated price elasticity for bus transport to be between -0.232 and -0.523.

The price elasticity for Metro rail systems is found to be on lower side as office goers usually prefer the Metro rail systems and they are generally inflexible in changing their transport schedule. *In absence of any other reliable data, this study has adopted a price elasticity for Delhi as -0.24 being one million plus city.* Further, the price elasticity also varies with time of the travel. The elasticity is low in peak hours as the commuters have limited choice to change his travel need which is mostly to access his/her office in time. However, the non peak demand is characterised by occasional travellers who have flexibility in the travel needs and may change their travel plan according to the prices. Various studies conducted in London, New York have observed that the non peak ridership is twice as sensitive to fare changes as peak [11].

Cross Elasticity: The cross elasticity with respect to differential fares is defined as % shifting of passengers from peak hours to non peak hours for 1 % difference in peak and non peak fares. As per TCRP Report 95 [11] on effect of differential pricing on peak and non peak ridership, the cross elasticity values for above US cities vary between 0.14 and 0.03 with an average value of 0.085.

X. ELASTICITY MODEL

A. Fixed Pricing Scenario

The fares remain in peak as well as the non peak hours as per the applicable fare structures adopted by the URT system. The peak hour per direction traffic (PHPDT) in fixed fare scenario is R_f .

B. Differential Pricing Scenario

The fares in the peak hours are more than that in the non peak hours to encourage more people to travel in the non peak hours. In differential pricing scenario- Peak hour per direction traffic - R_{pd} . Non peak hour per direction traffic- R_{npd}

C. Objectives of the Differential Pricing Model

The main objective of the differential pricing model is demand levelling without compromising upon the revenue generation. The main parameters of the objective of differential pricing are:

- The peak hour demand with differential pricing (R_{pd}) should be less than the peak hour demand in fixed pricing (R_{pf}) scenario.

$$R_{pd} < R_{pf}$$

- The non peak hour demand with differential pricing (R_{npd}) should be more than the peak hour demand in fixed pricing (R_{npf}) scenario.

$$R_{npd} > R_{npf}$$

Peak Hour Demand with Differential Pricing

$$R_{pd} = R_{pf} \left(1 + \frac{ep(F_{pd}-F_f)}{F_f} - \frac{ex(F_{pd}-F_{npd})}{F_{npd}} \right) \quad (1)$$

$$R_{pd} = R_{pf} \left(1 + ep \left(\frac{F_{pd}}{F_f} - 1 \right) - ex \left(\frac{F_{pd}}{F_{npd}} - 1 \right) \right) \quad (2)$$

Non Peak Period Ridership with Differential Pricing

$$R_{npd} = R_{npf} \left(1 + \frac{ep(F_{npd}-F_f)}{F_f} + \frac{ex(F_{pd}-F_{npd})}{F_{npd}} \right) \quad (3)$$

$$R_{npd} = R_{npf} \left(1 + ep \left(\frac{F_{npd}}{F_f} - 1 \right) + ex \left(\frac{F_{pd}}{F_{npd}} - 1 \right) \right) \quad (4)$$

Here, F_f - Fixed fare per km, F_{pd} -Peak hour fares per km in differential pricing, F_{npd} - Non Peak hour fares per km in differential pricing

Illustrative Example

$$e_p = -0.24, e_{np} = -0.48, e_x = 0.085$$

If $R_{pf} = 50,000$, $R_{npf} = 25,000$,

- Peak hour fares are 20% more than fixed fares ($F_{pd}/F_f = 1.2$)
- Non Peak hour fares are 20% less than fixed fares
- ($F_{pd}/F_{npd} = 1.2/0.8 = 1.5$, $F_{npd}/F_f = 0.8$)
- $R_{pd} = 45,475$ (9% reduction in peak hour ridership)
- $R_{npd} = 28,425$ (13.7 % increase in nonpeak hour ridership)

The peak hour demand will come down by 9% and non peak hour demand will be increased by 13.7%. The differential fares would help in levelling the hourly demand of traffic.

XI. CASE OF DELHI METRO RAIL CORPORATION (DMRC), INDIA

Delhi Metro Rail Corporation (DMRC) was incorporated in 1998 to construct, operate and maintain Metrorail services in Delhi, the capital city of India. Till date, DMRC has 212.5 kms network with 160 stations, commuting 2.7 millions passengers a day, maximum being 3.0 million. In DMRC, the peak hour demand (mornings & evenings) on weekdays is around 70% higher than the non peak hour demand. The hourly ridership for Line 2 (Jhangirpuri to Huda City Center) of DMRC is shown in Fig. 1.

As is evident from Fig. 1, the demand in the non-peak hours remains much below the supply of occupancy (number of trains/cars). Whereas in the peak hours, the capital intensive assets of DMRC (track, buildings, signalling, traction and rolling stock) are burdened with excessive demand and are being used up to their capacities but these assets remain underutilised during non-peak hours. On Line 2 of DMRC, the trains are running at a headway of 2'30'' (24 trains per hour). The length of trains has already been increased incrementally from 4 cars per train to 6 car per trains and from 6 cars per train to 8 cars per train from 2010 to 2014. The other supply management tools such as time table optimisation, minimisation of reversal time at terminals and dwell time at stations, enhancement of station capacity have also been adopted incrementally to the extent possible. The maximum achievable carrying capacity on the busiest section is 72000 (30 trains per hour x 2400 passengers per train) passengers per hour for a design headway of 2 mins (30 trains per hour). PHPDT on certain sections of DMRC has already reached to a level of 55,000 per hour in morning peak hours. With the double digit growth of the rider ship, the demand is likely to

surpass the supply in short span of time. The capacity constraint limits the application of incremental supply side management tools for management of overcrowding in the trains- the key lies in demand side management.

One of the potent demand side management tools may be differential pricing for peak and non-peak hours i.e. keeping fares lower during non-peak hours as compared to peak hours [8]. The differential pricing may encourage non-office goers, leisure travellers, occasional users to shift their travel during non peak hours. However, it shall be kept in mind that price elasticity of office goers is very low (almost inelastic) upto an acceptable level of fares. The price elasticity for others is likely to be high and differential pricing may promote others to shift from peak hours to non peak hours. Around 60% of the Delhi metro commuters are regular users and remaining passengers, occasional travellers. The smart card users can be considered as daily commuters with little price elasticity. The token users are occasional travellers and likely to be more elastic to fare changes.

The elasticity model has been applied for illustration purpose to determine hourly demand in terms of PHPDT to appreciate the effect of differential fares on hourly demand. The peak hour demand per direction for Line 2 (the busiest line of DMRC) = 51027 (Mar 2014 [2])

The elasticity model has been applied to determine the hourly demand for 20% increase in fares during peak hours and 20% reduction in fares during non peak hours as compared to present uniform fares. The hourly demand with differential fares is presented in Fig. 3.

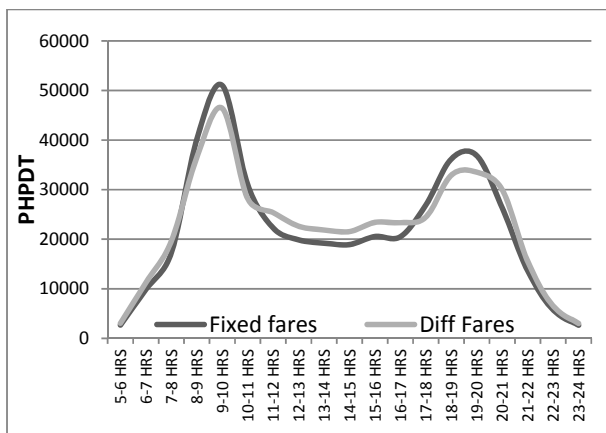


Fig. 3 Hourly demand for 20% Reduction in Non Peak fare and 20% increase in Peak Hour fare

Peak Hours (9.00-10.00 hrs)

- Base Line PHPDT (R_i) = 51027
- PHPDT with Diff Fares (R_d) = 46409
- % change in avg peak hour ridership = -9.05%

Non Peak Hours (14.00-15.00)

- Base Line PHPDT (R_i) = 18919
- PHPDT with Diff Fares (R_d) = 21539
- % change in avg peak hour ridership = +13.7%

The peak hour demand will come down by 9% and non peak hour demand will be increased by 13.7%. The differential fares would help in levelling the hourly demand of traffic.

XII. APPLICATION OF ELASTICITY MODEL

The above model can be used for following applications:

- To determine adjusted demand during peak hours and non peak hours for different combinations of fares in peak hours and nonpeak hours.
- To assess peak hours and nonpeak hours fares to achieve a target demand level
- A further extension of study may be to define Level of Service (LOS) inside trains and to determine fares to achieve an acceptable LOS.
- The model can also be used to determine fares for higher class accommodation and lower class accommodation for target LOS in respective classes.
- The model can also be used for analysis of behaviour of different passenger segments (Commuters, occasional travellers, students, Senior citizens etc.) with respect to differential fares

XIII. LIMITATIONS OF THE MODEL

Elasticity values considered in the study are based on literature survey. The findings are indicative in nature. Actual results may vary depending upon elasticity values with respect to fares for different segments of customers.

XIV. CONCLUSION

The high level of congestion in peak hours is one of the reasons for metro services not being attractive to the car users. The peak hour congestions needs to tackle to attract the car users to Metro services. Further, the optimal utilisation of the assets can also be achieved if demand is near constant throughout the day. The results show that the differential pricing can be effectively adopted as a Transport Demand Management Tool to ease out the peak hour traffic congestions in Metro trains [12]. The efficacy of differential pricing as a tool depends upon the values of price elasticity of different segments of customers. The current smart card based fare collection system offers adequate flexibility to the metro operators to charge time and distance based fares. The Metro systems need to know the price elasticity of demand and determine the peak hour and nonpeak hour fares using the elasticity model.

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