Workshop The Future of Shared Mobility and Public Transport
TU München, May 14th 2019

The economics of autonomous public transport: supply and fare optimisation

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Sion, Switzerland, 2016

Premiere Autonomous bus in Bavarian spa Bad Birnbach Oct 25th, 2017

The autonomous bus knows its way through software

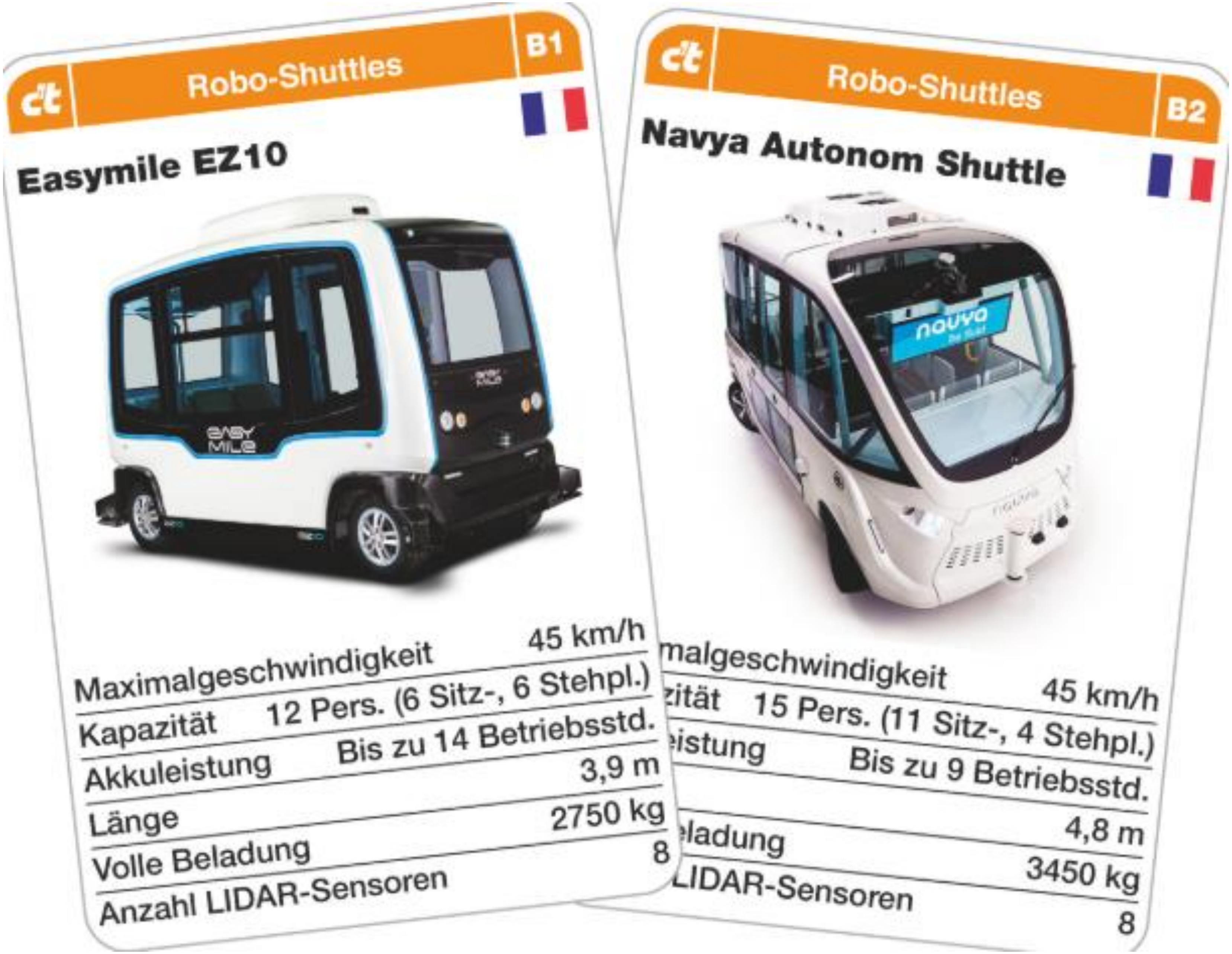
- Deutsche Bahn + EasyMile
- In the first six months the vehicle covered 4,000 km autonomously and transported around 8,000 passengers


30
VORSICHT!
Autonomes Fahrzeug

Öffentlich zugängliche autonome Shuttles in Europa

Ort	Betreiber	Strecke	Projektstart	Fahrzeug	Betriebszeiten
Deutschland					
Berlin	InnoZ, DB, BVG	EUREF-Campus, Schöneberg (800 m)	April 2018	Easymile EZ10	Mo – Fr von 9 bis 16 Uhr
Berlin	Berliner Verkehrsbetriebe	Charité-Krankenhaus, Mitte (1200 m)	März 2018	Easymile EZ10	Mo – Fr von 9 bis 16 Uhr
Berlin	Berliner Verkehrsbetriebe	Campus Virchow-Kliniken (800 m, geplant sind 1500 m)	Mai 2018	Navya Autonom Shuttle	Mo – Fr von 9 bis 16 Uhr
Bad Birnbach	Deutsche Bahn	Therme bis Marktplatz (660 m, davon 250 m öffentliche Straße)	Oktober 2017	Easymile EZ10	täglich von 8 bis 18 Uhr
Schweiz					
Sitten (Sion)	PostAuto Schweiz	Bahnhof bis Centre-Ville (1500 m)	Juni 2016	Navya Autonom Shuttle	Mi – Fr von 7-10 / 13-18 Uhr, Sa – So von 13-18 Uhr
Frankreich					
Paris, CDG-Flughafen	ADP / Keolis	RER Station bis ADP-Büro	April 2018	Navya Autonom Shuttle	Mo – Fr 7.30 bis 20 Uhr
Lyon	Keolis / Systral (Navly)	Centre commercial bis Confluence (1350 m)	September 2016	Navya Autonom Shuttle	Mo – Sa von 10 bis 19 Uhr
Vincennes (bei Paris)	RATP	Parc Floal bis INSEP	Oktober 2017	Easymile EZ10	Fr – So von 10 bis 20 Uhr
Toulouse	Toulouse Metropole	Natural History Museum, Quai des savoirs, Universität (600 m)	Dezember 2017	Easymile EZ10	Mo – Sa von 8.30 bis 19 Uhr
Schweden					
Kista (bei Stockholm)	SL / Nobina / Ericsson	Victoria Tower bis Kista Gallery (1500 m)	Dezember 2017	Easymile EZ10	Mo – Fr von 7 bis 18 Uhr

Heise Magazine:
https://www.heise.de/select/ct/2018/10/1526008148939708



https://www.heise.de/select/ct/2018/10/1526008148939708#&gid=1&pid=3

Nobina and Scania pioneer full length autonomous buses in Sweden

20 FEBRUARY 2019
News | Press releases | Autonomous Transport Systems | Electrification

- Trial to start in 2020 in Stockholm
- Phase 1: without passengers
- Phase 2: 300 passengers per day
- Driver aboard for safety reasons

Press release

NTU SINGAPORE AND VOLVO UNVEIL WORLD'S FIRST FULL SIZE, AUTONOMOUS ELECTRIC BUS

3/5/19

Press information

First of two Volvo Electric buses will soon begin trials at the NTU Smart Campus before being extended to public roads.

The bus is equipped with four Lidar sensors which enables it to detect and stop for objects coming in its way.

https://www.volvobuses.com/en-en/news/2019/mar/volvo-and-singapore-university-ntu-unveil-world-first-full-size-autonomous-electric-bus.html

March 2019

- Current pilot at Nanyang Technological University
- Testing elements of Singapore's urban roads, such as traffic signals, bus stops, pedestrian crossings, heavy rain and partially flooded roads.

- Autonomous buses: increase in pilots and announcements since 2016
- All early developments: electric vehicles

What does this all mean for the cost structure and supply levels of a public transport service?

Research questions

1. What is the cost impact of automation in public transport?
2. Is a cost reduction expected?
3. If yes, who should benefit from it and how?

Methodology

- Public transport total cost (operator cost plus user cost) minimisation.
- Optimisation of service frequency, veh size, fare and subsidy
  - Human-driven vehicles
  - Driverless vehicles

Jansson (1980)

TABLE 1

Composition of the Total Costs of 21 Swedish Urban Bus Companies in 1975 by "Cost Centres"

Cost Centres	*% of Total Cost*
Administration	3.6
Traffic (bus crew costs)	41.8
Workshops and garages (including repair and maintenance of buses)	13.0
Buildings	2.4
Insurance and taxes	3.9
Bus capital costs	20.9
Pensions	7.6
Fuel	6.8
Total	100

Source: Kollektivtrafik i tätort. Bilaga 1. SOU 1975: 48.

Current cost data

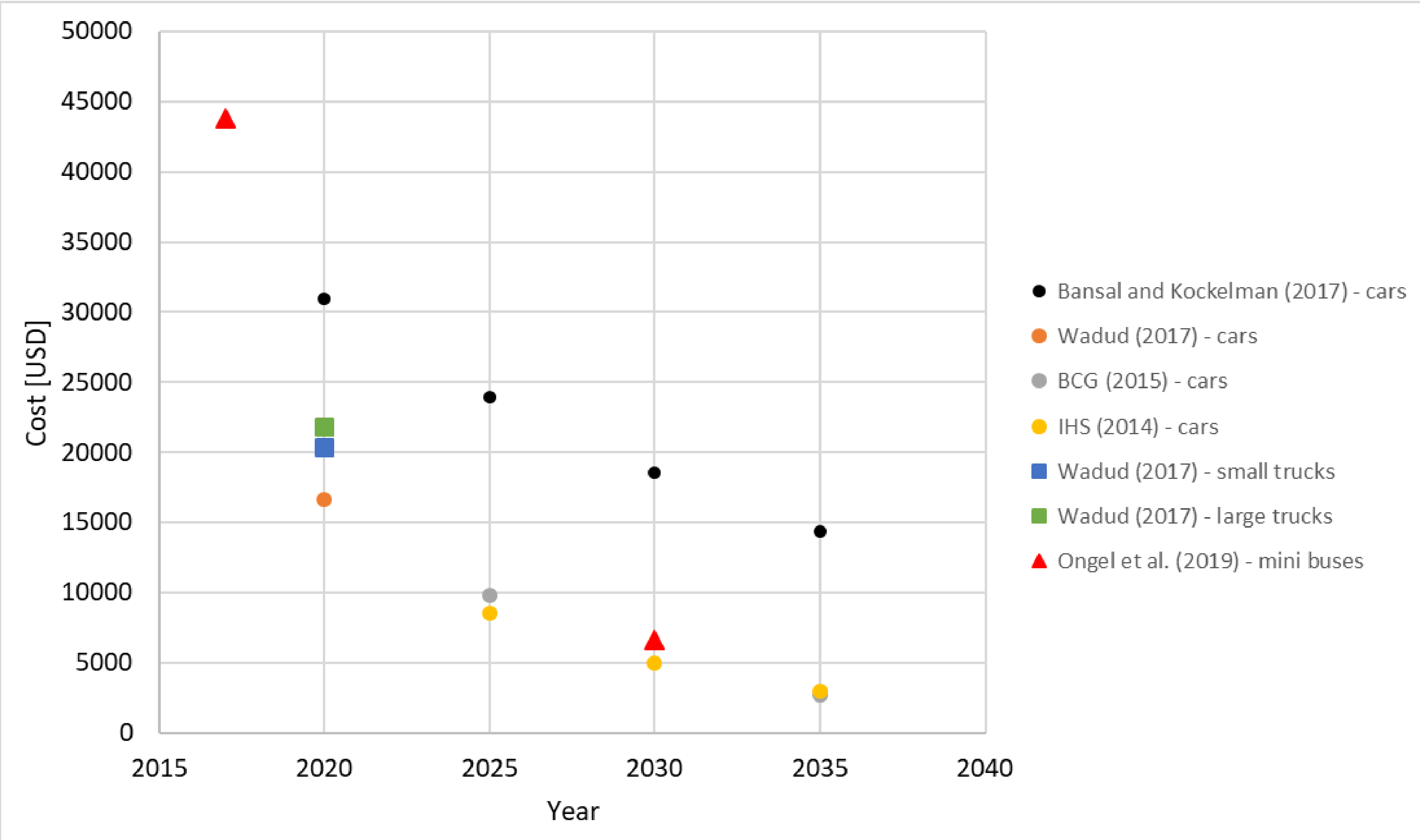
- Santiago, Chile (6500 buses total, 200 electric buses)

Item	Percentage of total cost
Capital costs (depreciation)	12%
Fuel	26%
Maintenance	12%
Drivers	34%
Other costs	16%
Total	100%

- Depending on bus type, driver cost account for 40-70 % of total operator cost in Singapore (Ongel et al. 2019) and in Australia (ATC 2006).

… and the cost of automation?

Estimations of additional vehicle cost to have full automation capabilities



Total cost (operators plus users) minimisation

$$C_{tot} = \underbrace{c\,B}_{operator\ cost} + \underbrace{P_w t_w}_{waiting\ time\ cost} + \underbrace{P_v t_v}_{in-veh\ time\ cost}$$

c: operator cost per bus unit [€/veh-h]
B: fleet size [veh]
t_w: total waiting time, t_v: total in-vehicle time.
P_w: value waiting time savings, P_v: value in-vehicle time savings [€/h].

Optimisation variables:
$-\ f$: service frequency [veh/h], K: bus capacity [pass/veh]

$$c = c_0 + c_1 K \qquad K = \theta \frac{q}{f}$$

$$C_{tot} = \underbrace{\left(c_0 + c_1\theta\frac{q}{f}\right)\left(R + t_b\frac{q}{f}\right) f}_{operator\ cost} + \underbrace{P_w a_1 \frac{q}{f}}_{waiting\ time\ cost} + \underbrace{P_v a_2 \left(R + t_b\frac{q}{f}\right) q}_{in-veh\ time\ cost}$$

q: total demand [pass/h]
R: running time, t_b: board/alight time per passenger
θ: Ratio of passenger load in the most loaded section to total demand.

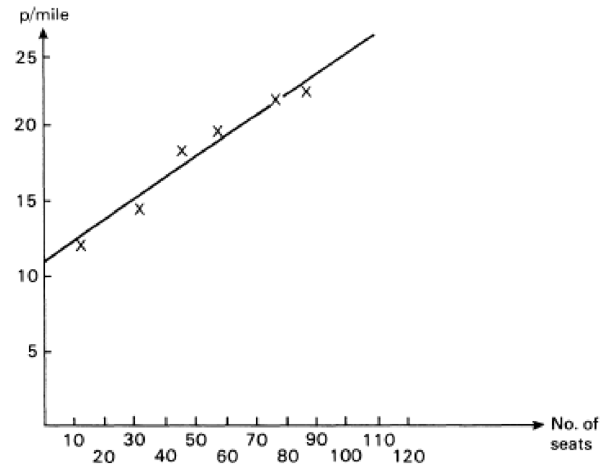


FIGURE 2a
Bus Running Cost

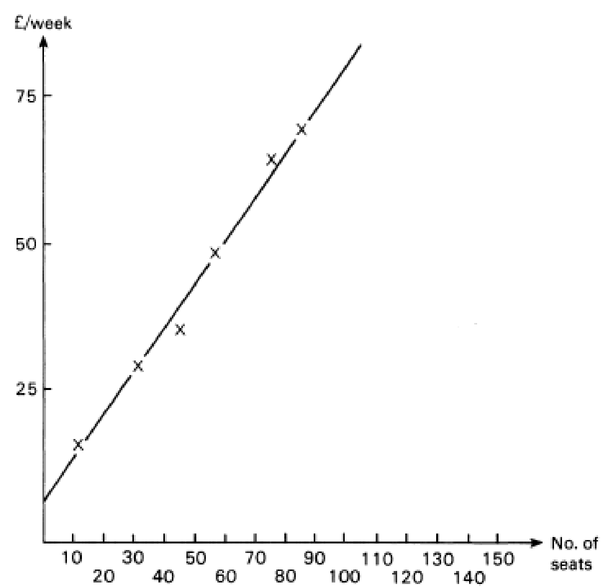


FIGURE 2b
Bus Standing Cost

$c = c_0 + c_1 K$?

Jansson (1980)

Total public transport cost minimisation

- Total cost minimisation: solution

$$Min\ C_{tot} = \underbrace{\left(c_0 + c_1\theta\frac{q}{f}\right)\left(R + t_b\frac{q}{f}\right)f}_{operator\ cost} + \underbrace{P_w a_1}_{waiting\ time\ cost}\frac{q}{f} + \underbrace{P_v a_2\left(R + t_b\frac{q}{f}\right)q}_{in-veh\ time\ cost}$$

$$f^* = \sqrt{\frac{P_w a_1 q + t_b q^2(c_1\theta + P_v a_2)}{c_0 R}} \qquad K^* = \theta\frac{q}{f^*}$$

Optimization and Scale Economies in Urban Bus Transportation

By Herbert Mohring*

at which service is provided. Differentiating equation (1) with respect to χ, setting the result equal to zero, and rearranging terms would then yield

$$\chi = [\alpha V \beta SB/C]^{\frac{1}{2}} \tag{2}$$

as the cost minimizing value of χ: *If* speed were independent of level of service, the optimum service frequency would be proportional to the square root of the demand for service.[8]

[8] William Vickrey first propounded this square root principle to me. I presume that he based his assertion on a similar analysis. Actually, Section II of this paper turns out to be merely an elaboration on the top half of page 615 of his 1955 article.

Mohring (1972)

Optimal pricing and subsidy

- The optimal (first-best) public transport fare P^* [€/pax] is equal to the total marginal cost minus the average user cost (Else 1985, Tisato 1998)

$$P^* = \left[\frac{dC_{tot}}{dq} - \frac{C_u}{q}\right]_{f=f^*} \qquad P^* = \frac{\sqrt{c_0 R}\; t_b q(2c_1\theta + P_v a_2)}{\sqrt{P_w a_1 q + t_b q^2 (c_1\theta + P_v a_2)}} + c_0 t_b + c_1 \theta R$$

- Optimal subsidy per trip?

$$s^* = \left[\frac{C_{op}}{q}\right]_{f=f^*} - P^* \qquad s^* = \frac{\sqrt{c_0 R}\; P_w a_1}{\sqrt{P_w a_1 q + t_b q^2 (c_1\theta + P_v a_2)}}$$

The cost effect of vehicle automation

Effect on $c = c_0 + c_1 K$

- For automated vehicles, we assume a unit operator cost, $\bar{c}$, as follows:

  $\bar{c} = \overline{c_0} + \overline{c_1} K = \alpha\, c_0 + c_1 K$

- $\alpha = \overline{c_0} / c_0$ is the percentage reduction in vehicle unit cost due to not having a driver, $0 < \alpha < 1$
- The cost parameters for automated vehicles are

$$\overline{c_0} = \alpha\, c_0 \quad \text{and} \quad \overline{c_1} = c_1$$

Total cost minimisation automated vehicles

$$Min\ C_{tot} = \underbrace{\left(\alpha c_0 + c_1 \theta \frac{q}{f}\right)\left(R + t_b \frac{q}{f}\right) f}_{operator\ cost} + \underbrace{P_w a_1 \frac{q}{f}}_{waiting\ time\ cost} + \underbrace{P_v a_2 \left(R + t_b \frac{q}{f}\right) q}_{in-veh\ time\ cost}$$

- **Let $\bar{f}$ and $\bar{K}$ be the optimal frequency and veh capacity with automated vehicles:**

$$\bar{f} = \frac{f^*}{\sqrt{\alpha}}, \quad \bar{K} = \sqrt{\alpha} K^*$$

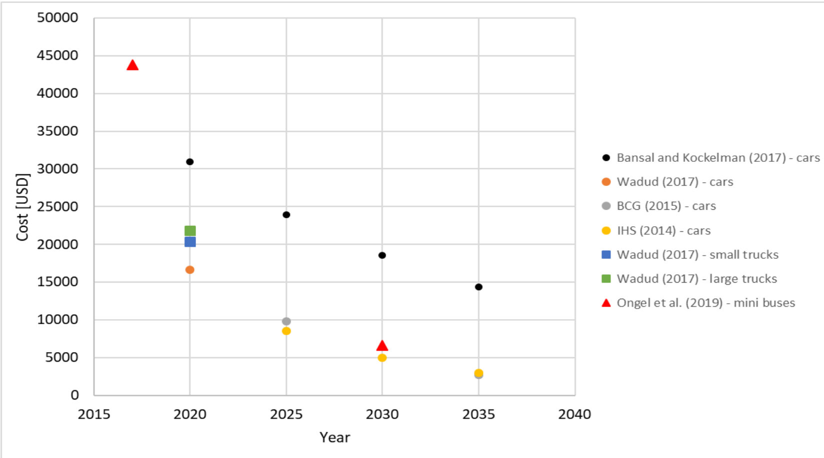
- **Optimal subsidy and fare:**

$$\bar{s} = \sqrt{\alpha}\, s^*, \quad \bar{P} < P^* \quad but \quad \bar{P} \neq \sqrt{\alpha}\, P^*$$

Empirical estimation of α

- Estimation in 3 cities
  - Munich
  - Berlin
  - Santiago de Chile
- Electric vehicles
- 2 factors behind α
  - Reduction in cost due to driverless operation
  - Increase in vehicle cost due to automation

City	Bus driver gross salary [€/month]
Munich	2700
Berlin	2300
Santiago	1200



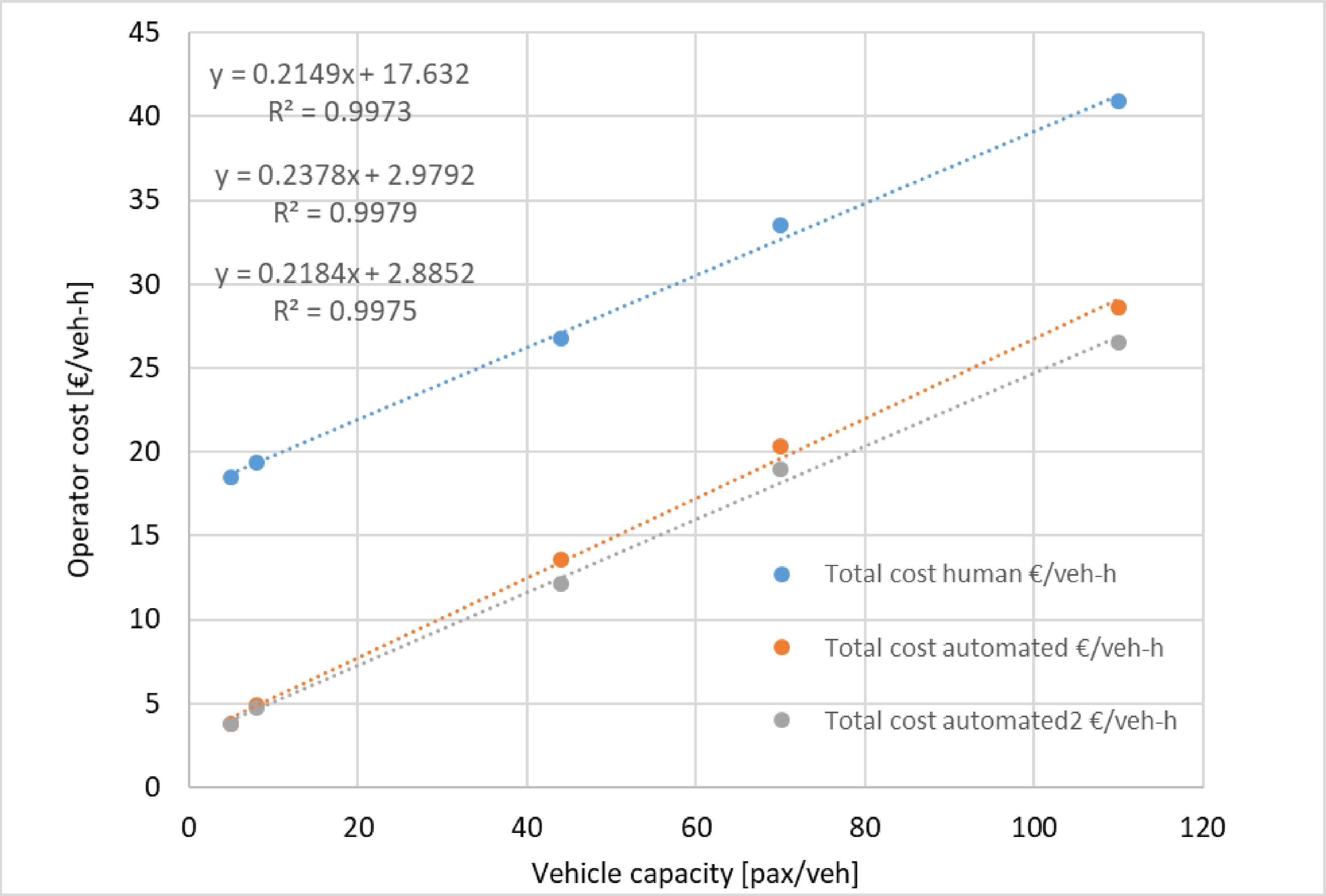
Munich case study

We need estimations of cost items for different vehicle sizes

$$c = c_0 + c_1 K$$

Vehicle type	Car	Van	Mini bus	Regular bus	Articulated bus
Vehicle length [m]	4	5	8	12	18
Vehicle capacity [passengers]	5	8	44	70	110
Vehicle price [€/veh]	29490	43433	281234	419429	627696
Energy consumption [KWh/km]	0.14	0.15	0.64	0.90	1.30
Cost of energy [€/kwh]	0.23	0.23	0.23	0.23	0.23
Average speed [km/h]	18.1	18.1	18.1	18.1	18.1
Energy cost [€/veh-h]	0.6	0.6	2.6	3.7	5.3
Driver cost [€/veh-h]	15.3	15.3	15.3	15.3	15.3
Veh capital cost [€/veh-h]	1.0	1.5	5.8	8.7	13.0
Veh maintenance cost [€/veh-h]	0.8	1.0	1.6	3.5	3.5
Charging infra cost [€/veh-h]	0.8	1.0	1.5	2.3	3.8
Increased cost due to automation	57%	57%	37%	25%	24%
Total cost human driven [€/veh-h]	18.5	19.4	26.8	33.5	40.9
Total cost automated [€/veh-h]	3.8	4.9	13.6	20.3	28.6

Munich: $c = c_0 + c_1 K$



Total cost minimisation automated vehicles

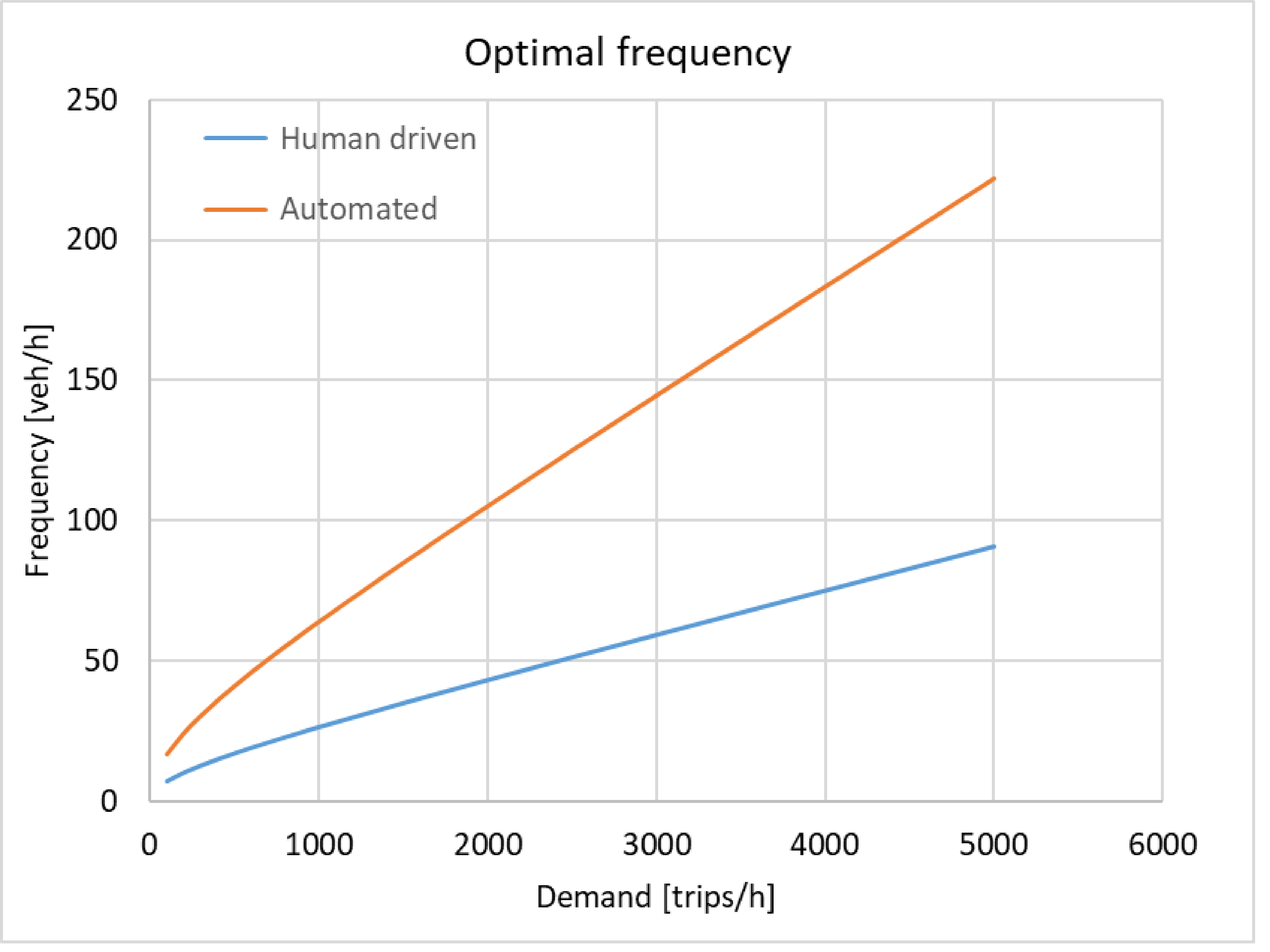
$$Min\ C_{tot} = \underbrace{\left(\alpha c_0 + c_1\theta\frac{q}{f}\right)\left(R + t_b\frac{q}{f}\right)f}_{operator\ cost} + \underbrace{P_w a_1\frac{q}{f}}_{waiting\ time\ cost} + \underbrace{P_v a_2\left(R + t_b\frac{q}{f}\right)q}_{in-veh\ time\ cost}$$

$$\bar{f} = \frac{f^*}{\sqrt{\alpha}},\quad \bar{K} = \sqrt{\alpha}\,K^*$$

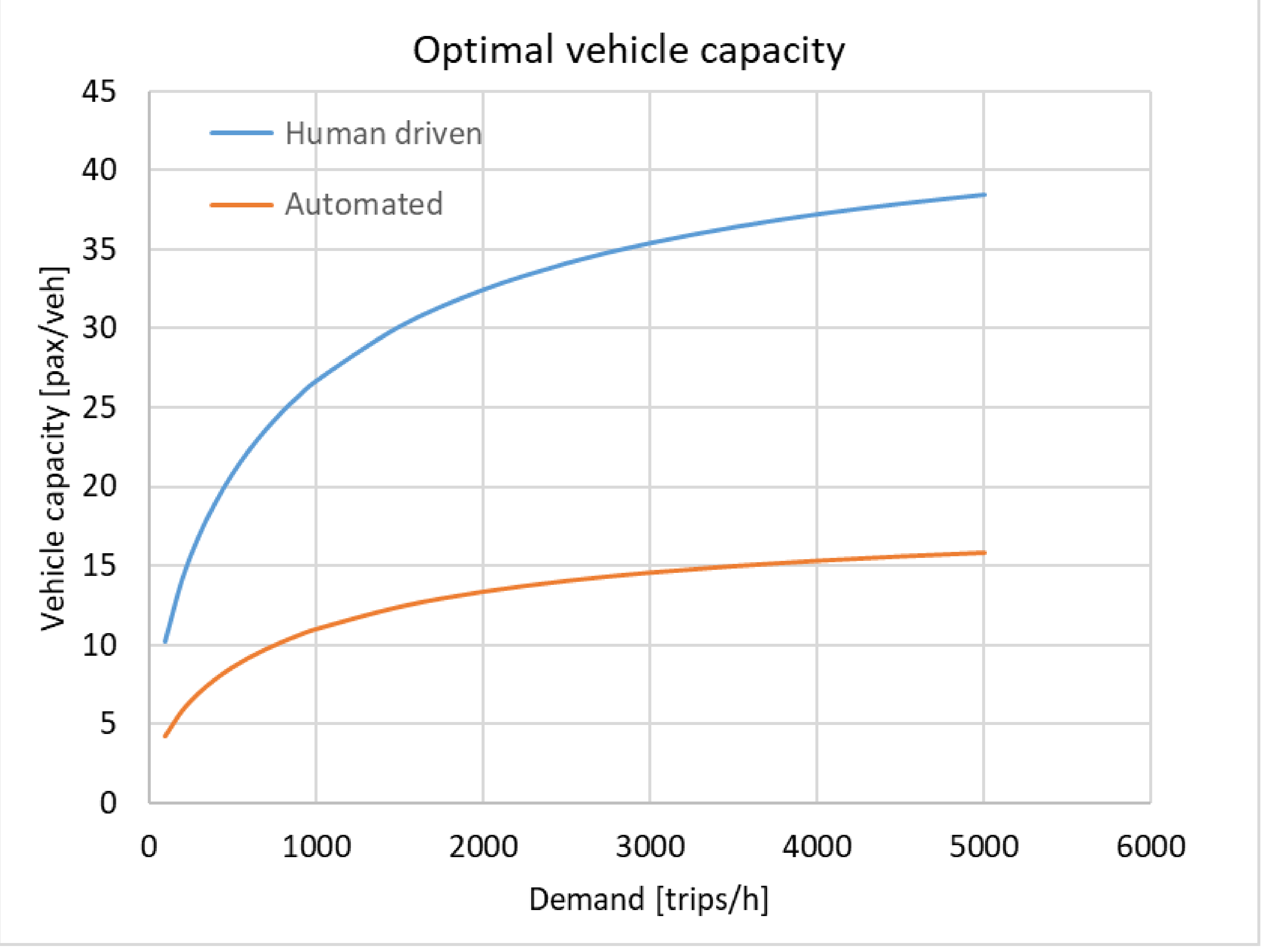
$$\bar{s} = \sqrt{\alpha}\,s^*,\quad \bar{P} < P^* \quad but \quad \bar{P} \neq \sqrt{\alpha}\,P^*$$

City	α	$\sqrt{\alpha}$	$1/\sqrt{\alpha}$
Munich	0.16	0.40	2.5
Berlin	0.19	0.44	2.3
Santiago	0.32	0.57	1.8

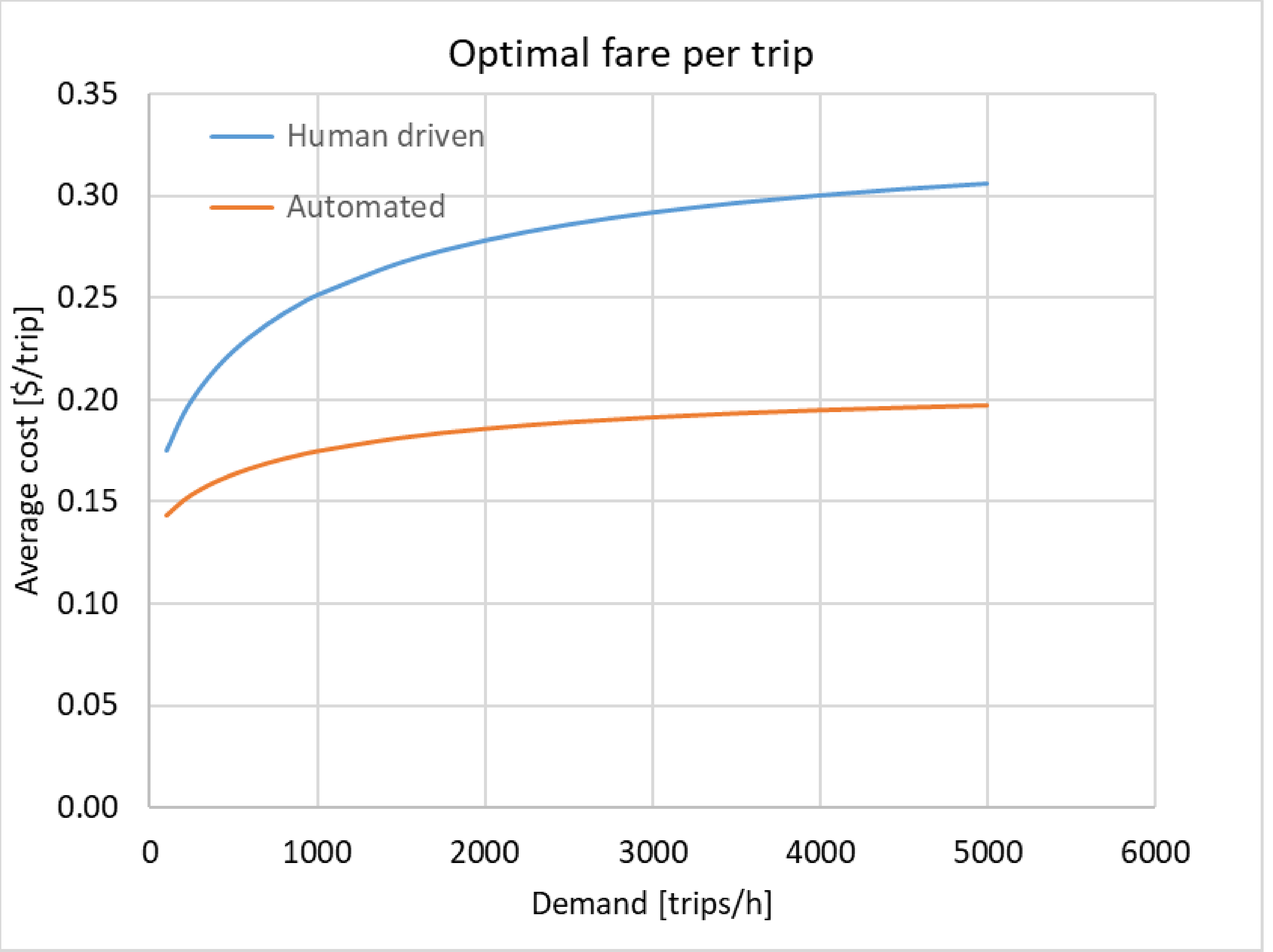
Solution of the full problem
Munich values



Optimal frequency
Human driven
Automated
Frequency [veh/h]
0
50
100
150
200
250
0
1000
2000
3000
4000
5000
6000
Demand [trips/h]



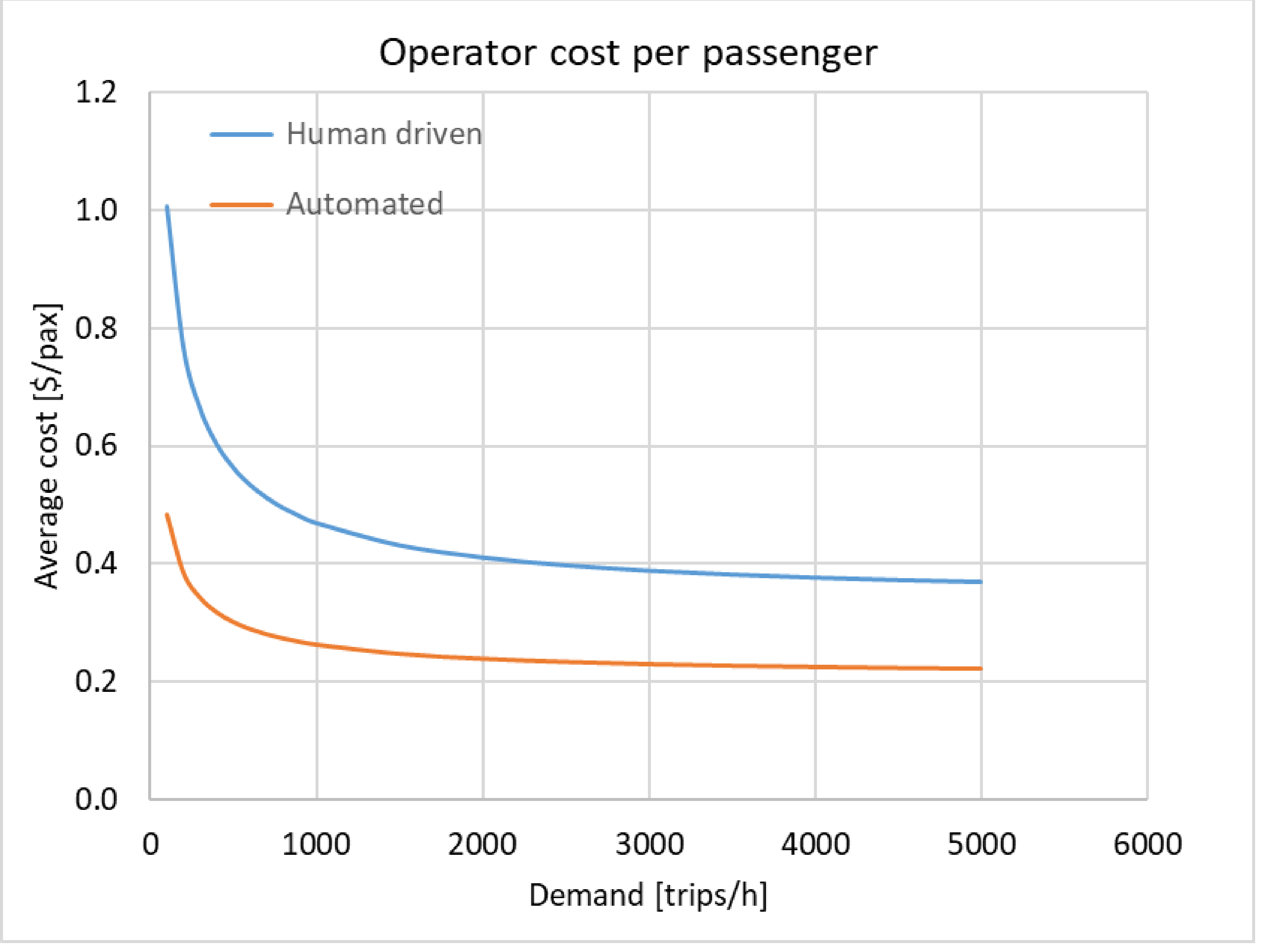
Optimal vehicle capacity
Human driven
Automated
Vehicle capacity [pax/veh]
Demand [trips/h]
0
5
10
15
20
25
30
35
40
45
0
1000
2000
3000
4000
5000
6000

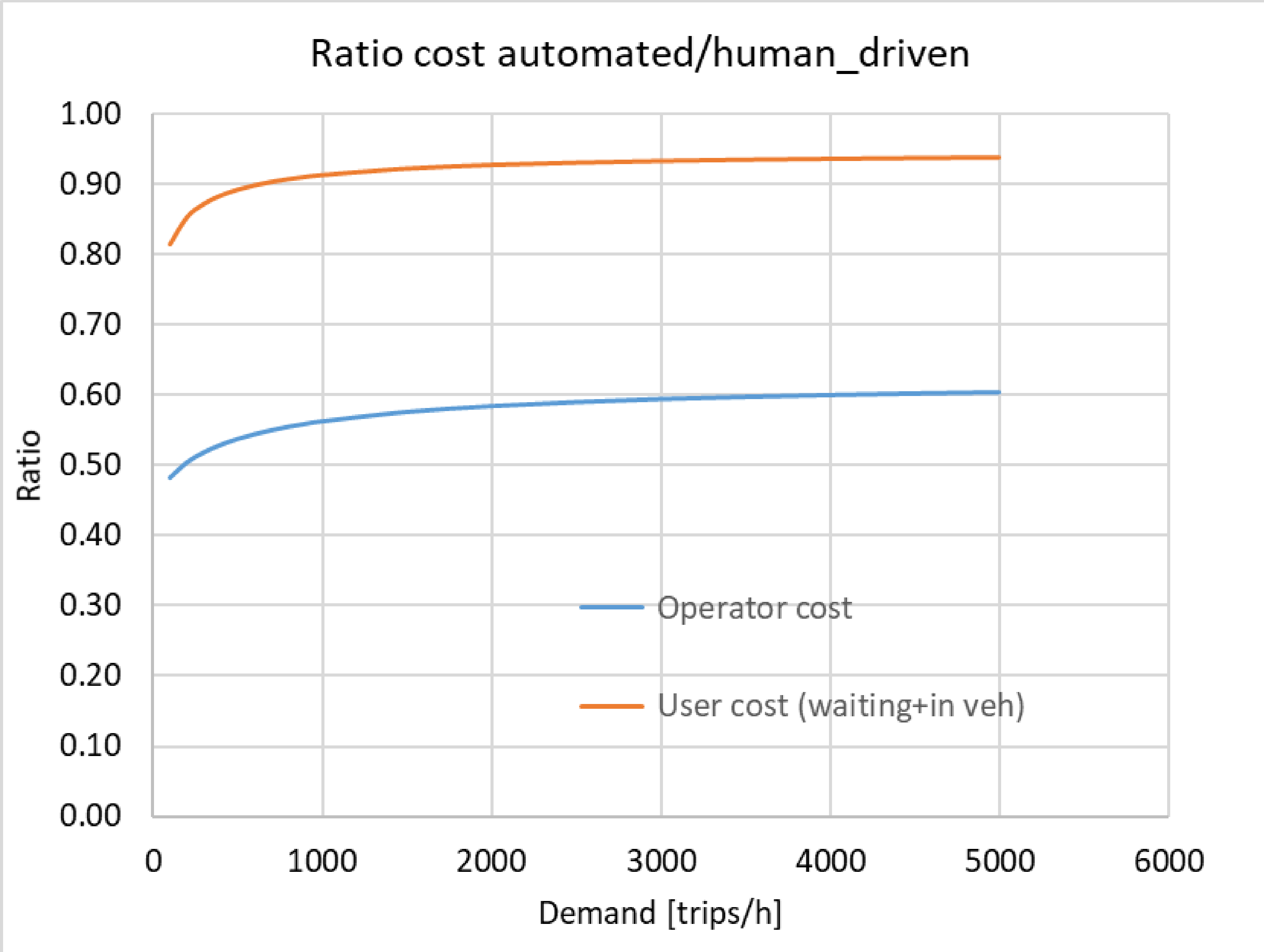


Optimal fare per trip
Human driven
Automated
Average cost [$/trip]
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1000
2000
3000
4000
5000
6000
Demand [trips/h]

Results

- Winners:
  - Operators: reduction operator cost
  - Users: reduction waiting time and fare
  - Public sector: reduction of optimal subsidy
- Losers:
  - Drivers (3 million municipal buses around the world, Bloomberg 2018)
- Extensions
  - Congestion
  - Crowding
  - Network effects: density of routes, feeder/trunk configurations
  - Shared on-demand services


Operator cost per passenger
Human driven
Automated
Average cost [$/pax]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
6000
Demand [trips/h]


Ratio cost automated/human_driven
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Ratio
0
1000
2000
3000
4000
5000
6000
Demand [trips/h]
Operator cost
User cost (waiting+in veh)