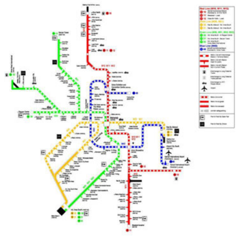

Social Welfare Maximization For Public Transportation In Qatar

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Abstract

In this research, we apply revenue management techniques to a timely and significant public policy question. In particular, we examine the potential benefit of influencing public transport usage in order to maximize the social welfare of residents. The approach we take is to regulate the passenger demand for Qatar's metro system by controlling the ticket prices and varying the combination of different train cars throughout the day. The passengers are heterogeneous in their preferences and choose the transport option that maximizes their own utility. Facing rational passengers, we begin by developing a game-theoretic model to determine optimal prices that maximize social welfare. We define social welfare as the total consumer surplus plus revenue generated by the metro operator. Then, we treat price as an exogenous variable and construct a choice-based deterministic linear programming (CDLP) model to maximize social welfare. Using the CDLP, we solve for the optimal offer set(s) of tickets to be offered by the metro operator in each headway period. The CDLP model differs from the traditional deterministic linear programming approach by incorporating a multinomial logit (MNL) model to estimate the probability of generating a ticket sale given the preferences of different customer segments. Running the model with the current metro demand rate suggests that it is possible to increase revenue by 5.71% on the Red Line of the Doha Metro without sacrificing social welfare by careful selection of tickets and seat options.

Background

The planned metro system consists of three lines: Red, Gold, and Green. For the purposes of this project, we are only considering the Red Line. There are three types of classes on the Doha Metro: Gold, Standard, and Family. The Gold cars are the most luxurious and thereby the most expensive at QAR10.00 per trip. Then, the Standard and Family are effectively the same class except that the Family is reserved for a subset of travelers with more privacy and comfort. Both of these classes cost QAR2.00.

Methodology

Following the approach laid out by Liu and van Ryzin (2008) in which we will enhance complexity by expanding the product offerings and determine the optimal offer set of tickets for the metro operator. In this case, we will consider prices to be exogenous variables that are externally determined to maximize social welfare, and then given those prices, maximize the revenue generated by the metro operator since social welfare incorporate the revenue generated by the metro operator.

Consider current prices as utility maximizing → Run quantity-based model to maximize revenue → Achieve maximum social welfare

Quantity-Based Model

Instead of focusing on price, let S denote the firm's offer set which includes the types of products a firm chooses to offer from the set of products. Given the offer set S, a customer arrives and chooses a product n ∈ S with probability Pn(S) where if n is not in S then Pn(S) = 0. To generate these probabilities, we will use the multinomial logit choice model to estimate class preferences. We assume that customers can be divided into distinct segments and that each segment is interested only in a certain subset of the available tickets which would be their consideration set. The following is the Choice-Based Deterministic Linear Programming Mode:

Maximize

$$\sum_{S \subseteq N} \lambda R(S) t(S)$$

← For each offer set, sum up probability of arrival per period multiplied by $R(S) = \sum_{n \in S} r_n P_n(S)$ multiplied by number of time periods offer set is offered.

Subject to

$$\sum_{S \subseteq N} t(S) \leq T$$

← Sum of all time periods each offer set is offered should be less than the headway.

$$\sum_{S \subseteq N} \lambda Q(S) t(S) \leq c$$

← Expected capacity utilization per leg is less than or equal to the capacity of each leg.

$$t(S) \geq 0$$

← Non-negative constraint of time periods each offer set is offered.

Results

We split incoming travelers into 12 possible segments depending on their ending destination and class preference. To come up with the probabilities of an arrival from each segment, we used insights given by Al-Mesned (2019) of the ranking of the different stations on the Red Line. In terms of the preference vectors, we will reflect in the preference vectors the probability of classes as explained by Al-Mesned (2019). The results indicate a substantial revenue improvement compared to offering all tickets. We can see that even at the current demand rate, the optimal offer set found by the model generates 5.71% more revenue for the train operator just by not offering Family class tickets to the fourth group of stations.

Leg capacity $[C_1, C_2, C_3, C_4]$ / Demand Arrival %	[100, 100, 50, 50]	[150, 50, 50, 50]	[200, 50, 25, 25]
5%	5.71%	5.71%	5.71%
50%	17.37%	50.34%	82.20%
100%	20.34%	68.97%	84.75%
150%	20.34%	68.97%	84.75%

Conclusion

In conclusion, it is clear that the Doha Metro operators can benefit from utilizing revenue management techniques to increase their revenues without reducing social welfare. We found that public policy can learn a lot from traditional business concepts and use them to promote the welfare of society, even for developing nations. In particular, the use of the CDLP model can yield substantial benefits, even at the current low utilization rates of almost 6% increase in revenues (and consequentially, social welfare). Our analysis found two key specific, actionable recommendations to the Doha Metro. Firstly, we found that the Family class acts as a hurdle against maximizing revenues. This is because many individuals applicable for the Family class may choose to ride in it for more comfort and privacy while at the same time paying the same amount as Standard class. In almost all of our results, the tickets that get offered the least are Family class tickets. Secondly, we also found that each metro station should focus on allocating capacity to its closest stations only. This is excepted because as the distance between the destinations increases, then it means that there is a higher opportunity cost of capacity since tickets to each destination cost the same.

Areas For Future Research

The first key limitation of this thesis is regarding the definition of social welfare. In this paper, we took a very specific definition of social welfare which is the combination of consumer surplus and revenues generated by the metro operator. However, this definition falls short in two key areas. Firstly, it does not consider other factors that presumably improve social welfare such as the availability of transport, affordability, accessibility, and many more. All though these factors are quite relevant to study when considering social welfare, they are extremely difficult to estimate accurately. Secondly, this definition of social welfare maximization does not consider positive externalities from operating the metro such as energy savings, pollution limits, etc. Combined, these two areas also expand the ethical consideration of social welfare. Therefore, future studies should try to expand the definition of social welfare to have a more coherent approach in benefiting the nation.

The second key limitation of this thesis is regarding the complexity of the model. Due to the nature of the thesis, we had to make numerous simplifying assumptions that could be revisited in future work. For example, in the CDLP model, we generated up to 12 segments of travelers. It would still be beneficial for future work to investigate more segments that interact differently or for instance to create provisions for segments at transit stations (those whose final destinations are not on the current line but on another one). Another example could be regarding the offer sets and how we are making a time homogenous demand assumption. This can be further scrutinized in future studies to vary demand through time. Finally, a third example is to formulate a full model with network optimization. Given the limited computational power, we only considered a single line from the Doha Metro.

Liu, Q. & van Ryzin, G. (2008). On the choice-based linear programming model for network revenue management. Manufacturing & Service Operations Management 10(2), pp. 288-310.
Al-Mesned, M. (2019, November 10). Personal Interview and follow-up emails.
NOTE: This is not all the referenced material. For the full list of all referenced material, please refer to the final paper.

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