CABLE CARS: FROM OPTIMAL DESIGN TO OPTIMAL PRICING

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ABSTRACT

Although cable car services have become an integral part of the transit system in many cities in the world, their optimal pricing has never been studied. Here we formulate, solve and apply a model for the optimal design and pricing of a cable car system considering operators' and users' costs. The links between cabins' density, speed, and capacity are unveiled to show that money prices fall short of average costs such that an optimal subsidy emerges.

Keywords: cable cars, optimal pricing, design, public transport

1. INTRODUCTION

Public transport services admit the coexistence and integration of many technologies such as buses, subways, tramways, and so on. Although cable car systems have operated for tourism purposes for decades, nowadays they have become an integral part of the transit system in many cities in the world, particularly in Latin America. This is the case of Medellín, Caracas, Rio de Janeiro, and La Paz, cities that have installed this technology as part of their public transport network in the last two decades, including the most extensive urban cable car network in the world (La Paz).

Many studies deal with different aspects of cable car operations: demand, acceptability, travel time, environmental and social impacts, design, and so on (e.g. Bocarejo et al., 2014; Garsous et al., 2019; Guzman et al., 2022; Posada and García-Suaza, 2022). Surprisingly, however, despite the importance of optimal pricing in cable cars (Reichenbach and Puhe 2022, Tiessler et al., 2020), this issue has been neglected. Some feasibility studies can be found including infrastructure, operation, and maintenance costs where the fares are assumed as given (e.g. Tahmasseby and Kattan, 2015; Tahmasseby, 2021). Yañez-Pagans et al. (2019) point out that cable car systems tend to be heavily subsidized and do not have the same capacity as other massive transport systems. Tischler and Mailer (2019) touch on the technical and economical aspects that are relevant from the operators' point of view. Brida et al. (2014) emphasize that the literature regarding the economic performance of cableways is limited.

The main objective of this paper is to address the optimal pricing of cable cars considering operators' and users' costs and the links with optimal design. It is worth recalling that the optimal public transport pricing literature has received renewed attention in recent years starting from the fact that design and pricing are intimately linked (Jara-Diaz et al, 2023). This occurs because the production of trips requires two types of resources, those coming from investment and operation of the system and those contributed by the users, namely their time walking to and from a station, waiting for a vehicle, and riding the vehicles. As known, users' time as a resource has an impact on first-best (marginal) pricing only if one additional user impacts the time that has to be inputted by other users. The best-known examples are the reduction in waiting time because of larger frequencies (a positive externality, the so-called Mohring effect) or the increase in travel time because of congestion (a negative externality), contributing to an optimal subsidy in the first case or to an optimal charge in the second. This happens because in general, when time externalities exist, the optimal money price should equal the total marginal cost including users' and operators' resources, but what is already "paid" by the user, i.e. the average user cost (travel time properly valued), has to be subtracted. As shown by Jara-Diaz and Gschwender (2009), optimal design induces the right optimal prices and non-optimal prices induce erroneous designs: design and pricing of transport systems are two sides of the same coin. The technical relations between the design variables in cable car operations have been studied indeed, but optimal pricing has not and is the main objective of this paper.

In the following section, we develop a stylized model for the optimal design and pricing of a mono cable car line taking into account operators' and users' costs. In the third section, the model is solved numerically using La Paz-like parameters, showing that observed fares are slightly above average operators' costs but a subsidy seems advisable. Section four concludes.

2. A DESIGN-PRICING MODEL FOR A CABLE CAR LINE

In this section, we develop a model for a single mono cable car line with two stations whose location (and associated length) is known. As shown in Figure 1 schematically, the line involves three circuits: a long one of length L that operates between stations, and two short ones of length $l/2$ each that operate within each station, with $L >> l$. The vertical rise between stations is H.

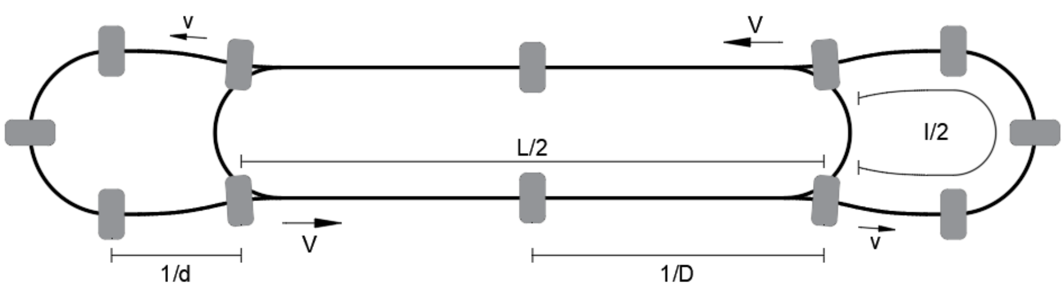

Figure 1. The cable car system

Total demand Y passengers/hour enter the system at the origin station and travel an exogenous distance $\frac{l}{4} + \frac{L}{2} + \frac{l}{4} = \frac{1}{2}(L + l)$. Cabins circulate at a speed V in the long circuit (between stations) and at a speed v in the short ones (i.e. within a station); the former is a design variable while the latter is set such that users can board and alight comfortably while the cabin is in very slow motion. The cabin densities in the long and short circuits are D and d cabins/km respectively.

Frequency f in cabins/hour can be looked at as density times speed in either circuit, i.e.

$$f = VD = vd \tag{1}$$

Because v is exogenous, cycle time does not depend on the time passengers take to board and alight. As d is cabin density in those spaces where passengers enter and exit the cabins it equals the inverse of s, the separation between two successive cabins ($s = 1/d$) including cabin length. Separation s must fulfill $s \geq a$, the minimum safe separation that follows a linear form $a = \varphi K + \theta$, where K is cabin capacity. So $1/d \geq a$ and, because of (1), $VD \leq v/a = v/(\varphi K + \theta)$.

Regarding the operator's cost, there are various components, beginning with the acquisition, operation, and maintenance of a cabin. Empirical information indicates that this hourly cost C increases linearly with the cabin capacity within a minimum K_{min} and a maximum K_{max}. Then $C = c_0{}' + c_1(K - K_{min}) = c_0{}' - c_1 K_{min} + c_1 K = c_0 + c_1 K$.

Secondly, according to CERTU (2012), the energy cost depends on speed V. Then there is a cost c_3 associated with the pylons and rope - whose number depends on $L/2$ - and a fixed cost c_4 that includes stations' infrastructure, the control systems, and the personnel. For short, the operator's cost is:

$$C_{Op} = B(c_0 + c_1 K) + c_2 V + c_3 L/2 + c_4 \quad (2)$$

where the fleet B of cabins is given by $B = DL + dl = DL + \frac{DV}{v} l = D(L + \frac{V}{v} l)$.

Technical considerations indicate that energy consumption due to the speed (c_2) depends on the vertical rise between stations H (CERTU, 2012), and on the fleet circulating in the long circuit (equal to DL), i.e. $c_2(D, L, H) = p_E(\alpha H + \beta DL)$ where p_E represents energy price per kWh and the expression in parenthesis represents the kWh consumed per kilometer.

Length l should be at least equal to the minimum distance necessary to allow passengers to board and alight. Boarding time varies between t_{max} (for a passenger walking the whole cabin width) and zero, such that the average boarding time in a fully loaded cabin would be $t_{max}/2$ and the total boarding time would be $K t_{max}/2$. If b is the cabin width and v_w is the average boarding and alighting walking speed, then $l \geq 2bvK/v_w$. As seats distribute such that passengers face each other, b is approximately $gK/2$ where g is the width of a seat. Then $l \geq gvK^2/v_w$. As C_{Op} and C_{Us} (see below) grow with l we finally get $l = gvK^2/v_w$, which makes the fleet equal to $B = DL + dl = DL + \frac{DV}{v} l = D(L + \frac{gV}{v_w} K^2)$.

Let us now formulate users' costs that include waiting and in-vehicle trip time. We consider that users travel from one station to another arriving at the origin at a constant rate. They board in the second half of the short circuit at the origin station and alight in the first half of the circuit at the destination station. Then, in-vehicle trip time has three components: time traveling $L/2$ at speed V, time boarding the cabin along $l/8$ at speed v, and the time alighting the cabin also along $l/8$ at speed v. The system operates with regular headways $1/f$. If p_w and p_v are the value of waiting and in-vehicle time respectively, the total users' cost is:

$$C_{Us} = p_w \frac{Y}{2VD} + p_v\left(\frac{LY}{2V} + \frac{ldY}{4VD}\right) \quad (3)$$

The problem can now be formulated by minimizing the value of the resources consumed VRC given by the sum of (2) and (3), with D, V, and K as design variables. Given that $l = gvK^2/v_w$, and considering cabins' spacing at stations and capacity restrictions, the optimization problem is:

$$min\, VRC(V,D,K) = D(L + \frac{gK^2V}{v_w})\,(c_0 + c_1K) + p_E(\alpha H + \beta DL)V + c_3L/2 + c_4 + p_w\frac{Y}{2VD} + p_v(\frac{LY}{2V} + \frac{ldY}{4VD}) \quad (4)$$

subject to

$$VD - \frac{v}{\varphi K+\theta} \leq 0 \quad (4a)$$

$$Y - VDK \leq 0 \quad (4b)$$

$$0 < V \leq V_{max} \quad (4c)$$

$$K_{min} \leq K \leq K_{max} \quad (4d)$$

It is worth noting two properties of model (4). First, VRC increases with K for all values of V and D, i.e. $dVRC(V,D,K)/dK > 0$, which indicates that the minimum feasible K within K_{min} and K_{max} should be chosen; as discussed below, it is not evident that making $K = Y/VD$ is optimal because of constraint (4a). Second, as K is available in a few sizes only, Problem (4) can be represented in space (V, D) parametrically in K and Y. Let us analyze this further.

Constraint (4a) states that frequency ($f = VD = vd$) in the short circuits cannot be larger than a value determined by cabin length (associated with K), and by a speed that permits boarding and alighting the cabins (slow movement). Then (4a) imposes a technical boundary on f and *does not* depend on Y, making $VD \leq v/(\varphi K + \theta)$. Constraint (4b), however, imposes that frequency should be enough to support a flow Y given K, making $VD \geq Y/K$. Therefore, when Problem (4) is represented in space (V, D) parametrically in K and Y, constraint (4b) moves away from the origin as Y increases while (4a) remains stable. Therefore, there might be no feasible solution space and the adjustment must occur by increasing K. Consequently, Problem (4) can be solved by letting K be continuous and, if $K* \equiv Kc$ is not available in the market, the optimal available K (Km*) is the one immediately larger than Kc. Note that making K continuous constraints (4a) and (4b) would coincide for some Y such that $Y = Kv/(\varphi K + \theta)$; for all $Y \leq Kv/(\varphi K + \theta)$ there would be no solution.

After the optimal design is found as a function of Y, the optimal prices can be obtained in the usual way, i.e. by subtracting the average users' cost AC_{US} from the total marginal cost MC_T as recalled in the introduction.

3. SIMULATION AND RESULTS

The model is solved numerically using La Paz-like parameters. In La Paz there are 10 mono-cable lines, each involving from 2 to 5 stations with slopes within the range of 0 to 45%, moving from 500 to 4000 pax/hour one way during the peak hour. We use parameter values of one section of the

Purple Line[1] for our simulations, the one with the largest demand, involving two stations only with a 20% slope. Parameter values are presented in Table 1 (see Appendix for data sources and assumptions for the estimations).

Table 1. Parameters values

Parameter	**Unit**	**Value**
L, long circuit length	[km]	4.80
H, vertical rise between stations	[m]	480
$c_0{}'$, cabin capital and maintenance cost	[US$/h-cab]	0.0113
c_1, marginal cabin capital and maintenance cost per passenger	[US$/h-pax]	0.2633
p_E, energy price	[US$/kWh]	0.19
α, coefficient that captures the effect of rise H on energy consumption		0.0331
β, coefficient that captures the effect of fleet size in the long circuit DL on energy consumption		0.251
c_3, pylons and rope capital and maintenance cost	[US$/h-km]	114.82
c_4, stations capital and maintenance, and personnel cost	[US$/h]	523.91
V_{max}, maximum cabin speed	[km/h]	21.6
v, cabin speed inside stations	[km/h]	1.08
K_{min}, minimum cabin capacity	[pax/cab]	4
K_{max}, maximum cabin capacity	[pax/cab]	14
g, width of a seat	[cm]	45
$a = \varphi K + \theta$, minimum cabin spacing at stations	[m]	0.08K+1.62
v_w, boarding and alighting walking speed at stations	[km/h]	1.20
p_v, value of in-vehicle time	[US$/h-pax]	1.87
p_w, value of waiting time	[US$/h-pax]	3.74

K is available in six capacities 4, 6, 8, 10, 12, and 14 passengers. As stated above, Problem (4) can be represented in space (V, D) for given values of K and Y; let us illustrate this with two levels of Y. Figure 2 represents Problem (4) for Y=500 and K equals 4, 8, and 12. The feasible solution space is the intersection among three sub-spaces: below the black curve (constraint 4a), above the red

[1] Strictly speaking, each section of the Purple Line constitutes a fully independent line, where passengers have to transfer mandatorily at the in-between station.

curve (constraint 4b), and to the left of the blue line (constraint 4c). The unconstrained optimum lies outside the feasible space such that constraints 4b and 4c are active; in the cases shown the optimal speed is V*=21.6 km/h (the maximum), and $D*$ decreases with K. The resulting VRC are 1006.4, 1019.9, and 1037.7 US$/h for K equals 4, 8, and 12, respectively. Considering all six cases for K, the optimal design variables happen to be K*=4 pax/cabin, V*=21.6 km/h, D*=5.79 cabins/km, and B*= 29 cabins.

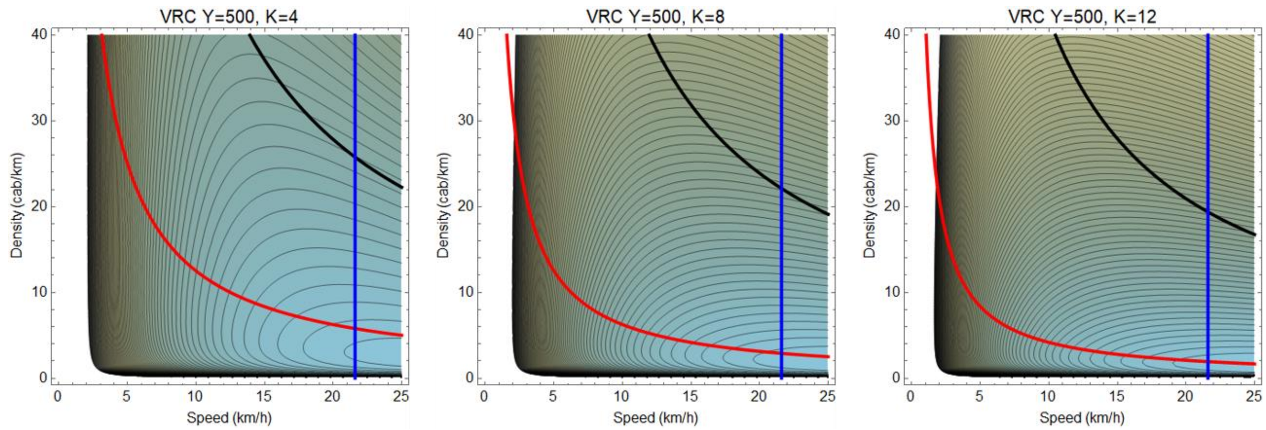

Figure 2. Model representation with Y=500 pax/h

When Y=3000 (Figure 3), there is no feasible solution for K=4, while for the other two K values, the optimum speed is V*=21.6 km/h (the maximum), and D* decreases with K. As argued above, the minimum feasible K should be chosen which yields K*=6. This confirms that constraints (4a) and (4b) play a key role in the solution of Problem (4).

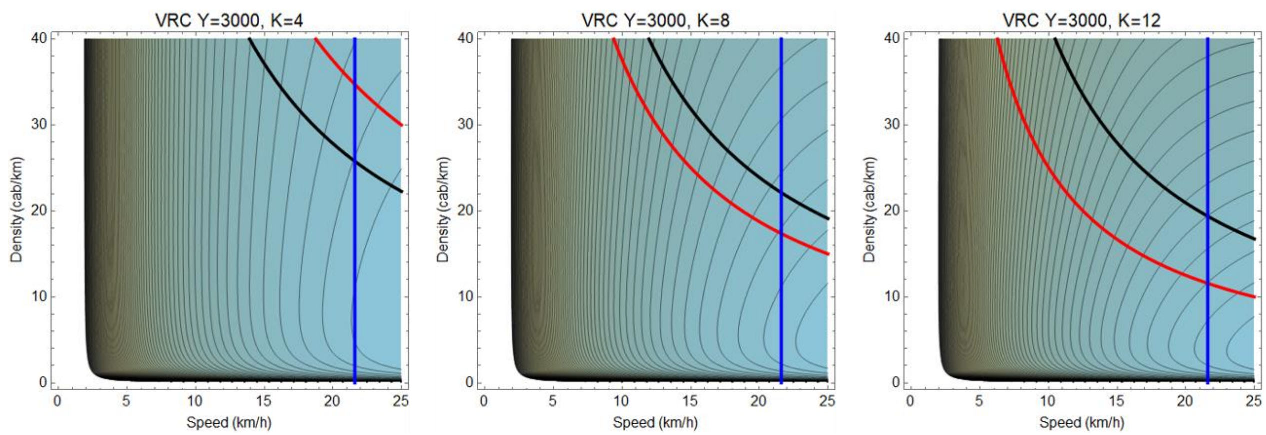

Figure 3. Model representation with Y=3000 pax/h

Considering the property shown in the previous section, Problem (4) was solved for all $500 \leq Y \leq 4500$ letting K be continuous and, if the resulting optimal K is not available in the market, the feasible optimal value for K is the one immediately larger.

Figure 4 shows the resulting design variables as a function of demand Y. Optimal speed is not shown as it always resulted to be the maximum feasible V_{max} (more on this below). As Y grows from 500 pax/hour the adjustment in system capacity is made via cabins' density keeping cabin capacity at the feasible minimum. Beyond a certain flow level (around 2200 in this case), system capacity adjusts by increasing K discreetly diminishing density locally because density is limited by the operation at the stations (constraint 4a). The process repeats, i.e. cabins' density grows until a new change in cabin capacity occurs. Note that as cabin capacity grows, the maximum density at the stations drops because cabins become longer.

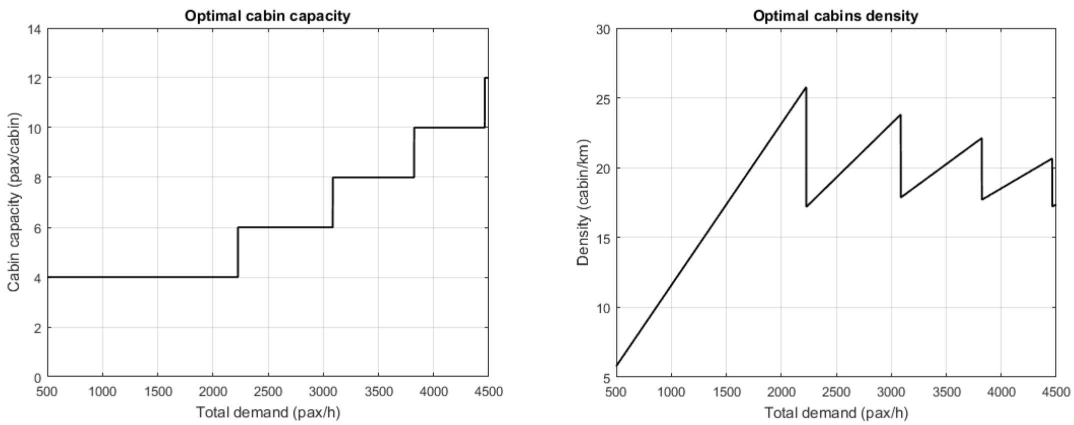

Figure 4. Optimal design variables as a function of demand

In Figure 5 we show the resulting (optimal) frequency, fleet size, and total stations length. As optimal speed V is always equal to V_{max}, optimal frequency $f*$ follows the variation in $D*$ because $f = VD$; the same happens with fleet size because $B = D(L + \frac{V}{v} l)$. The length of the short circuit depends on K because $l = gvK^2/v_w$ and K increases discreetly with Y.

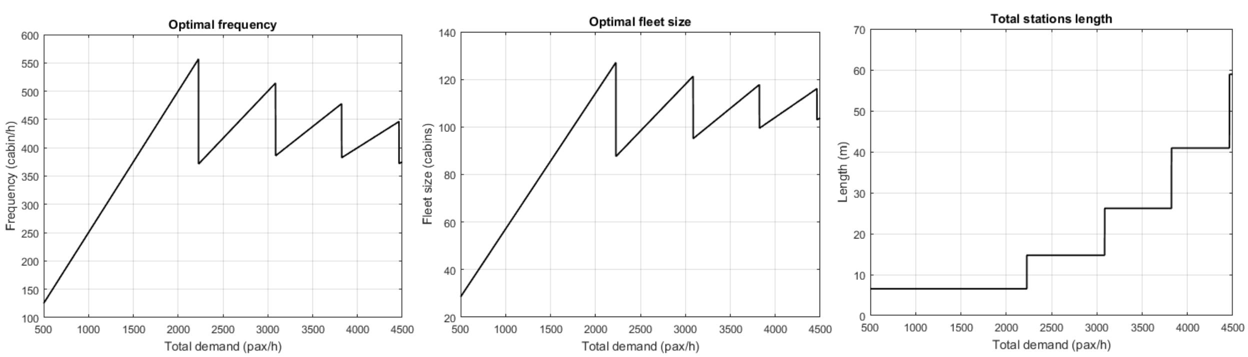

Figure 5. Derived design variables as a function of demand

In Figure 6 the system cost function and the corresponding total marginal costs are shown. The cost function corresponds to VRC in equation (4) evaluated at the optimal design variables, $VRC*$. Total cost "jumps" every time $K*$ changes, and increases linearly in between. This translates into a marginal cost figure that is constant after every jump, increasing very slightly with $K*$.

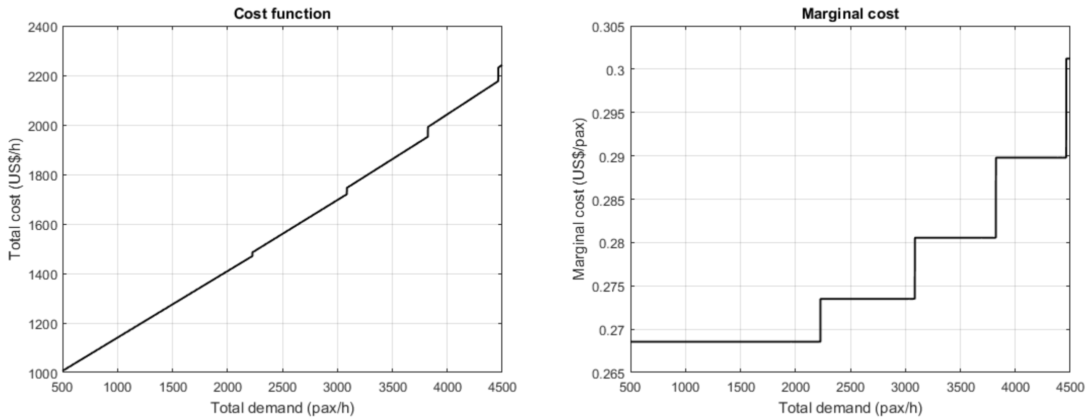

Figure 6. Cost function and marginal costs

In Figure 7 (left) total average costs exhibit a decreasing shape, which yields a degree of scale economies - calculated as AC_T/MC_T - that decreases with Y as shown in Figure 6 right. Scale economies are mainly due to AC_{Op} that decrease significantly with Y. AC_{Us} vary slightly between 0.226 and 0.238 US$/pax, always smaller than MC_T that falls within 0.269 and 0.301 US$/pax. This yields the optimal prices shown in Figure 8 left.

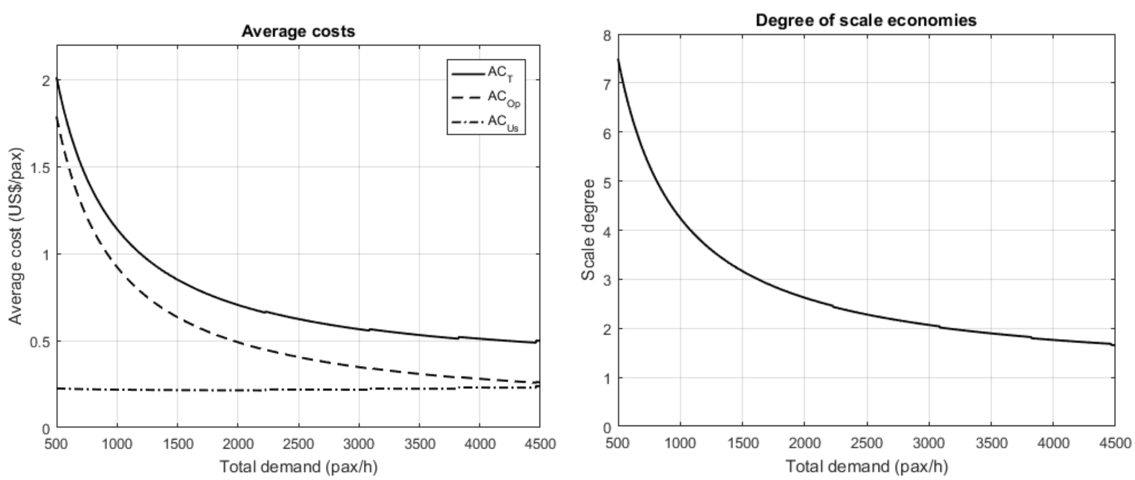

Figure 7. Average cost functions and degree of scale economies

The optimal fare for the cable car system represented in our exercise increases from 0.043 to 0.063 US$/pax falling short of AC_{Op} which induces an optimal subsidy that falls from 1.74 to 0.20 US$/pax as Y grows from 500 to 4500 pax/hour (shown in Figure 8 right). The observed fare today is about 0.44 US$/pax with no user subsidy.

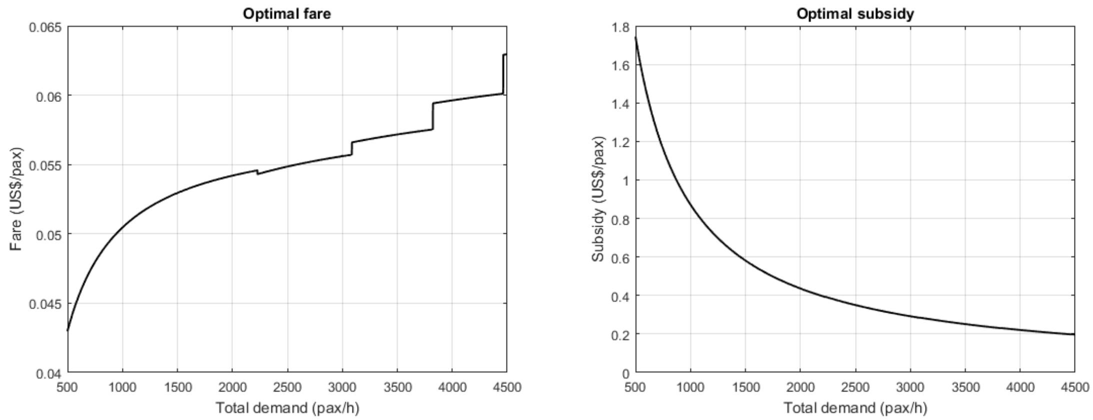

Figure 8. Optimal fare and subsidy as a function of *Y*

The results obtained in the example indicate that the optimal subsidy should cover 97.6% of the average operators' costs for very low levels of demand (i.e. 500 pax/hour), falling to 75.8% when the system reaches 4500 pax/hour. It should be noted that the fixed costs $c_3L/2+c_4$ represent 89% to 68% of total operators' costs as Y increases from 500 to 4500 pax/hour.

Is optimal speed always equal to V_{max}? Inspection of problem (4) suggests that increasing H might influence $V*$. To study this we simulated the system by varying the slope while keeping all other parameters constant. In Figure 8 left we show the optimal speed as the slope increases from 0 to 40% keeping demand at 500 pax/h. At 32% slope, the optimal speed becomes lower than V_{max} and decreases with H (i.e. with slope) as expected. So, we run a second simulation with varying demand while keeping the slope at 40% (it was 20% in our original exercise). The result is shown in Figure 8 right, where we can see that optimal speed increases from 19.3 km/h up to V_{max} and remains there for Y>630 pax/h.

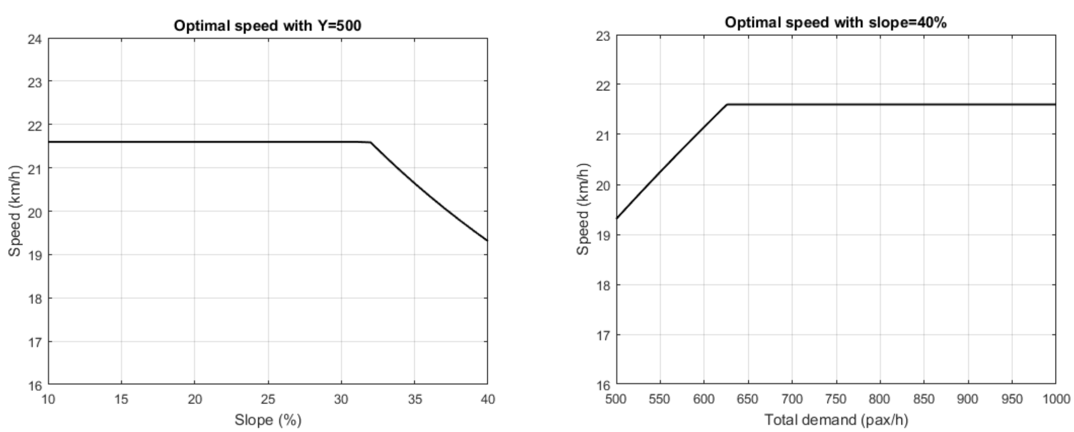

Figure 8. Sensitivity of optimal speed to slope and demand

4. SYNTHESIS AND CONCLUSIONS

A first model for the optimal price of cable car systems has been developed by identifying the technical relations among the many design variables and their role in both operators and users' costs considering speeds, vehicle densities, and lengths of the short and long circuits; frequency; cabin capacity; and so on. The minimization of the value of the resources consumed by operators and users subject to capacity and non-traditional operational constraints produced the optimal values of the design variables as a function of total flow and input prices. Optimal cabin capacity increases discreetly with demand while optimal density adjusts (increases) within the range of flows where cabin capacity remains constant[2]. The optimal money prices were obtained from the corresponding cost function as the marginal costs minus the average users´ costs. Simulation with parameters inspired in the case of La Paz, Bolivia, produces optimal prices that grossly increase with patronage at a decreasing rate falling below the average operators' costs such that an optimal subsidy emerges.

The basic elements of the cable car model presented here can be expanded in many directions. One is the model formulation including more than one period (say peak and off-peak); very likely the speed variable will acquire importance as it is easier to adjust than density during the day. Another aspect is the introduction of crowding by means of a value of in-vehicle time that increases with passenger density or with the load factor. Yet a third (technical) aspect worth considering - somehow related with the previous - is the ability to accommodate demand using other types of cable car installations that can handle and support larger cabins. In that case the number and type of cables become a new design variable with an impact on the optimal design and pricing of the system. Finally, the strategic design of a cable car network and its integration with other modes is an interesting challenge that might complete the optimal design-pricing analysis of this relatively novel element in urban public transportation.

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[2] The adjustment of cabin density is a process that can take place overnight.

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APPENDIX. SOURCES OF PARAMETERS IN TABLE 1

Operators' cost parameters are estimated from reference values reported in CERTU (2012) and Rivera (2005), including acquisition costs and asset life. Acquisition costs were adjusted proportionally by components to the total investment cost of the first three cable car lines in La Paz and updated to 2022. For cabins, acquisition costs are in the range from US$ 20,000 to US$ 65,000 depending on capacity; their asset life is 25 years. Acquisition costs for each pylon and km of rope are US$ 500,000 and US$ 200,000 respectively. We assume that each kilometer between stations requires 8.4 pylons and 2.1 km of rope, based on the first three cable car lines in La Paz. The asset life of pylons and rope is 40 and nine years respectively. The drive station has an acquisition cost of US$ 15,000,000 and the return station, US$ 5,000,000. Stations have an asset life of 40 years. Annualized acquisition costs are obtained considering a residual value of 5%, a discount rate of 12.67% (VIPFE, 2006), and an asset life that depends on each element.

For operation, we consider that each station requires five persons, including one ticket officer, one guard, two platform operators, and one supervisor. Maintenance is required for the cabins, pylons, rope, and stations, with an annual cost equivalent to 1.5% of their corresponding acquisition cost (RPA, 2012). To calculate the hourly costs, total annual costs are divided by 5883 hours. It considers the operation of 17 hours from Monday to Saturday and 15 hours on Sunday, with maintenance routine deducted.

In the expression $p_E(\alpha H + \beta DL)$ for energy consumption, p_E is the energy price per kWh which also considers a monthly power charge and administrative costs. In the case of La Paz, $p_E = 0.19$ US$/kWh (AETN, 2019). $\alpha H + \beta DL$ captures the effect of the vertical rise between stations H and the number of cabins moved in the long circuit DL on the kWh consumed per km. Parameters α and β are obtained from CERTU (2012) where relations between P and V for different H and given L and D are shown. Adequate manipulation of these relations yields $0.0331H + 0.251DL$.

Maximum cabin speed is 6 m/s with capacities ranging from four to 15 passengers (Alshalalfah et al. 2012). The maximum capacity considered is 14 passengers due to the seating arrangement. Cabin speed inside stations is set to 0.3 m/s (Težak et al. 2016). The standard cabin seat width for public transport is 450 mm (Federal Ministry for Digital and Transport, 2022). The minimum distance between cabins was estimated based on information from manufacturers' websites, which indicated that the length of a six-passenger cabin (including a safe separation) is 2.0 meters, while a ten-passenger cabin is 2.4 meters. The average walking speed for boarding and alighting a cabin is calculated as 1.20 km/h, given that it takes six seconds to board a four-passenger cabin (Težak and Lep, 2019).

The value of in-vehicle time is based on Yanaguaya (2010) and updated to 2022. The value of waiting time is assumed to be twice the in-vehicle time.