Optimal Public Transit Hybrid Network Structure in Greater Jakarta towards the Autonomous Buses

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Abstract: This research aims to grasp an understanding and more in-depth analysis of the most optimum public transport network design in consequence of the total cost. Moreover, the adoption of autonomous vehicles also significantly impacts the agency cost as the public transport service provider. The objective function of the optimization is to minimize the total cost regarding the available decision variables. The total cost is consisting of agency cost (infrastructure length, total vehicle distance traveled, total vehicle hours traveled) and user cost (waiting time, access time, in-vehicle time), and the minimization process needs to follow the constraint of headway, spacing, and vehicles capacity (occupancy). The research scope is the Greater Jakarta region, assuming that Jakarta is the central area and the rest (Depok, Bekasi, Tangerang, and Bogor) would be the peripheral area. In general, the study finds that the most optimum PT network structure occurred when the grid network covers 40% of the total area while the radial network comprises the peripheral area.

Keywords: Public Transit, AVs, Network Design, Hybrid, Total Cost

1. INTRODUCTION

Rapid population growth generates several significant problems in the transportation sector, particularly in the urban area. The rapid population also indicates a rapid vehicle ownership rate and vehicle kilometer distance. Therefore, several problems such as traffic congestion, air pollution, traffic accident, and low quality of life are inevitable. Meanwhile, the Jakarta population will keep increasing until 2040 where the population reaches its saturation point and starts to stagnate around 11.3 million inhabitants compared to 10.7 million in 2020. It is worth noting that the projection is not affected by the current COVID-19 pandemic. However, this number is not the total population in Jakarta; people from other areas such as Depok, Bekasi, Bogor, and Tangerang also conduct their activity in Jakarta as the main business center. In other words, the total population in Jakarta during the day would be higher than during the night (assuming commuter travel).

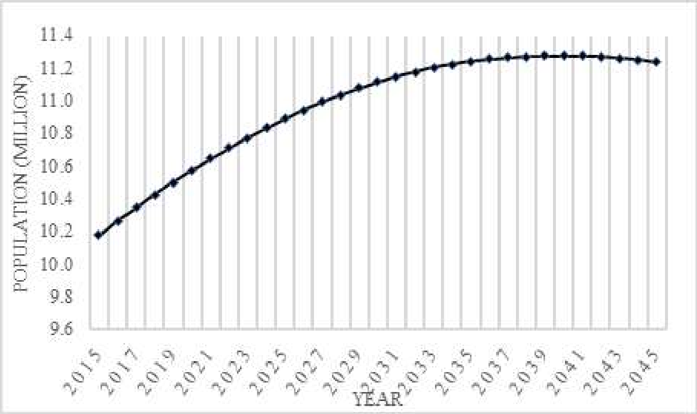


Figure 1 Population Growth Forecast in Jakarta

1.1 Technology Development

Alongside the emerging transport problem, there is also a rapid development of transport sector technology. By 2040, there should be several transformations in the transport system. (1) the electrification of the transport system where more than half of car sales and 33% of the global fleet will be electric. (2) the emerging of micro-mobility usage, the current usage rate of bike-share, and e-scooter show remarkable adoption. Moreover, (3) automation of the transport system, if the automation is proven beneficial, would dominate the transport system by 2040. Automation technology has started to infiltrate vehicle manufacture. In April 2014, Google tried to implement self-driving cars over 700,000 miles on California public roads and followed by some big vehicle manufacturer companies such as Audi, BMW, Cadillac, Ford, General Motors, Mercedes-Benz, Nissan, Toyota, Volkswagen, and Volvo.

AV development is supposed to be on the large-scale test and cost-benefit evaluation under actual operating conditions. There are several pieces of study about the development of the various stage of AVs development. Fagnant and Kockelman (2015) analyzed the potential benefits (safety, parking, traffic congestion, vehicle ownership), barriers (cost, certification, litigation, security), and policy recommendations of autonomous vehicles. Abe (2019) worked on the potential benefit of AVs as bus or taxis in Japan, where he found that the cost of public transport trips could decrease considerably due to vehicle automation. Specifically, he found a decrease of 44-61% for taxi trips and 13-37% for bus trips with taxi access. Moreover, Krueger et al. (2016) concluded the potential users of shared autonomous vehicles (SAVs) with Dynamic Ride Sharing (DRS). Meanwhile, Zhang et al. (2019) evaluated the impact of semi and fully automated buses on the design of a bus corridor and implementing operating measures such as platooning.

1.2 Autonomous Buses

Autonomous vehicles or self-driving vehicles are those in which at least some aspects of a safety-critical control function (e.g. steering, acceleration, or braking) occur without direct driver input. There is no need for drivers to control the vehicles, while several essential commands may still be crucial. The continuing evolution of automotive technology aims to deliver even more significant safety benefits and Automated Driving Systems (ADS). There is 5 level of automation based on Society of Automotive Engineers (SAE). It starts from level 0, where no automation is applied on the vehicle, to level 5, where full automation is implemented.

Autonomous vehicles have the potential to increase traffic safety by reducing the number of accidents. Over 40% of fatal accident involve some combination of alcohol, distraction, drug involvement and/or fatigue of the driver (National Highway Traffic Safety Administration, 2019); therefore, self-driven vehicles would not fall prey to human failings. Driver error is believed to be the main reason behind over 90% of all accidents (Fagnant & Kockelman, 2015) Some analyst predicts that AVs will overcome many of the obstacles that inhibit them from accurately responding in complex environments. Papadoulis et. Al (2019) tried to evaluate the effect of Connected Automated Vehicle (CAV) based on simulation results. Five different scenarios were tested based on their market penetration ratio: 0%, 25%, 50%, 75%, and 100%. The results indicated that the CAV control algorithm improves road safety significantly, as the reduction of conflicts was 12-47%, 50-80%, 82-92%, and 90-94% for all the scenarios, excluding 0% market penetration.

1.3 Research Objective

The paper intends to develop a new network structure model to provide a tool for analyzing the public transport system. The paper seeks to combine several previous related research and model formulation into a new network model. Moreover, the paper would also analyze the different scenarios of the implementation of autonomous vehicle development and the characteristics of the area of service and demand. Greater Jakarta trip demand would be the reference for the study.

2. METHODOLOGY

2.1 Scope of Study

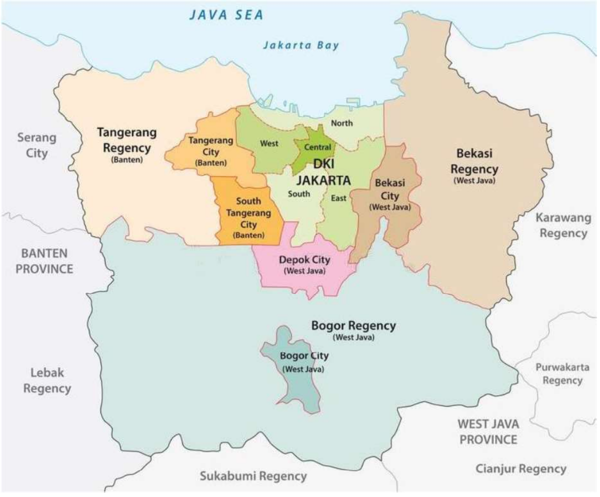


Figure 2 Greater Jakarta Metropolitan Area including Bogor, Depok, Bekasi, and Tangerang

Jakarta develops rapid economic growth that triggered urbanization towards the city. Consequently, Jakarta has grown spatially. Starting from 664 km^2 in 1960, Jakarta corresponds with Bogor, Bekasi, Depok, and Tangerang have become a new megapolitan with a region of 5,500 km^2 (Douglass, 2010). Greater Jakarta (also known as Jabodetabek) is the most populous metropolitan area in Indonesia. It consists of one core city (Jakarta) and five satellite cities including, Bogor, Depok, Tangerang, South Tangerang, and Bekasi. Some people even call Greater Jakarta as Megapolitan Area due to becoming the second-most populous urban area (after Tokyo) and acting as the center of government, culture, education, and Indonesia's economy. Figure 2 shows the map of greater Jakarta. Bogor and Depok are the southern areas of Jakarta, Bekasi is the eastern area, and Tangerang (Tangerang city and South Tangerang) is the western area of Jakarta.

Table 1 shows the demographic data of greater Jakarta in 2020 and also demonstrates that

Jakarta holds the largest area and highest density as the core city and activity center compared to the rest. Meanwhile, Depok and Bekasi are the second and third highest density areas in Greater Jakarta, respectively.

Table 1 Demographic Data of the Study Area

	Jakarta	Bogor	Depok	Tangerang	Bekasi	South Tangerang
Area (km^2)	662.3	118.5	200.3	153.9	210.5	147.2
Population	10,763,324	1,048,610	2,406,826	1,771,092	2,448,830	1,696,308
Density	16,251	8,849	12,016	11,508	11,633	11,523

2.2 Proposed Hybrid Network Design

In 2010, Carlos Daganzo developed a hybrid structure for the public transport network design optimization. The hybrid schemes provide the grid structure (double coverage) in the central square (core area) while the peripheral area would have a radial structure (single coverage). All lines run from one edge of the city to the opposite edge (N-S-N or E-W-E). The line runs vertically through the central square and emerge at the north and south ends, and the horizontal lines through the central square emerge at the east and west ends.

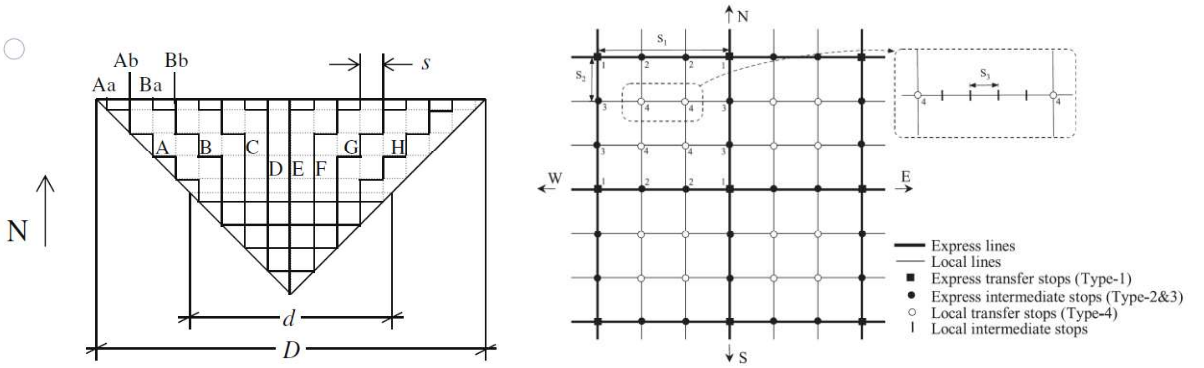
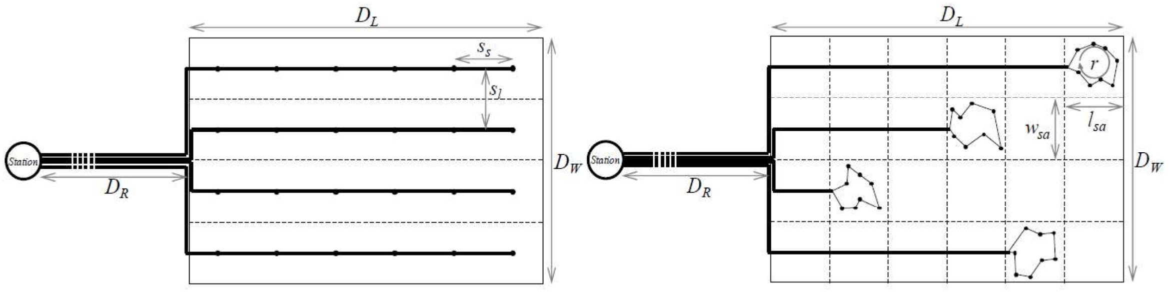


Figure 3 (a) Hybrid Network Structure (Daganzo, 2010) (b) Bimodal Network (Fan, 2018)

Fan (2018) proposed a network design that accommodates two types of modes (rail and bus), considering that most of the urban areas consist of various modes of transport. An urban public transit system often consists of two overlapping and interweaving single-mode networks. (1) Local bus network that features high "line and stops" densities but low speed and operating costs, and (2) Express transit network that features high speed and capacity but must be sparsely spaced due to the high costs. The latter is often operated by Bus Rapid Transit (BRT) or rail (Fan, Mei, & Gu, 2018). Therefore, the availability of more than one mode needs to be a consideration to develop a proper network design

Additionally, Badia and Jenelius (2020) proposed the feeder service model for the peripheral area. They assumed the feeder service into two alternatives, namely fixed route and door-to-door service. Fixed route system is composed by a group of parallel lines that cross the area completely in the longitudinal direction. The alternative to fixed routes is a door-to-door service. In this case, the suburban area is divided into smaller zones served independently each other. One bus starts the cycle at the station, picking up the passengers that request service to go to the zone served by that bus.



(a) Fixed routes (*FR*)

(b) Door-to-door service (*DtD*)

Figure 4 (a) Fixed Route and (b) Door to Door Service Scheme on the Peripheral Area (Badia and Jenelius, 2020)

The paper seeks to combine the three proposed network models into a new hybrid model that could fulfill the study area travel demand as each model has its advantages to some degree. For example, Daganzo's model is suitable for a network with only one type of mode. Therefore, Fan's model is proper to supplement the hybrid model. However, Fan's bimodal model consists of both supply and demand-side formulation. In that case, the paper only conveys the supply side formulation from Fan's bimodal model. Finally, the paper also includes a feeder service network model to hold the peripheral trip.

3. MODELLING

Figure 5 is the proposed network structure design for the study. A square area which consists of two sub-area. The first area is the center square. It represents the Central Business District (CBD) of the city where people mostly conduct their daily activity. It has a grid network structure and consists of two different transport modes, namely Bus and Metro. On the outer area, there is a peripheral area that represent suburban characteristic.

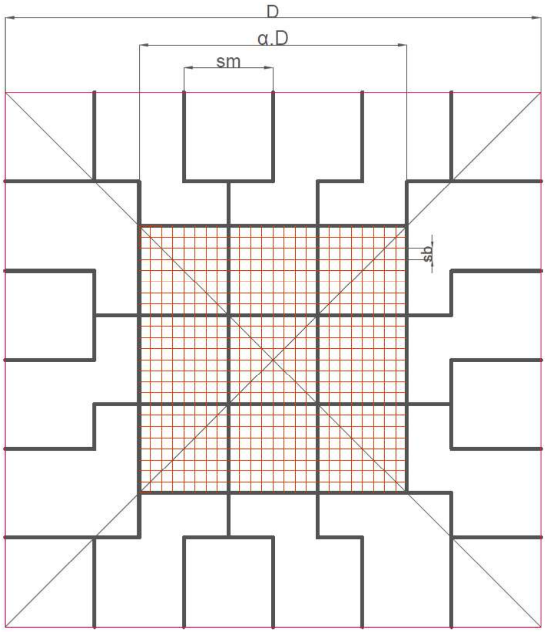


Figure 5 Proposed Hybrid Network Design

As stated on the previous chapter, the network model is the combination of several previously published works. The combination between grid and radial network that become a hybrid model (Daganzo, 2010), the intersection between two modes, metro and bus (Fan, et al., 2018) and the optimum last mile solution on the peripheral area between fixed route and door to door service (Badia & Jenelius, 2020). In the central area, there will be two public transport operation (i.e. bus and metro). The total side length is **D** while the side of central area length is **α.D**. The bus line marked as the red line with bus spacing of $\mathbf{s_b}$ and the metro line is the thick line with spacing of $\mathbf{s_m}$. On the peripheral area, the feeder service operates on an area of $\mathbf{s_m}$ **. 0.5**$\mathbf{s_m}$

The following are the formulae derivation for agency cost and user cost:

3.1 Agency Cost

Agency cost is generally the expenditure of the public transport infrastructure. Therefore, it consists of total length of the two-way infrastructure system (L), total vehicle distance traveled per hour (V), and total vehicle hours traveled during rush hour (M). In an assumption that there is two-way infrastructure within the central area and also due to its flexibility, there is no need to construct a dedicated line for feeder transport. Therefore, infrastructure cost only applied on the central area. D, α, s_b and s_m indicate the lateral length of the total area, the ratio between the central and total area, bus spacing, and metro spacing, respectively.

$$L_{metro} = (D^2 . (1+\alpha^2)) / s_m$$

$$L_{bus} = 2 . (\alpha . D)^2 . (1/s_b - 1/s_m)$$

Meanwhile, total vehicle distance traveled per hour can be obtained from double L (two-way) and divide it by the corresponding headway. Door-to-door service formulation consists of number of areas $0.5(s_m/w)^2$ determination where the total length for each area trip could be calculated. The model works where the number of stops for each area are $n = \delta.H_f.w^2$ (w: feeder service area; H_m: metro headway; H_b: bus headway; H_f: feeder headway; s_m: metro spacing; s_b: bus spacing; s_f: feeder service spacing)

$$V_{metro} = 1/H_m \{[4 (\alpha.D)^2/s_m] + [6\alpha . D^2(1- \alpha) /s_m]\}$$

$$V_{bus} = [4(\alpha.D)^2 . (1/s_b - 1/s_m)] . 1/H_b$$

$$V_{feed} = [0.5 . (s_m/s_f) . (3s_m - s_b)] . 1/H_f \qquad \textit{(Fixed Route)}$$

$$\{(s_m/w)^2 . [(s_m/2 - w) + s_m/2 + \gamma.r]\} . 1/H_f \qquad \textit{(Door to Door)}$$

M is also the required fleet size. therefore the total vehicle distance travelled per hour (V) need to be divided by cruise speed of each mode. (v_m: metro cruise speed; v_b: bus cruise speed; v_f: feeder service cruise speed)

$$M_{metro} = 1/(H_m.v_m) \{[4 (\alpha.D)^2/s_m] + [6\alpha . D^2(1- \alpha) /s_m]\}$$

$$M_{bus} = [4(\alpha.D)^2 . (1/s_b - 1/s_m)] . 1/(H_b.v_b)$$

$$M_{feed} = [0.5 . (s_m/s_f) . (3s_m - s_b)] . 1/(H_f.v_f) \qquad \textit{(Fixed Route)}$$

$$\{(s_m/w)^2 . [(s_m/2 - w) + s_m/2 + \gamma.r]\} . 1/(H_f.v_f) \qquad \textit{(Door to Door)}$$

3.2 User Cost

In the other hand, user cost consists of waiting time, access time, and in-travel time in which all of them would be transform into real cost using multiplication by value of time (VoT), therefore, value of time holds significant impact on the results of the optimization. CC, CP, and PP represents Central-Central, Central-Peripheral, and Peripheral-Peripheral trip respectively.

The base assumption in regard to the simplicity, all user considered to have transit, in the other words, there is no direct trip, particularly people in the peripheral area with the destination within the central area. The additional assumption although people have to make a transfer, they would try to minimize the number of the transfer. Therefore the expected number of transfer (e_T) for each trip are:

e_T = *1 (CC)*; *1 (CP)*; *1.5 (PP)*

The waiting time is the time for user waiting before get access to the corresponding vehicles. The waiting time is highly associated with the mode's headway and spacing. Based on Badia & Jenelius, for the door to door service user need to wait for the metro for $[H_f + (\gamma.r/v + ((\tau_s + \tau_b)\ \delta\ .\ Hf\ .\ w^2)/n)]$ or σ (assumption). The average waiting time would be dependent on the number of transfer. Therefore it would be used to weigh the waiting time.

W_{CC} = $(s_b/s_m)^4 \,.\, H_m + (s_b/s_m)^2 \,.\, [1 - (s_b/s_m)^2] \,.\, (H_m + H_b) + [1 - (s_b/s_m)^2]^2 \,.\, H_b$

W_{CP} = $[H_m \,.\, (1-\alpha^3) / (3\alpha\ (1- \alpha^2) + H_m/2 + H_f/2] + [H_m.\ (1-\alpha^3) / (3\alpha\ (1- \alpha^2) + H_b].\ (1 - s_b/s_m)$ *(Fixed Route)*

$\{[H_m \,.\, (1-\alpha^3) / (3\alpha\ (1- \alpha^2) + H_m/2 + 0{,}5.\sigma.(sb/sm)] + [H_m \,.\, (1-\alpha^3) / (3\alpha\ (1- \alpha^2) + H_b/2 + 0{,}5.\sigma\}.(1-s_b/s_m)$ *(Door to Door)*

W_{PP} = $[H_m \,.\, (1-\alpha^3) / (3\alpha\ (1- \alpha^2)] + 0.75H_m + H_f$ *(Fixed Route)*

$[H_m \,.\, (1-\alpha^3) / (3\alpha\ (1- \alpha^2)] + 0.75H_m + \sigma$ *(Door to Door)*

In regard to the access time, user would prefer the nearest stop either it is a metro stop or bus stop (central area). Meanwhile, the access time for door-to-door service on peripheral-peripheral trip would be 0 because the door-to-door service would take and drop off passengers to their destination.

A_{CC} = s_b/v_w

A_{CP} = $[(s_b+s_l)/4v_w + s_b/2.v_w]$ *(Fixed Route)*

= $s_b/2v_w$ *(Door to Door)*

A_{PP} = $(s_b + s_l)/2$ *(Fixed Route)*; 0 *(Door to Door)*

Manhattan and Chebyshev method are used in order to develop in-vehicle time (Gaboune, et al., 1993). Manhattan method could calculate the expected distance in case there are no preferences among transport modes. Meanwhile, when user prefer vehicle such as metro for longer trip, Chebyshev method is more suitable. Additionally, there is a simplification for $\psi = D[2 - 3\alpha + \alpha^3]/4V_m$

T_{CC} = $2\alpha D/3V_m \,.\, (s_b/s_m)^4 + 2[(7\alpha D/15V_m) + (3\alpha D/15Vb)]\ (1 - (s_b/s_m)^2) + 2\alpha D/3V_b\ (s_b/s_m)^2$

T_{CP} = $[\psi + 2\alpha D/3V_m + s_m/2V_f]\ (s_b/s_m) + [\psi + 7\alpha D/15V_m + 3\alpha D/15V_b + s_m/2V_f]\ (1 - s_b/s_m)$

(Fixed Route)

= $[\psi + 7\alpha D/15V_m + 3\alpha D/15V_b + s_m/2V_f]\ (s_b/s_m) + [\psi + 7\alpha D/15V_m + 3\alpha D/15V_b + (s_m - w + yr)/2V_f]\ (1 - s_b/s_m)$ *(Door to Door)*

T_{PP} = $2\psi + \alpha D/4V_m + s_m/V_f + \alpha D/6$ *(Fixed Route)*

$2\psi + 11\alpha D/24V_m + (s_m-w+\gamma r)/V_f$ (Door to Door)

3.3 Objective Function

The most competitive transit network's determination should satisfy a proper trade-off between the user and agency point of view (Badia, Estrada, & Robuste, 2014). The minimum cost for both parties would generate the optimum decision variables hence identify the optimum trade off. The agency cost consists of transport infrastructure length, vehicle distance travelled per hour and vehicle hours travelled during rush hour. While the user cost is the combination of waiting time, in-vehicle time, and access time. All of the cost would be in time unit for the respective cost per passenger. Appendix A shows the initial value for each parameter for the base condition.

$$\min \{Z = [(1/\lambda\mu)(€_V V + €_M M + €_L L)] + [A + W + T + (\delta/v_W)\, e_T)]: s \geq 0, H \geq 0, 0 \leq \alpha \leq 1, O \leq C\} \quad (1)$$

	Agency Cost	
L	[km]	Transport infrastructure length (double direction)
V	[veh-km/h]	Vehicle distance traveled per hour of operation
M	[veh-h/h]	Vehicle hours traveled during rush hour
O	[pax/veh]	Peak vehicle occupancy during the rush hour
$€_L$	[€/km-h]	
$€_V$	[€/veh-km]	Unit Monetary Cost
$€_M$	[€/veh-h]	
$1/\lambda\mu$	[h^2/pax-€]	Equivalent hour of passenger factor
	User Cost	
A	[h/pax]	Average walking access time
W	[h/pax]	Average walking time
T	[h/pax]	Average in-vehicle travel time
E	[km/pax]	Average in-vehicle travel distance
v_c, v_W	[km/h]	Vehicle's commercial speed; walking speed
e_T		Expected number of transfers per passenger
δ	[km]	Fixed distance penalty for transfers

Impact of automation on the model would heavily affect the required fleet size cost. In this paper, the automation of the vehicle is assumed to reduce the cost by 60%. Therefore, during the optimization process, for the base scenario, the fleet size cost would be multiplied by 1 (basic condition). Meanwhile, for the scenario where automation is implemented, the fleet size cost would be multiplied by 0.4.

4. RESULTS AND ANALYSIS

4.1 Ratio between central and total area (α)

The proportion between central area length (d) and the whole area (D) would generate the value of α (d/D). As one of the decision variables, α could give an understanding of the relationship between the public transport scope and total cost. Initially, the greater area would induce higher total cost. However, in this study, the combination of two types of area and its different public transport operations demonstrates different outcomes.

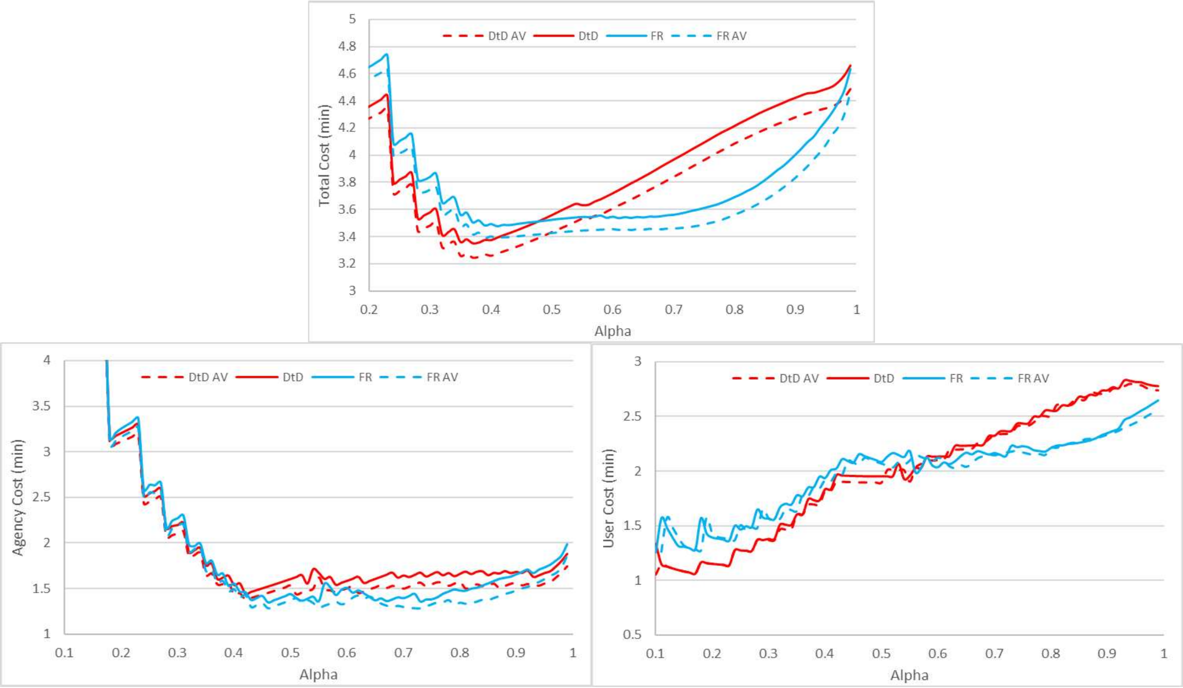


Figure 6 (a) Total Cost (b) Agency Cost (c) User Cost

Table 2 List of Abbreviation

Abbreviation	Description
FR	Fixed Route with No Automation
FR AV	Fixed Route with Automation
DtD	Door to Door with No Automation
DtD AV	Door to Door with Automation

Table 2 shows the definiton for each abbreviation during optimization process. Both type of service, either fixed route or door to door only applied as the feeder service. In other world, these type of service only operate on the peripheral area, therefore it would have affected by the size of the corresponding area. The term FR AV could be translated into fixed-route service on the peripheral area with full automation for the entire public transport system.

Figure 6 shows that at the beginning of the area with a small fraction of the grid network would generate very high total cost where it almost reaches 4.8 hours. According to the other two figures, the agency cost has a significant impact that caused the total cost to be very high. To determine the optimum proportion of the grid network or central area, one needs to find the proportion that produces the lowest total cost. The optimization shows that for door to door service, an alpha value of **0.37** would be the most beneficial, while for fixed-route service, the value of **0.41** has the minimum total cost. Besides, the implementation of autonomous buses has not significantly affected the optimization process except would generate lower cost for both fixed and door-to-door service.

Figure 6 also demonstrate the relationship between alpha and both agency and user cost. agency cost have high cost at the small grid network extension, however, it start to decrease in parallel with the increase of grid network extension until it reach the optimum point and change into stagnant phase. Meanwhile, user cost tend to keep increasing along with the extension of grid network on the study area. Interestingly, from the user cost perspective, when the proportion of grid network is below 50%, the fixed route network would have a higher cost compared to door-to-door service. However, when the grid network has a higher share or even almost dominates the whole network, door-to-door service costs rise to be higher than the fixed route network.

4.2 Bus Headway

Based on figure 7, the optimum bus headway to achieve the lowest total cost is **15 minutes** (Fixed Route), **12 minutes** (Fixed Route with Automation), **12 minutes** (Door to Door), and **9 minutes** (Door to Door with Automation). Agency cost and user cost display an intriguing point. Door to door service would generate more total cost from the agency perspective, on contrary, it establishes lower cost from the user perspective. The same pattern also applied for fixed route service. However, the gap between fixed route and door to door service turn out to be different for the two cost. agency cost has closer gap between fixed route and door to door service, while user cost has broader gap between the two services.

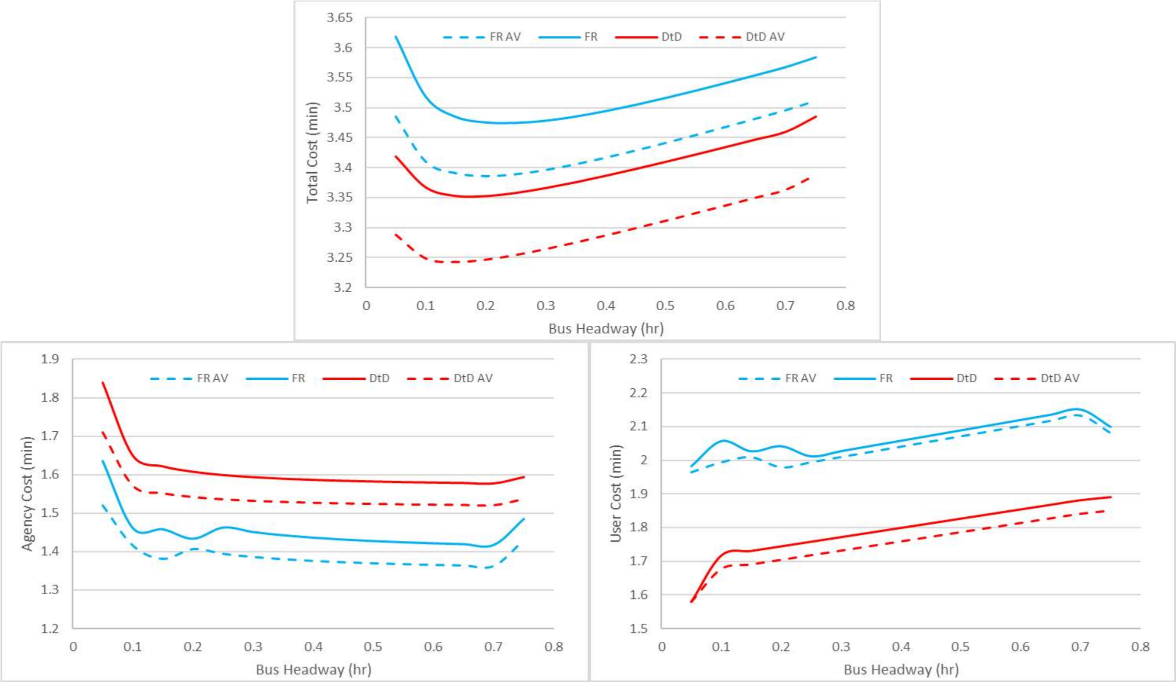


Figure 7 (a) Total Cost (b) Agency Cost (c) User Cost vs Bus Headway

The pattern between both cost and both services also similar. On the agency cost, small bus headway (3-6 minutes/vehicle) would generate higher cost but then decrease and start to steady. It was logical considering that smaller headway means more fleet and simultaneously increase the operating cost. Meanwhile, on the user cost aspect, the higher bus headway increases the user cost as passengers need to wait longer due to the higher headway.

4.3 Metro Headway

Unlike bus headway, metro headway shows different pattern regarding the relationship towards the total cost. Both services (with and without automation) achieve the optimum point at the same value, **6 minutes per vehicles**. The total cost would keep increasing alongside the increment of metro headway. However, both services not exactly follow the same pattern. Although both will keep increasing over the headway, they have different slope. At the smallest headway door to door service would be cheaper. Yet, when the metro headway is longer than **12 minutes**, door to door service would be more expensive and the gap would keep broader until the point (**24 minutes**) when the increment start to be slower and the gap start to be closer.

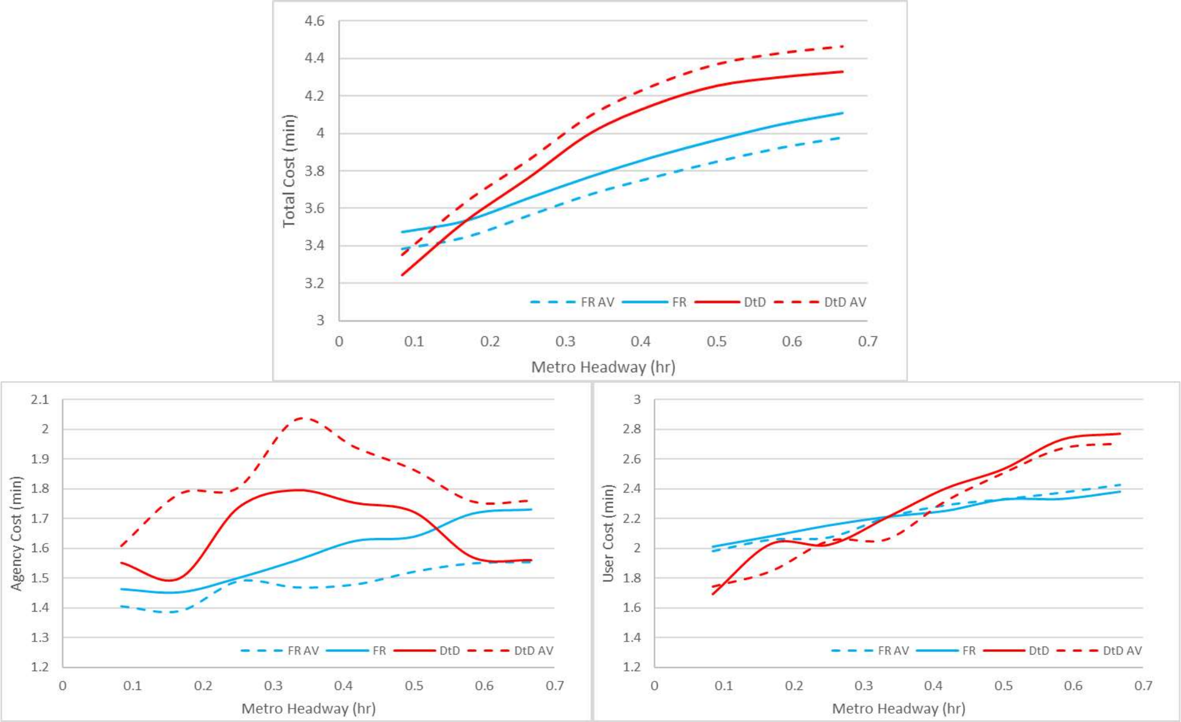


Figure 8 (a) Total Cost (b) Agency Cost (c) User Cost vs Metro Headway

The relationship between user cost and metro headway vaguely depicts the relationship between total cost and metro headway. Door-to-door service starts to be cheaper then fixed route service but, in the end, becomes more expensive. The agency cost pattern may explain the phenomenon. There is a sudden increase in agency cost when the metro headway increases from **12 minutes** to **18 minutes**—the cost even higher when the agency implements automation on the system. Meanwhile, fixed-route service only experiences a slight increase steadily by the longer metro headway.

4.4 Sensitivity Analysis

Although not considered as the decision variables. There are several parameters worth noticing regarding the optimization of transport network design, i.e. area length, demand, cruise speed, and value of time. In the previous section, there is an analysis of the relationship between alpha and total cost. In this section, there would be an analysis concerning the relationship between area length (D) and the value of time regarding alpha and total cost.

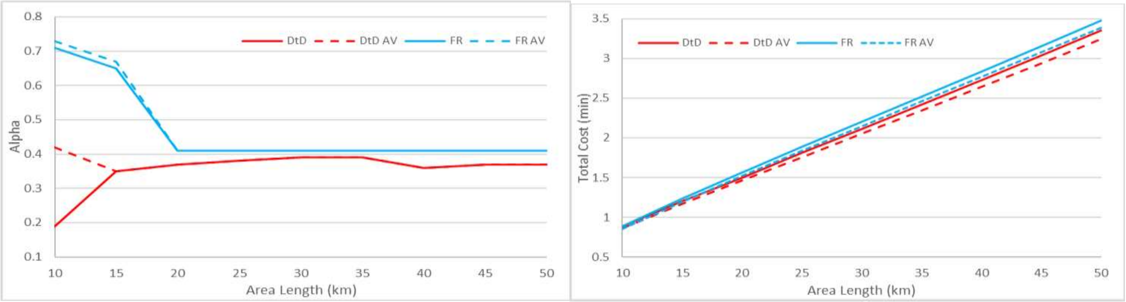


Figure 9 (a) Alpha (b) Total Cost vs. Area Length

The relationship between the value of alpha and area length shows an unusual pattern. Each service generates different alpha values in the area smaller than 20 km length or 400 km2. However, when the area length exceeds 20 km, alpha value generally would be steady and find a similar optimum value around **0.4**. Therefore, it could be concluded that in most cases, the value of alpha would be 0.4 regardless of the implemented feeder transit service. meanwhile, the total cost would increase linearly in parallel with the expansion of the service area. however, the slope for each type of service is different where door-to-door service has a cheaper cost and the gap between door-to-door service and fixed-route would be farther.

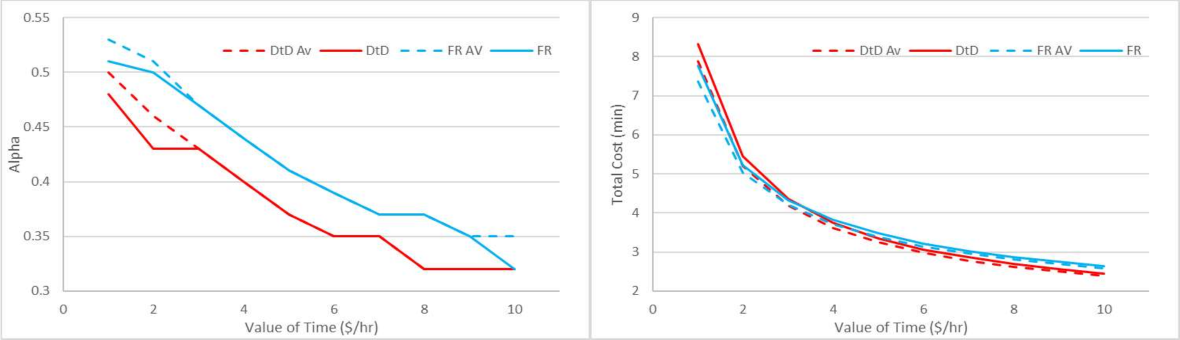


Figure 10 (a) Alpha (b) Total Cost vs Value of Time

Value of time (VOT) is the opportunity cost of the time that a traveler spends on their journey. It is one of the parameter on the agency cost perspective during the objective function optimization process. According to figure 10, the increase of value of time would impact on the reduce size of alpha and total cost simultaneously. The relationship between value of time and alpha tend to be linear while the relationship with total cost produce negative exponential. This phenomena demonstrate that people with high value of time would prefer shorter distance in order to reduce travel time. Small value of alpha indicate the higher accessibility within the central area due to the smaller length of the area (shorter distance). In parallel, the higher value of time related to lower total cost. transport infrastructure is one of the most expensive cost from agency cost, in case VoT correlate to the alpha

5. CONCLUSIONS

Hybrid network structure success highly associated with the optimum total cost. Based on the optimization process, it is found that the most optimum implementation of hybrid network occurred when the value of alpha or the proportion between central area (grid network) and the total network approximately 0.4, or in the other words 40% of the total area should be grid network. In general, there is no significance benefit between fixed route and door to door service for the feeder service, regarding to the bus headway, fixed route service would be more expensive. However, in regard to metro headway, door to door service would generate more total cost than fixed route.

Sensitivity analysis show the relationship between area length and value of time regarding the value of alpha and total cost. While the total cost tends to keep increase in parallel with the increase of area length. In contrary, total cost will reduce even dramatically when the value of time (VoT) is increasing. Additionally, the new technology may reduce the total cost per passenger. However, from network design perspective, level of automation does not have any significant impact on the network transformation. For future research, it would be better to consider the implementation of electric vehicles in addition of the automation on the transport system.

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7. REFERENCES

Abe, R. (2019). Introducing Autonomous Buses and Taxis: Quantifying the Potential Benefits in Japanese Transportation Systems. *Transportation Research Part A, 126*, 94-113.

Badia, H., & Jenelius, E. (2020). Feeder Transit Services in Different Development Stages of Automated Buses: Compating Fixed Routes versus Door-to-Door Trips. *Transport Research Procedia, 47*, 521-528.

Badia, H., Estrada, M., & Robuste, F. (2014). Competitive Transit Network Design in Cities with Radial Street Patterns. *Transportation Research Part B, 59*, 161-181.

Chan, C.-Y. (2017). Advancements, Prospects, and Impacts of Automated Driving Systems. *International Journal of Transportation Science and Technology, 6*, 208-216.

Daganzo, C. (2010). Structure of Competitive Transit Networks. *Transportation Research Part B, 44*, 434-446.

Douglass, M. (2010). Globalization, Mega-projects and the Environment: Urban Form and Water in Jakarta. *Environment and Urbanization Asia, 1*(1), 45-65. doi:https://doi.org/10.1177/097542530900100105

Fagnant, D., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167-181. doi:https://doi.org/10.1016/j.tra.2015.04.003

Fan, W., Mei, Y., & Gu, W. (2018). Optimal Design of Intersecting Bimodal Transit Networks in a Grid City. *Transportation Research Part B, 111*, 203-226.

Krueger, R., Rashidi, T., & Rose, J. (2016). Preferences for Shared Autonomous Vehicles. *Transportation Research Part C, 69*, 343-355.

National Highway Traffic Safety Administration. (2019). *https://www.nhtsa.gov/*. Retrieved February 2020, from https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

Papadoulis, A., Quddus, M., & Imprialou, M. (2019). Evaluating the Safety Impact of Connected and Autonomous Vehicles on Motorways. *Accident Analysis and Prevention, 124*, 12-22. doi:https://doi.org/10.1016/j.aap.2018.12.019

Zhang, W., Jenelius, E., & Badia, H. (2019a). Efficiency of Semi-Autonomous and Fully Autonomous Bus Services in Trunk-and-Branches Networks. *Journal of Advanced Transportation*.

APPENDIX A

Parameter	Description	Value
D	Total area length [km]	50
v_w	Walking speed [km/h]	2.5
v_m	Metro cruising speed [km/h]	40
v_b	Bus cruising speed [km/h]	20
v_f	Feeder cruising speed [km/h]	10
δ	Transfer distance penalty [km/h]	0.05
€$_{\text{L-Metro}}$	Unit fixed cost for infrastructure [€/veh-hr]	900
€$_{\text{L-Bus}}$	Unit fixed cost for infrastructure [€/veh-hr]	90
€$_{\text{L-Feeder}}$	Unit fixed cost for infrastructure [€/veh-hr]	0
€$_{\text{V-Metro}}$	Unit fixed cost for vehicle distance traveled [€/veh-km]	6
€$_{\text{V-Bus}}$	Unit fixed cost for vehicle distance traveled [€/veh-km]	2
€$_{\text{V-Feeder}}$	Unit fixed cost for vehicle distance traveled [€/veh-km]	1.5
€$_{\text{M-Metro}}$	Unit fixed cost for vehicle hours traveled [€/km-hr]	120
€$_{\text{M-Bus}}$	Unit fixed cost for vehicle hours traveled [€/km-hr]	40
€$_{\text{M-Feeder}}$	Unit fixed cost for vehicle hours traveled [€/km-hr]	34
τ_s	Dwelling time [h]	40/3,600
τ_b	Boarding time [h]	10/3,600
γ	Route factor [-]	1
Q	Total demand [pax/h]	56,000
k	Demand parameter [-]	0.192
C_M	Metro capacity [pax/veh]	800
C_B	Bus capacity [pax/veh]	150
C_F	Feeder capacity [pax/veh]	30
VoT	Value of Time [€/pax]	5