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Introducing autonomous buses and taxis: Quantifying the potential benefits in Japanese transportation systems

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ABSTRACT

The introduction of autonomous buses and taxis is expected to generate such benefits as cost reductions—and particularly for regional bus operations with a substantial deficit—as well as enhancing public transit accessibility through decreased trip costs. The purpose of this paper is to provide an overview of the impacts of introducing autonomous buses and taxis on metropolitan transportation systems by quantifying the costs of travel in Japan, and to discuss the potential benefits. First, this study sets the assumptions on autonomous driving technology, including its impacts on vehicle costs, the decreased labor costs for driving and safety monitoring in buses and taxis, and decreased driving stress for private car users. Next, operating costs are computed for autonomous buses and taxis in Japanese metropolitan areas. The costs of travel, or the sum of monetary and time costs, are then computed with and without vehicle automation for different trip types in high- and low-density metropolitan areas. The results highlight that the costs of public transit trips that currently have a smaller share of time costs in overall trip costs could decrease considerably due to vehicle automation. For instance, costs for 10–20-km trip lengths could decrease by 44–61% for taxi trips and 13–37% for rail/bus trips with taxi access, followed by a decrease of 6–11% for bus trips and 1–11% for rail trips with bus access. Further, private car trip costs could decrease by 11–16%. More substantial cost reductions in rail/bus trips with taxi access could occur in the case of smaller trip distances and/or in residential areas far from stations; larger reductions in rail trips with bus access could occur in low-density metropolitan areas. Finally, it is expected that vehicle automation in more fixed modes of public road transit could primarily benefit the transit industry and government, with such effects as improved labor productivity and reduced subsidies, while vehicle automation in more flexible modes could benefit metropolitan residents as well as the transit industry. This further suggests that a deficit of regional bus operations could be recovered during the transition to the full performance of autonomous buses.

1. Introduction

Autonomous vehicles (AVs) have recently experienced rapid technological development. For example, SAE (Society of Automotive Engineers, J3016) Autonomy Levels 1 (Drive Assistance) and 2 (Partial Automation) technologies are increasingly common in new car markets worldwide (Perslow and Carlson, 2015), while Audi has begun to mass-produce a car with a Level 3 (Conditional Automation) function called "Traffic Jam Pilot" (Paukert, 2018). A Level 3 self-driving system can monitor the driving environment in a limited space or under special circumstances, but requires a driver onboard to take over control when the system

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cannot execute a task. Vehicles with Level 4 or 5 technologies or those with self-driving systems that require no human overrides (i.e., full self-driving systems) are projected to contribute to 2% of worldwide passenger car sales by 2025 (Berret et al., 2017) and 3.8% by 2030 (Bailo et al., 2018). Commercial fleet operators are expected to be early adopters of full self-driving systems, as they can better absorb early-stage high technology costs than households or individual consumers (Guerra, 2016; Lienert, 2017; Wadud, 2017).

Technology companies, car manufacturers, traditional transit operators, and governments have launched many mobility service projects using AVs. For instance, both Waymo and GM have planned a large-scale launch of self-driving ride-sharing services in U.S. cities (Sage and Lienert, 2017), possibly representing one of the biggest and earliest efforts in the sector worldwide. In Japan, Nissan has tested a self-driving ride-sharing service in Yokohama, a high-density city (Tajitsu, 2018). Further, the Odakyu railway company has field-tested autonomous buses in the suburbs of Tokyo to provide feeder services to the company's rail station (Japan Automotive Daily, 2018). In general, rail companies in Japan's major metropolitan areas (MAs) are actively seeking the development of new mobility businesses. Japan's central government has primarily focused on low-density cities and rural areas, where field testing of AV mobility services first started in 2017 (Cabinet Office, 2018).

The transition to large-scale AV penetration in passenger travel might generate both advantages and disadvantages for the rail, bus, and taxi industries as well as metropolitan residents, thus involving challenges to overcome. For instance, policymakers are concerned with the impacts of AVs on public transit ridership (Lang et al., 2016; Merlin, 2017). Specifically, substantial funds have been allocated to mass rapid transit systems to date, particularly in high-density cities. In many cases, capital costs related to these systems are expected to be recovered in the coming decades thanks to ridership and fare revenues. A critical aspect of the management of these systems is how AV penetration could influence ridership and fare revenues. Indeed, more attention should be paid to the transition period, which will likely occur over several decades (Henaghan, 2018).[1]

During this period, introducing AV mobility services—such as autonomous buses and taxis—may primarily benefit metropolitan transportation systems in two ways. First, it could improve labor productivity in the bus and taxi industries. Operators in these industries could decrease costs by introducing AV technology, as this technology directly affects their labor-intensive cost structures. Specifically, bus operators in the Japanese regional MAs and rural areas have an average operating deficit of 13.3% (Table A4) and have weak financial sustainability. One caveat is that AVs' impacts on workers would differ by country. In countries like Japan, bus and taxi operators suffer from a shortage of drivers owing to a decreasing workforce, and AVs could help compensate for this shortage (MLIT, 2017a; TMG, 2018b). On the other hand, if AVs reduce jobs in specific sectors, their introduction might require mitigating policy measures for affected workers (Groshen et al., 2018 provide a U.S. case).

Second, this introduction could also benefit metropolitan residents. For instance, a decrease in operating costs for buses and taxis due to vehicle automation might lead to decreased fares. It might also enable shorter wait times for taxis, as well as more frequent bus services and larger networks, and eventually enhance public transit accessibility. Further discussions might first involve understanding how the introduction of autonomous buses and taxis could influence metropolitan trips. Enhancing public transit accessibility with AVs is one measure to address an increasing elderly population, and particularly those who cannot drive in towns in Japan's urban and rural areas.

This paper aims to provide an overview of the impacts of introducing autonomous buses and taxis on metropolitan transportation systems by quantifying the costs of travel in Japan, and discuss the potential benefits. The next section reviews literature related to this study. The third section sets the assumptions on autonomous driving technology. The fourth section explains the methods to compute the operating costs of buses and taxis, as well as trip costs or the sum of monetary and time costs, both with and without vehicle automation. The fifth section presents the trip-cost impacts of introducing autonomous buses and taxis. The sixth section discusses the potential benefits of this introduction to transportation systems. The final section summarizes the study's findings.

2. Literature review

The introduction of AVs in transportation systems is expected to generate social and economic benefits, such as improved traffic safety; improved mobility for those too young to drive, the elderly, and the handicapped; improved accessibility in underserved communities; improved productivity in the transit and trucking industries; reduced congestion and fuel consumption; and parking savings. Each country's government anticipates such benefits to varying degrees (Taeihagh and Lim, 2019).

The potential advantages and disadvantages of AVs have been quantified, and specifically, AVs' possible daily travel impacts have been investigated. Those impacts can be summarized into two categories: the impacts of AVs owned by households; and those of autonomous buses and taxis, with companies owning and operating such vehicles.[2]

Previous studies addressing AVs' impacts on travel demands have focused on privately owned AVs in most cases. These studies have suggested that a higher ownership of private AVs could lead to an increase in the aggregate demand for car travel due to the

[1] As of 2019, the Japanese government has aimed to help deploy Level 3 private cars on public roads in 2020 and Level 4 private cars on expressways in 2025. As for mobility services, it expects Level 4 practical deployment in specific regions by 2020. Additionally, the "general policy for establishing a legal system concerning AVs" in Japan was made public in 2018. It aims to establish the legal system in the period 2020–2025 (the definition as of today), officially called the "transition period," wherein conventional and autonomous fleets would exist together on public roads, but with the former dominating the latter. It covers every legal issue, including vehicles' safety standards, road traffic rules, and liabilities, among others (Cabinet Secretariat, 2018).

[2] A third category could include the impacts of sharing autonomous cars owned by companies or households. This AV sharing is included in an autonomous taxi category in this review because most of the reviewed studies have analyzed (long-term) situations that involve few differences in the service characteristics between autonomous taxis and AV sharing.

increased mobility for the elderly and handicapped (Harper et al., 2016), and decreased generalized costs of car travel in terms of less driving stress and diversified in-vehicle activities (Childress et al., 2015; Trommer et al., 2016). Consequently, the widespread penetration of private AVs could increase the vehicle miles traveled by a maximum of 10% (Wadud et al., 2016) to 14% (Harper et al., 2016) in the United States, making the country's modal splits of passenger travel more car-oriented (Trommer et al., 2016). This increased demand for car travel implies more road congestion and urban sprawl (Litman, 2014), while AV penetration still seems to be preferable in the United States in terms of AVs' social benefits by counting improved road safety and other advantages (Fagnant and Kockelman, 2015).

Meanwhile, knowledge is still scarce regarding how introducing autonomous buses and taxis could affect travel demands, such as rail travel demands. This is because previous studies have primarily analyzed autonomous taxis, both with and without ride-sharing, to convey operators' deployment. For instance, the operation of autonomous taxis (shared AVs) has been simulated for citywide deployment (e.g., Fagnant and Kockelman, 2014; Merlin, 2017) and train trips' first- or last-mile services (Liang et al., 2016; Shen et al., 2018). Further, Stocker and Shaheen (2017) reviewed business models for shared AVs, and categorized them by the entities of vehicle ownership and network operations. Studies have also computed AV mobility services' operating costs (Burns et al., 2013; Bösch et al., 2018; Wadud, 2017) and have investigated users' preferences for these services (Krueger et al., 2016; Haboucha et al., 2017; Lavieri et al., 2017). These studies have typically focused on (long-term) situations involving the full performance of autonomous buses and taxis. However, they may not include a strong reference to conventional buses' and taxis' existing operators; for instance, it has not been well-analyzed how current bus and taxi systems can improve with AVs, or the related potential benefits.

This study investigates the impacts of introducing autonomous buses and taxis on metropolitan transportation systems and discusses the related potential benefits, focusing on the following points: first, the analysis synthesizes the supply- and demand-side perspectives of bus and taxi systems, and quantifies the impacts of introducing autonomous buses and taxis on operating costs of these systems and daily trip costs. Second, it also considers the impacts in the transitional stage to the full performance of autonomous buses and taxis by utilizing the concept of monitoring of AVs. This reveals the changes in such costs due to vehicle automation.

3. Assumptions

This study assumes the principal technology-level impacts of AVs, including (1) an increase in vehicle acquisition costs, (2) a decrease in the labor costs for driving and safety monitoring for operators in the bus and taxi industries, and (3) a decrease in driving stress for private car users. This study omits other related technologies and assumptions to make the analysis more explicit about the assumptions used. Table 1 summarizes the specific assumptions used in this study, detailed as follows:

(1) Increased car acquisition costs: A 40% increase in car acquisition costs is assumed for passenger cars installing Level 4 or 5 self-driving systems relative to conventional cars. This value follows a conservative estimate by Wadud (2017) and the price of a conventional car considered in this study (Table A1). The insurance costs of cars with vehicle automation are assumed to remain the same as those without, following Wadud (2017), who concluded that the potential reduction due to improved safety can be canceled out by the increase due to the AV's higher value.

(2) Decreased labor costs for driving and safety monitoring: This assumption could considerably impact the estimation results of autonomous bus- and taxi-operating costs when the estimation is based on current levels, and this requires further elaboration. For instance, drivers' salaries in Japan currently comprise 70% of operating costs in taxi services and 53% in bus services (MLIT, 2016; Table A4).

This study classifies the autonomous bus/taxi monitoring method into two conceptual types. First, "remote human-based monitoring" involves only passengers riding in each vehicle, and a remote operator at another location visually monitors the vehicle's operations. In emergencies, the remote operator can direct and stop the vehicle. Second, "remote system-based monitoring" involves only passengers in each vehicle but with a computer system monitoring the vehicle's operation. When the system detects an emergency, a remote human operator directs and stops the vehicle.

It should be noted that many companies are currently involved in developing remote-monitoring/control systems for AVs. These systems allow professionals to remotely direct or drive vehicles by using devices to monitor in-vehicle and surrounding environments. Specifically, these systems could be used in operating mobility services using AVs because the AV safety guidelines in many regions or countries (Cabinet Secretariat, 2018; MLIT, 2019b for Japan) require their operators to have the means to communicate with AVs and

Table 1
Assumptions of technology-level impacts.

Technology-level impacts and profit margin	Assumption by mode			Note/Source
	Taxi (with/without ride-sharing)	Bus	Private car	
(1) Car acquisition costs	+40%	±0%	+40%	Autonomous driving systems added (Wadud, 2017).
(2) Labor costs for driving and safety monitoring	$-(1-1/x)^{*}$ 100% e.g., −40% (x = 1.66) and −100% (x = ∞).	–	–	x = number of vehicles per remote operator. Remote monitoring/control system and communication costs are assumed to be JPY 3.4 per km (Keeney, 2018).
Profit margin (fraction of operating revenues to costs)	3%		–	The ratio of fare to operating revenues is assumed to be 94–95% for buses and 100% for taxis.
(3) Driving stress (VTTS)	–		−30%	Steck et al. (2018)

the ability to safely stop them in case of emergency. Customer service is also provided remotely.

This study makes a conservative assumption that the current drivers' salaries per hour can apply to remote operators, although the labor costs of monitoring AVs could depend on the required skills and official qualifications.

Further, this study uses the number of vehicles that can be managed by a remote operator to determine the rate of the reduction in labor costs of driving/safety monitoring during the transition to completely system-based monitoring (i.e., 100% of the reduction). For instance, operators may prefer to increase the number of vehicles per remote operator to avoid incurring labor costs for monitoring vehicles. This means that they might prefer remote computer-system-based monitoring rather than remote human-based monitoring.

One final case assumes a full decrease in drivers' salaries per hour due to vehicle automation, or the completely system-based monitoring of vehicles, and another transitional case assumes a 40% decrease where a remote operator manages 1.66 vehicles (i.e., 3 people manage 5 vehicles). Note that an onboard attendant may also be required particularly in early-stage introductions of autonomous buses to monitor safety and communicate with disabled passengers (Dong et al., 2019; Lutin, 2018). This study does not explicitly consider this situation.

Finally, an estimate indicates that the remote monitoring/control system will cost 5 cents per mile (JPY 3.4 per km), including the operator and cellular network, and assuming a large fleet size with each car requiring help 1% of the time (Keeney, 2018). This study uses this value for the system cost without the labor costs of monitoring.

The bus and taxi industries' market structures: It is assumed that bus and taxi industries' average structure even with AVs will include free entry and exit, and no economies of scale, although this assumption is arbitrary to provide lower-bound estimates for autonomous bus and taxi fare levels.

Specifically, operating revenues are assumed to be the sum of operating costs and a 3% profit margin. Note that the margin currently ranges from 1% to −3% for Japanese taxi operators depending on the city (MLIT, 2016), and is 1.3% for bus operators in major MAs and −13.3% in other areas (Table A4).[3] The rationale for the substantial operating deficit includes public service. Related business profit or these operators' transfer from other accounts recovers the deficit if this occurs while the government subsidizes bus operations. For instance, central, prefectural, and local governments paid JPY 67 billion in 2015 to financially support "regional bus lines (bus lines in the regional MAs and rural areas in most cases)" (Nihon Bus Association, 2017). Nonetheless, this study assumes a positive margin in the autonomous bus and taxi markets *per se*, but applies a much more conservative rate.

Fare revenues and average fares are then calculated by deducting non-fare revenues, such as advertising in the vehicle. The fraction of bus fare revenues to operating revenues is 0.942 in the major MAs and 0.951 in other areas (for public buses; MIC, 2019). This study uses these values for buses and does not consider these non-fare revenues for taxis.

(3) Decreased driving stress for private car users: A 30% decrease in the value of travel time savings (VTTSs) is assumed for the private car drivers' travel time due to vehicle automation. This value follows work by Steck et al. (2018), which estimates changes in VTTSs for commuting due to vehicle automation based on a stated preference survey conducted in Germany. The study's 30% value is employed in the Japanese context as such VTTS estimates are still scarce (Milakis et al., 2017), including those in Japan. One caveat is that mobility preferences could still differ across countries. Recently, Correia et al. (2019) also reported a similar value in the Netherlands: namely, a 26% VTTS reduction due to vehicle automation for car drivers if they worked in the vehicle.

4. Method

4.1. Data and measures

This study uses a sample of 62 cities in the analysis, including central and peripheral cities located in four types of Japanese MAs, as summarized in Table 2. The sampled cities and definitions of the city and metropolitan categories follow those in the National Person Trip Survey in Japan (MLIT, 2015). This survey is conducted to create a representative sample of travel behavior of individuals who live in Japanese cities after clustering these cities. The survey's original sample represents 85% of the nation's population.

Data on city categorical averages are used to compute taxi costs and fares and private car usage costs. It is appropriate to use city-level data for taxis, as a city's geographical area approximately corresponds to the region's regulated taxi (business) area in Japan. The city categorical average is a simple average of all cities included in each city category. Each city's indicators are directly employed from city-level data in most cases. Some of the indicators are tabulated from the sample of individuals living in each city, where the sample represents the city's residents in terms of the shares of age and gender groups.

Data on metropolitan categorical averages are used to compute bus costs and fares and rail fares, as well as time and trip costs. The considered metropolitan categories include both major and regional MAs. Each MA category's indicators are employed directly from metropolitan-level data. Taxi costs and fares and private car usage costs in each MA category are the average values of those

[3] The Japanese taxi industry includes a total fleet of approximately 234,000 vehicles nationwide, among which 16% of these taxis are owned by drivers who have passed a strict safety review. The industry had operating revenues of approximately JPY 1.7 trillion in 2015, which is 40% lower than those peaking in 1991 (MLIT, 2018b). Details of the Japanese taxi regulatory framework is available in the Tokyo Hire-Taxi Association (2017). The Japanese bus industry has 600 operators nationwide (holding 10 vehicles or more), among which approximately 30 operators are managed by the public sector. The total fleet includes approximately 60,000 vehicles, with operating revenues of approximately JPY 1 trillion in 2016 (MLIT, 2018b; Nihon Bus Association, 2017).

Table 2
Categorical averages of city characteristics.

City characteristics	Metropolitan and city categories								
	Major (Tokyo, Osaka, Nagoya) MAs			Regional MAs					
				Regional Core MAs		Regional Large MAs		Regional Small MAs	
	Central (n = 8) [a]	Near Peripheral (n = 7) [b]	Peripheral (n = 13) [c]	Central (n = 5)	Peripheral (n = 6)	Central (n = 6)	Peripheral (n = 6)	Central (n = 6)	Peripheral (n = 5) [e]
Population (in thousands)	1929	373	201	1346	100	591	91	269	109
Density (/km^2)	6468	5253	2120	2174	1203	1155	398	653	384
Distance traveled per trip maker (km)	32.3	32.7	27.7	25.8	26.2	24.0	24.4	20.7	20.0
% of car	21.8%	27.3%	48.3%	51.9%	53.3%	64.2%	79.9%	72.5%	77.7%
Distance traveled per trip (km)	12.4	12.8	10.9	10.0	10.2	8.9	10.0	8.1	8.5

Population and density data are based on the 2015 National Census. Data on individuals' weighted averages of distance traveled are based on the 2015 National Person Trip Survey (MLIT, 2015), and cover weekday car, motorcycle, public transit, walking, and cycling distances.

[a] The city-level unit (23 special wards area) of Tokyo is not included, although it is included in the survey's original targets, as it can be an outlier in this category in terms of all the characteristics.

[b] This category includes the peripheral cities located 40 km or less from the central business district in the Tokyo MA, and 30 km or less in the Osaka MA.

[c] This category includes other peripheral cities in the major MAs.

[e] Urazoe City, Okinawa, is not included, although it is included in the survey's original targets, as it can be an outlier of this category in terms of density.

from all city categories included in each MA category; averaging is one of the simplest approaches to combining these values, but further improvements can be possible in the future.

Regarding the measure of costs, this study computes these *per passenger-kilometer* for taxi and bus services and private car use to compare the different modes. Note that these services' costs per passenger-kilometer incorporate capacity utilization rates in kilometers and hours and the occupancies of vehicles, as well as service supply levels measured by the costs per *vehicle or seat-kilometer*.

Regarding the measure of fares, this study computes these per *passenger-kilometer* for taxi, bus, and rail services. In practice, taxi fares are charged as per the *vehicle-kilometer* when carrying passengers, while bus and rail fares are charged as per the *passenger-kilometer*. Therefore, the taxi fares in this study are regarded as practical taxi fares, divided by the average occupancy.

4.2. Taxi costs and fares, and private car usage costs, with and without vehicle automation

Taxi operating costs are computed with the method used by Bösch et al. (2018), which can simultaneously compute the operating costs of taxis both with and without ride-sharing by setting different operating patterns for a chosen passenger car. The taxi operating costs in this method are computed from the chosen car's (1) vehicle costs including car acquisition, annual ownership, and running costs; (2) operating patterns; and (3) other values such as the driver's salary, vehicle lifetime, and interest rates.

Data for this computation are summarized as follows: Table A1 shows the vehicle costs (of a Toyota Prius, in this study) and other values for both taxi and private car use in all the city categories. Table A2 summarizes those that differ by city category (i.e., parking costs, taxi insurance costs, and drivers' salaries). Table A3 summarizes the operating pattern values in each city category. This study simply explains the operating costs of taxis with ride-sharing as having a higher average occupancy than taxis without ride-sharing due to the poor data availability for ride-sharing taxis in Japan. Note that Japan prohibits unrelated passengers from sharing a taxi in most MAs, except for specific rural areas.

Next, autonomous taxi operating costs are obtained by Assumptions 1 and 2 (Section 3) and this method. Specifically, these assumptions are applied to the corresponding variables in the above process of computing taxi operating costs.

Taxi fares both with and without vehicle automation are computed from the assumption of the taxi market structure (Section 3) and the computed taxi operating costs with and without vehicle automation.

Finally, the private car usage costs are also computed with the method used by Bösch et al. (2018), which sets unique vehicle costs (Tables A1 and A2) and operating pattern values for private car use (Table A3); the costs of private car use with vehicle automation are then computed using Assumption 1 and this method.

4.3. Bus costs and fares with and without vehicle automation, and rail fares

Autonomous bus operating costs are computed directly from Assumption 2, and Table A4 summarizes the current bus operating costs (without vehicle automation) and driver's salaries.

Autonomous bus fares are computed from an assumption of the bus market structure (Section 3) and the computed autonomous bus operating costs. “Subsidized” autonomous bus fares are not considered.

Current (regular) rail fares per passenger-kilometer are employed for the analysis, as summarized in Table A4. Note that rapid rail transit in Japan’s major MAs earns operating profits, but regional rail does not on average (Table A4). The central, prefectural, and local governments have many financial schemes to support, for instance, the construction of new rail lines, rail infrastructure improvements, and regional rail operations (JRTT, 2018; MLIT, 2018c).

4.4. In-vehicle time costs and costs of trip stages

This study considers non-business (e.g., commuting and leisure) trips and business trips in the analysis and employs the relevant VTTSs.

The in-vehicle time costs (per passenger-kilometer) of each transportation mode are obtained as the mode’s average travel time per kilometer—obtained as an inverse of the mode’s average travel speed in each MA—multiplied by the VTTS of the mode’s in-vehicle time. Table A5 summarizes each mode’s average travel speed, and Table A6 summarizes each mode’s VTTS.

The in-vehicle time costs of private cars with vehicle automation are obtained by Assumption 3 (Section 3) and the above computation method of in-vehicle time costs. Specifically, this assumption is applied to the VTTS of the private car’s in-vehicle time in the process of computing private cars’ in-vehicle time costs.

The costs (per passenger-kilometer) of trip stages are computed as the sum of monetary and in-vehicle time costs for each mode. The monetary cost includes the fares for rail, bus, and taxi services (with and without ride-sharing), and the costs of private car use.

4.5. Other time costs and trip costs

The waiting and transfer time costs are computed for the trips involving rail, bus, or taxi (with and without ride-sharing) stages. Specifically, 5 or 10 min are considered as potential total waiting and transfer times in transit stations for these trips. The waiting and transfer VTTSs (Table A6) are used to convert these total waiting and transfer durations into time costs. Note that the frequencies of rail and bus services in their networks and the number of taxis in a business area are relevant to each service’s waiting time while this study takes an approach that waiting times are set exogenously at 5 or 10 min.

Trip costs are then computed for individuals who live in three types of distances from transit stations (in trunk lines). Specifically, for individuals living in a five-minute walking or cycling distance from these stations, the costs of this time are incorporated in the trips that include rail or bus stages. The five-minute walking (e.g., 400 m) and cycling (e.g., 1250 m) distances are in the same category because time costs are only accounted for in using these modes with no distance charges. For individuals living in two- or four-kilometer distances from these stations, the costs of a five-minute walking or cycling time are incorporated when the bus is used as an access mode to these stations. The walking VTTSs (Table A6) are used to convert these walking or cycling durations into time costs.

Trip costs (for specific distances) are computed as the sum of the costs of all stages in the trip, and this incorporates the time costs for total waiting and transfer in as well as the walking/cycling access to transit stations. Trip distances of 10 and 20 km are computed based on the Japanese MAs’ average trip distances as summarized in Table 1, made by individuals who live in the three types of distances from transit stations (in trunk lines).

5. Results

5.1. Costs and fares with and without vehicle automation

Fig. 1 and Table 3 show the computation results for the costs of taxis and private car use, with and without vehicle automation, in Japanese cities.

Fig. 1 shows that current taxi operating costs are relatively cheaper in larger MAs, which can be primarily explained by the higher hours taxi vehicles are utilized there. They are also relatively inexpensive in regional small MAs, which can be primarily explained by the less expensive taxi insurance costs, parking costs, and drivers’ salaries there. Fig. A1 compares these computed current taxi operating costs with the actual taxi fares in these cities to validate the computed costs. This comparison indicates that the computed costs reproduce the cost differences across cities, but slightly overestimate actual costs; this bias should be considered when interpreting the computed taxi costs.

Table 3 indicates that taxi operating costs with and without ride-sharing, could decrease by 29–33% in the transitional case (1:1.66) of vehicle automation, and by 71–78% in the final case. A sensitivity check is also conducted to test the impacts of variation in the assumption of a decreased driver’s salary on autonomous taxi-operating costs (for those without ride-sharing). Table 3 indicates that doubling the number of vehicles that a remote operator can manage could decrease these costs. However, this impact could be small with the increased number of vehicles, for instance, during the transition from the 1:20 case to the final case.

Table 3 also indicates that the costs of private car use could increase by 15–18% due to vehicle automation.

Fig. 2 illustrates the current costs, revenues, and fares for buses without vehicle automation, and the computed costs of autonomous buses in Japanese MAs as well as these MAs’ current rail costs, revenues, and fares. The results indicate that bus operating costs could decrease by 21% in the transitional (1:1.66) vehicle automation case, and by 53% in the final case.

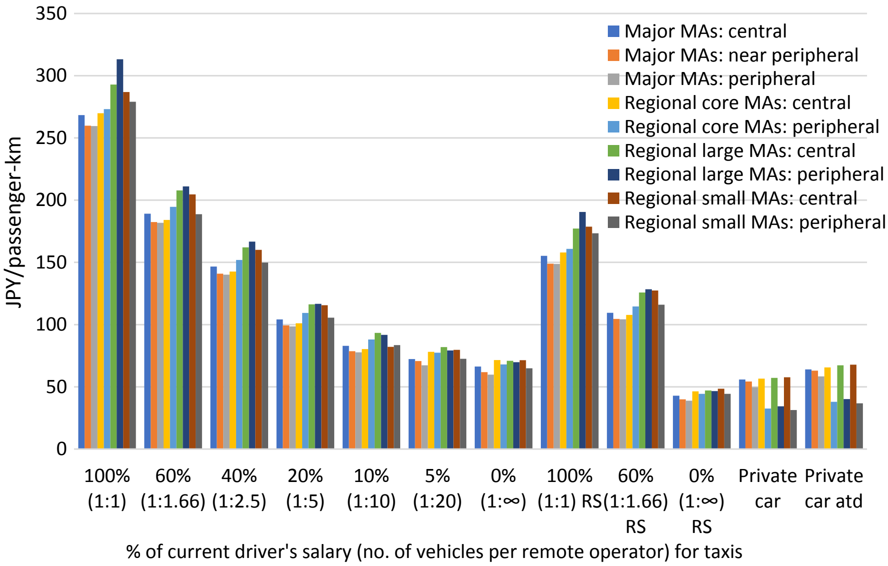

Fig. 1. Costs of taxis and private car use with and without vehicle automation. *Note:* atd = autonomous; RS = ride-sharing. USD 1 = JPY 110 (March 2019).

Table 3
Percentages of changes in costs of taxi and private car use due to vehicle automation (from the current costs).

City category	% of current driver's salary (no. of vehicles per remote operator) for taxis								Private car use
	Without ride-sharing						With ride-sharing		
	60% (1:1.66)	40% (1.2.5)	20% (1.5)	10% (1:10)	5% (1:20)	0% (1:∞)	60% (1:1.66)	0% (1:∞)	
Major MAs: central	−30%	−45%	−61%	−69%	−73%	−75%	−30%	−72%	+15%
Major MAs: near peripheral	−30%	−46%	−62%	−70%	−73%	−76%	−30%	−73%	+16%
Major MAs: peripheral	−30%	−46%	−62%	−70%	−74%	−77%	−30%	−74%	+17%
Regional core MAs: central	−32%	−47%	−63%	−70%	−71%	−73%	−32%	−71%	+16%
Regional core MAs: peripheral	−29%	−44%	−60%	−68%	−72%	−75%	−29%	−72%	+17%
Regional large MAs: central	−29%	−45%	−60%	−68%	−72%	−76%	−29%	−73%	+18%
Regional large MAs: peripheral	−33%	−47%	−63%	−71%	−75%	−78%	−33%	−76%	+17%
Regional small MAs: central	−29%	−44%	−60%	−71%	−72%	−75%	−29%	−73%	+18%
Regional small MAs: peripheral	−32%	−46%	−62%	−70%	−74%	−77%	−33%	−74%	+17%

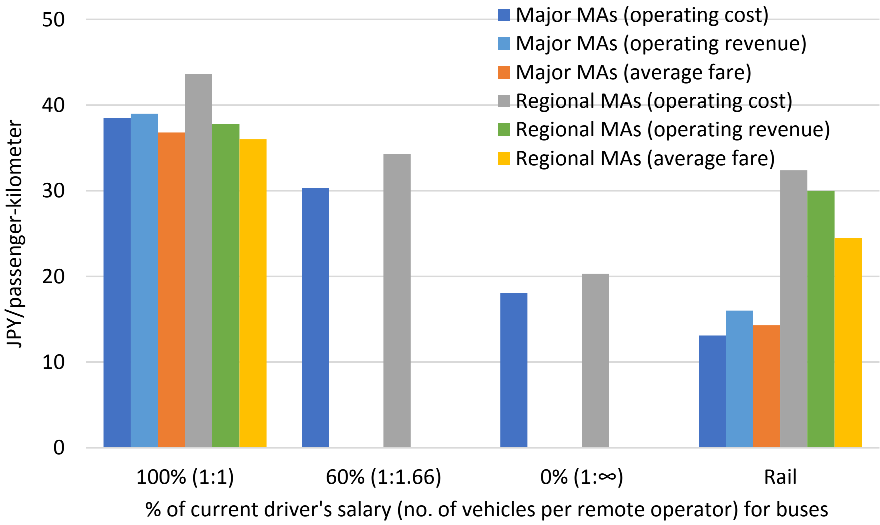

Fig. 2. Costs of buses with and without vehicle automation, and related indictors *Note:* USD 1 = JPY 110 (March 2019).

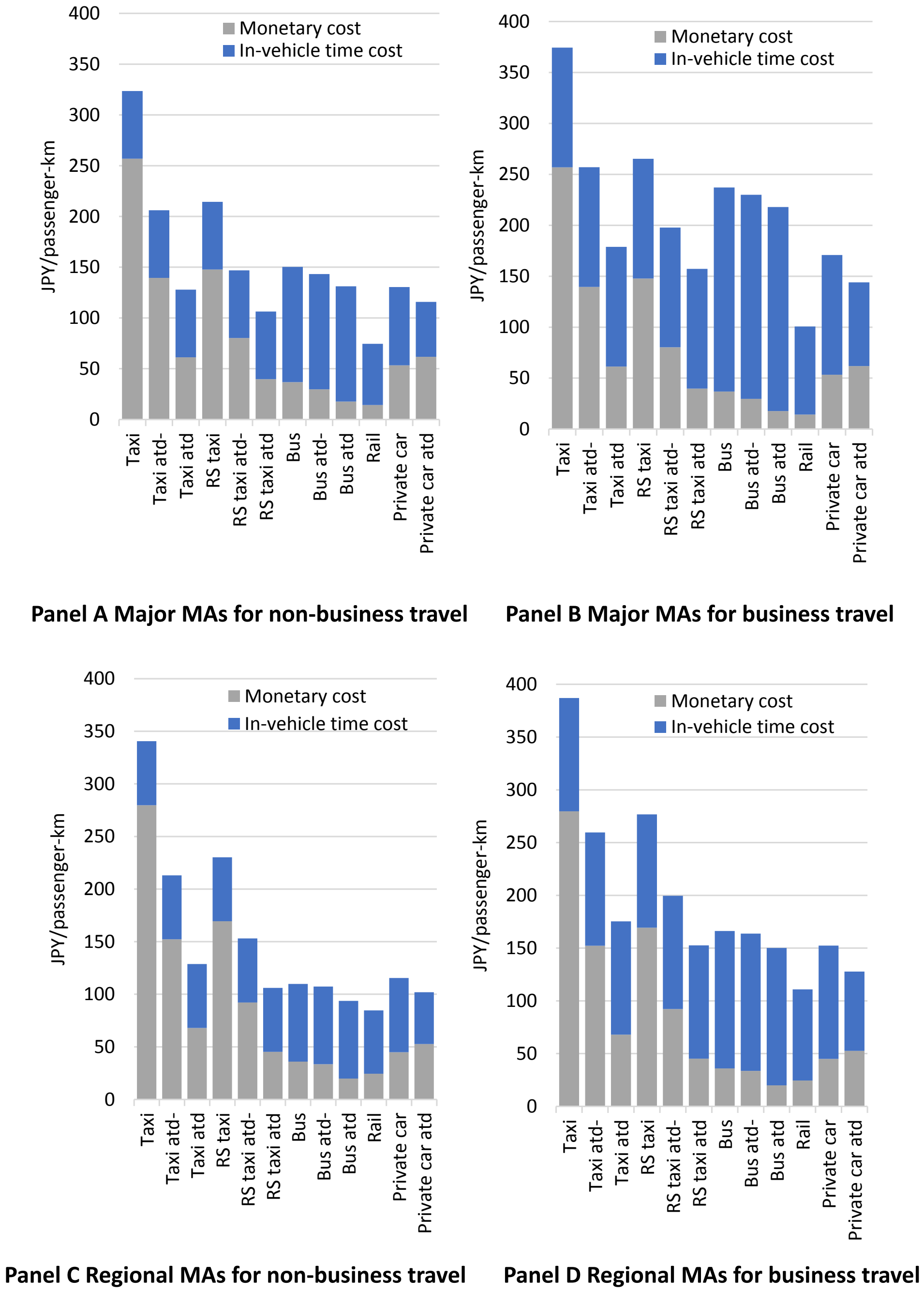

Fig. 3. Costs of trip stages with and without vehicle automation. *Note:* atd = autonomous; atd- = autonomous transitional (1:1.66 case); RS = ride-sharing.

5.2. Costs of trip stages with and without vehicle automation

Fig. 3A and B display the costs of trip stages with and without vehicle automation in the major MAs for non-business and business travel, respectively; Fig. 3C and D display those in the regional MAs.

Fig. 3 indicates that taxi stages' costs with and without ride-sharing could decrease by 36–40% for non-business travel and 31–36% for business travel in the transitional case of vehicle automation; and by 59–64% for non-business travel and 51–60% for business travel in the final case. These percentages are slightly larger for regional MAs than for the major MAs. Although autonomous taxi stages' costs could still be larger than the costs of private car stages in the transitional case, both could be at a similar level in the final case in both MA categories.

Table 4
Percentages of changes in trip costs (from the current to final case of vehicle automation).

Distance, residence relative to station, and type of MA	Mode and purpose													
	Bus		Rail + fTaxi		Bus + fTaxi		Private Car		Taxi		RS Taxi		Rail + fBus	
	NBT	Dff. to BT	NBT	Dff. to BT	NBT	Dff. to BT	NBT	Dff. to BT	NBT	Dff. to BT	NBT	Dff. to BT	NBT	Dff. to BT
20 km–5 min (400 m walk/1.25 km cycling) (Fig. A2 *Panel A, B)*														
Major MAs	−10%	(+4)	—	—	—	—	−11%	(−4)	−56%	(+8)	−45%	(+9)	—	—
Regional MAs	−11%	(+3)	—	—	—	—	−12%	(−4)	−58%	(+7)	−48%	(+8)	—	—
10 km–5 min (Fig. A2 Panel C, D)														
Major MAs	−9%	(+3)	—	—	—	—	−11%	(−4)	−52%	(+8)	−40%	(+8)	—	—
Regional MAs	−9%	(+3)	—	—	—	—	−12%	(−4)	−54%	(+7)	−44%	(+8)	—	—
20 km–2 km (Fig. A3 Panel A, B) [a]														
Major MAs	—	—	−17%	(+4)	−20%	(+7)	−11%	(−4)	−58%	(+8)	−47%	(+9)	−2%	(0)
Regional MAs	—	—	−16%	(+3)	−24%	(+7)	−11%	(−4)	−61%	(+7)	−52%	(+9)	−11%	(+2)
10 km–2 km (Fig. A3 Panel C, D) [a]														
Major MAs	—	—	−24%	(+5)	−24%	(+7)	−11%	(−4)	−56%	(+8)	−45%	(+9)	−3%	(+1)
Regional MAs	—	—	−24%	(+5)	−29%	(+8)	−11%	(−4)	−59%	(+7)	−49%	(+8)	−10%	(+2)
20 km–4 km (Fig. A4 Panel A, B) [b]														
Major MAs	—	—	−26%	(+5)	−26%	(+8)	−11%	(−4)	−58%	(+8)	−47%	(+9)	−3%	(+1)
Regional MAs	—	—	−26%	(+5)	−31%	(+8)	−11%	(−4)	−61%	(+7)	−52%	(+9)	−11%	(+2)
10 km–4 km (Fig. A4 Panel C, D) [b]														
Major MAs	—	—	−34%	(+6)	-32%	(+9)	−11%	(−4)	−56%	(+8)	−45%	(+9)	−5%	(+1)
Regional MAs	—	—	−35%	(+6)	−37%	(+9)	−11%	(−4)	−59%	(+7)	−49%	(+8)	−9%	(+2)

f = access mode; RS = ride-sharing; NBT = non-business trips; BT = business trips.
The costs of 5- or 10-min total waiting and transfer times are incorporated in the trips involving rail, bus, or taxi (with and without ride-sharing) stages. The costs of five-minute walking/cycling times are incorporated in bus trips and rail trips with bus access.
[a] The actual length is 10 or 20 km for private car and taxi (with and without ride-sharing) trips, while this is 12 or 22 km for other trips.
[b] The actual length is 10 or 20 km for private car and taxi (with and without ride-sharing) trips, while this is 14 or 24 km for other trips.

Fig. 3 also indicates that bus stages' costs could decrease by 2–5% for non-business travel and 1–3% for business travel in the transitional case; and by 13–15% for non-business travel and 8–10% for business travel in the final case. These percentages are larger for regional MAs than for the major MAs. Further, buses had a smaller percentage in decreasing operating costs than taxis due to vehicle automation, and even had a smaller percentage of the reduction in trip stages' costs. The smaller reduction in bus stages' costs occurred because the decreased bus fare from vehicle automation had less of an impact due to a larger share of time costs in the current bus stages' costs.

Fig. 3 demonstrates that private car stages' costs could decrease by 9–16% for non-business travel and 14–20% for business travel due to vehicle automation. These percentages are almost the same across the two MA categories. Vehicle automation could lead to an increase in monetary costs for private car use, but this increase could be nullified by the reduction in time costs.

5.3. Trips costs with and without vehicle automation

Table 4 summarizes the percentages of the changes in the considered trips' costs (from the current to the final case of vehicle automation). Trips are categorized by mode, purpose, origin-destination distance, the distance to transit stations (in trunk lines), and the type of MA. Figs. A2, A3, and A4 illustrate the considered trips' costs with and without vehicle automation only for non-business travel.

The costs of taxi trips (door-to-door), with and without ride-sharing, could decrease by 52–61% for non-business travel and 44–53% for business travel due to vehicle automation. These reductions do not strongly depend on either the type of MA or the trip distance.

Bus trip costs could decrease by 9–11% for non-business travel and 6–8% for business travel due to vehicle automation for those living near transit stations. These reductions do not strongly depend on either the type of MA or the trip distance. Fig. A2 indicates that the magnitude of the decrease in trip costs due to decreased bus fares from vehicle automation is comparable to the costs from a five-minute wait.

The costs of rail and bus trips with taxi access to transit stations could decrease by 16–37% for non-business travel and 13–29% for business travel due to vehicle automation for individuals living far from these stations. Although these reductions are substantial, they are smaller than those for taxi trips. These reductions do not strongly depend on the type of MA, but are larger for smaller trip distances and/or for individuals living longer distances from transit stations.

The costs of rail trips with bus access could decrease by 2–11% for non-business travel and 1–9% for business travel due to vehicle automation. These reductions do not depend on either the trip distance or residents' proximity to stations, but they are larger in regional MAs than in the major MAs.

The costs of private car trips could decrease by 11–12% for non-business travel and 15–16% for business travel. These reductions do not depend on either the type of MA or the trip distance. Among the considered trips in Table 4, only private car trips could experience a larger reduction in business travel than in non-business travel.

6. Discussion

Autonomous buses and taxis' impacts on trip costs can be interpreted by whether the trip entails more fixed or flexible modes of public road transit. This most fixed mode includes buses, while the most flexible mode includes taxis without ride-sharing. More fixed modes would bundle travel demands in more fixed routes and provide relatively cheaper fares at the cost of individual trip speeds. Thus, time costs would share a large part of the current costs of the trips that involve such fixed modes. For instance, one such trip involves rail trips with bus access, as shown in Table 4 and Figs. A2-4. Meanwhile, introducing autonomous buses and taxis might primarily affect fares by replacing human drivers. Therefore, public transit trips that currently have a larger share of time costs in overall trip costs could experience a smaller decrease in trip costs due to vehicle automation. This general mechanism can also apply to interpret the results that cost reductions in multi-modal public transit trips interacted with trip distance, the place of residence relative to stations, and the type of MA; namely, the current share of time costs could vary based on these factors.

This study's results can extend the discussion on the advantages of introducing autonomous buses and taxis for metropolitan transportation systems. First, vehicle automation in more fixed modes of public road transit may primarily benefit the transit industry and government. Improved labor productivity is a well-acknowledged gain of vehicle automation in the bus and taxi industries. Additionally, bus systems' operations often involve subsidies or other financial support from the government—and particularly in low-density areas—and thus, productivity improvements could create more financially sustainable conditions for these systems. Although metropolitan residents would also benefit from the conditions under which bus service levels either remain the same or avoid deteriorating due to vehicle automation, this gain may be measured from industry or government perspectives, such as decreased subsidies. Therefore, vehicle automation in buses should not be discounted for metropolitan transportation systems, even if smaller cost reductions may occur in the trips involving buses than in those involving taxis.

For instance, the impacts of introducing autonomous buses could also be measured in the transitional stage to their full performance. Given the current fare and demand levels, an average operating deficit of 13.3% for regional bus operators (Fig. 2; Table A4) could be recovered by decreasing operating costs during the transition to the full performance of autonomous buses; autonomous buses could have significant potential when measured in the current bus market.

Second, vehicle automation in more flexible modes of public road transit may benefit residents as well as the transit industry. This study's results indicated that the trips involving taxis had larger cost reductions than those that did not. However, one caveat is that these gains for residents might be discounted to some extent once autonomous taxis' impacts on aggregate travel demands are considered in the analysis. For instance, an increase in the number of taxi trips (door-to-door) due to cost reductions might induce congestion and decrease each taxi trip's speed (and increase trip costs). Although each taxi trip's speed might improve by introducing some mitigating technology or pricing scheme in each car or road network, this introduction might increase fares for each taxi trip and eventually increase trip costs. In terms of the concern for aggregate demand, this study's costs for the trips entailing more flexible and autonomous modes of public road transit can be considered as lower-bound estimates.

7. Conclusions

With the expected large-scale deployment of AV mobility services, this study provided an overview of how these services could affect metropolitan transportation systems, and in particular, by quantifying the costs of travel in Japan. The analysis included different urban settings, typologies, modes, and trip types, as well as supply- and demand-side perspectives, with the same method and homogeneous dataset. As this service is still in the early stages of its introduction, this overview is a first step to elaborate on each component in understanding its impacts on travel demands.

The results highlighted that the costs of public transit trips that currently have a smaller share of time costs to overall trip costs—could decrease considerably due to vehicle automation. For instance, if all trips have 10 to 20 km lengths, costs could decrease by 44–61% for taxi trips and by 13–37% for rail/bus trips with taxi access, followed by a decrease of 6–11% for bus trips and 1–11% for rail trips with bus access; the costs of private car trips could decrease by 11–16%. More substantial cost reductions in rail/bus trips with taxi access could occur in the case of smaller trip distances and/or in residential places far from stations; larger reductions in rail trips with bus access could occur in lower-density MAs. Although the exact quantified values could be country-specific, the overall trends and mechanisms could be shared with other countries.

As the potential benefits, it is expected that vehicle automation in more fixed modes of public road transit could primarily benefit the transit industry and government, with such effects as improved labor productivity and reduced subsidies, while vehicle automation in more flexible modes could benefit metropolitan residents as well as the transit industry. This further suggests that a deficit of regional bus operations could be recovered during the transition to the full performance of autonomous buses.

The analysis has some limitations. First, this study potentially addressed only trips to primary destinations in each MA, as the considered destinations were relevant (close) to rail lines and bus trunk lines. Additionally, this study did not address the change in the aggregate demand for each trip type due to the change in its cost. For instance, the changes in the behaviors of both metropolitan residents and bus and taxi operators due to AVs' technology-level impacts may affect the transportation network's equilibrium—such as congestion levels—while the resulting change in aggregate demand conditions affects individual behaviors; however, this feedback is not considered in the analysis. These issues include the costs of providing an overview across different MAs, although detailed simulations in each MA could help overcome these issues. Second, this study did not explicitly address the possibility of sharing autonomous cars. Although its characteristics might be approximated to some extent by taxis (with and without ride-sharing) in the final case of vehicle automation, autonomous car sharing can also be considered as an independent mode.

Further, the results of this study should be regarded as indicating the potential of autonomous buses and taxis. Clearly, the costs of AVs are considerably larger than those of conventional vehicles at the current stage, and depend on engineering elaboration for taxis and buses. For instance, additional costs will be needed if autonomous taxis further avoid accidents with bicyclists in boarding and alighting of passengers. How to deal with an emergency in autonomous buses needs further elaboration. Required engineering and related institutional factors will be made clearer with early-stage introductions of these services, and then the results of this study need to be updated.

Finally, introducing autonomous buses and taxis creates specific opportunities and challenges for transportation planners that require related research. For instance, these services might enable more efficient and inclusive regional transportation systems. Business models and related simulations of AV mobility services in lower-density areas will need to be developed, and especially to consider private sector-based activities in profitable high-density areas. Many countries currently subsidize bus operations in lower-density areas, but how this situation should evolve to include AVs is another topic for further investigation. Meanwhile, another research subject involves the coordination of AV mobility services with the existing transit system in high-density areas as introduced.

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Appendix A. Values used

See Tables A1–A6.

Table A1
Vehicle costs and other values in all city categories (for taxis and private cars).

Vehicle costs and other values	Private passenger car	Taxi
Vehicle costs (JPY, taxi premium)[a]		
Acquisition cost	2,461,850	–30%
Insurance cost per year	72,000	Depending on city[c]
Tax per year	39,500	–76%
Parking cost per year	Depending on city[c]	0
Inspection cost per year	7,500	260%
Maintenance cost per km	1.74	–25%
Tire cost per km	1	–25%
Fuel cost per km	6.16	–5%
Other values[b]		
Interest rate (%)	2.65	1.5
Credit period (year)	5	3
VAT (%)	8	8
Vehicle lifetime year (km for taxis)	12.91	431,760
Driver's salary per hour (JPY)	—	Depending on city [c]
Overhead cost per day (JPY)	—	2,430
Cleaning price (JPY)	1,950	1,950
Cleaning frequency per year (per trip for taxis)	8	0.025

Acquisition: JPY 2,470,000 for new car price; JPY 11,350 for car recycling costs (deposit on purchase); JPY 19,500 for an eco-friendly car tax decrease in the first year after purchase only (MLIT, 2018d).
Insurance: JPY 12,000 for mandatory automobile liability insurance for private passenger cars (660 cc +), where JPY 35,950 (valid 3 years) is divided by 3 years; JPY 60,000 for the average cost of fully comprehensive insurance for Prius (Kakaku.com, 2018).
Tax: Car tax for private passenger cars with a 1500–2000 cc engine. The model (DAA-ZVW50) is currently exempt from the car acquisition tax (a one-time payment) and tonnage tax (annual payment) through eco-car tax breaks (MLIT, 2018d; TMG, 2018a); the car tax is JPY 9500 for commercial passenger cars with a 1500–2000 cc engine (TMG, 2018a).
Parking: Vehicle (both private and commercial) owners must have garages for their cars as per the garage law; thus, no large increase is expected for commercial fleet operators.
Inspection: A mandatory motor vehicle inspection is required 3 years after a new car purchase and every 2 years after the first inspection for private passenger cars. The average inspection cost for a Prius is JPY 19,510 (Rakuten Shaken, 2018). The inspection is required 5 times in 12.9 years (the average lifetime); thus, a weight of 5/13 is given to JPY 19,510. A mandatory motor vehicle inspection is required every year for commercial passenger cars.
Maintenance: JPY 174,000/100,000 km is assumed (Freeb. Co., 2018).
Tires: JPY 50,000/50,000 km is assumed. This value is approximately the same as the tire cost per km for passenger cars in the cost-benefit analysis manual for road projects in Japan (MLIT, 2018a, 2008).
Fuel: JPY 135/liter for gasoline price. 21.9 km/liter for actual fuel consumption of the model (DAA-ZVW50) (e-Nenpi, 2018).
[a] Toyota Prius (DAA-ZVW50) values. Toyota Prius was the best-selling car in the 2017 sales of new cars with a 660 cc + engine in Japan (Japan Automobile Dealers Association, 2018).
[b] The sources are summarized as follows: interest rate for a private car loan (Tokyo Tomin Bank, 2018); average lifetime (in kilometers) of taxis in Tokyo Prefecture (Tokyo Hire-Taxi Association, 2017); average lifetime (in years) of passenger cars (660 cc +) in Japan (Automobile Inspection & Registration Information Association, 2017); cleaning frequency (Bösch et al., 2018); cleaning price for mid-size vehicles (KeePer Technical Laboratory, 2018). Overhead costs are derived by JPY 9.79/km for operators with 100 vehicles or more (MLIT, 2016), multiplied by a taxi vehicle distance of 248.2 km per day (Tokyo Hire-Taxi Association, 2017), Note that Bösch et al. (2018) estimate USD 10.24 for overhead costs and USD 8.39 for vehicle management costs per vehicle per day for operators with 150 vehicles or more in the United States, concluding that these values are relatively stable for operators with a large fleet. The Japanese accounting of overhead costs includes these two cost categories.
[c] Table A2 provides the specific value in each city category.

Table A2
Vehicle costs and other values in each city category (for taxis and private cars).

Vehicle costs and other values	Major MAs			Regional core MAs		Regional large MAs		Regional small MAs	
	Cent.	Near Peri.	Peri.	Cent.	Peri.	Cent.	Peri.	Cent.	Peri.
Parking cost per year (in thousand JPY)[a]	195	137	84	140	75	79	61	83	54
Insurance cost (taxi premium)[b]	361%	267%	267%	361%	235%	309%	267%	267%	235%
Driver's salary per hour (in thousand JPY)[c]	1.48	1.48	1.48	1.27	1.25	1.20	1.28	1.14	1.25

The table shows the average of all cities included in each city category (sampled cities follow those in Table 2).
[a] Average parking cost in each city is collected from Nippon Parking Development (2018).
[b] Average insurance cost of a taxi (in four city categories) is obtained from the MLIT (2016).
[c] Average driver's salary in the prefecture that includes each city is obtained from the Japan Federation of Hire-Taxi Associations (2017).

Table A3
Operating patterns in each city category (for taxis and private cars).

Operating patterns	Major MAs			Regional core MAs		Regional large MAs		Regional small MAs	
	Cent.	Near Peri.	Peri.	Cent.	Peri.	Cent.	Peri.	Cent.	Peri.
Taxi (all-day average)									
Vehicle operation hours per day[a]	19.4								
Total hours traveled (incl. carrying and not carrying passengers)/ operation hours (%)[b]	54.0	46.3	42.0	42.0	42.0	39.3	27.0	32.7	28.6
Travel speed (km/h)[c]	21.8	21.9	22.8	22.7	22.8	22.3	27.9	23.7	27.3
Kilometers carrying passengers/total kilometers traveled (%)[b]	44.2	45.3	42.6	39.2	39.0	41.8	41.7	40.1	41.9
Occupancy (%)[b]	34.7	34.4	35.6	35.1	35.3	36.3	36.5	37.4	37.3
Ride-sharing occupancy (%)[d]	60.0								
Passenger trip length (km)[b,e]	3.76	3.96	3.89	3.45	3.46	3.79	3.88	3.83	3.93
Private passenger car (peak, non-peak, night hours)[f]									
Travel time expenditure (min)[c]	32.0, 30.2, 28.7	30.7, 23.5, 27.0	26.2, 32.3, 23.6	30.3, 19.8, 27.0	26.8, 98.1, 22.5	27.0, 15.3, 24.0	23.9, 62.3, 21.7	25.7, 17.8, 23.0	24.2, 78.5, 21.3
Travel speed (km/h)[c]	21.7, 20.4, 22.3	21.8, 21.5, 21.0	22.8, 21.6, 22.0	22.6, 23.1, 21.4	22.8, 21.6, 22.0	22.3, 22.0, 22.0	27.8, 25.9, 26.1	23.6, 22.2, 22.0	28.3, 26.8, 26.8
Occupancy (%)[c]	25.9, 27.4, 25.4	26.6, 27.8, 26.7	26.4, 26.8, 27.0	26.5, 26.6, 25.8	26.4, 26.8, 27.0	26.0, 26.8, 26.8	26.8, 27.0, 26.5	25.8, 25.8, 26.0	26.0, 26.4, 26.3
Trip length (km)[c]	14.1, 10.7, 12.3	12.8, 11.3, 11.3	11.3, 9.50, 9.92	12.7, 12.0, 10.7	11.3, 9.50, 9.92	11.8, 10.9, 10.8	12.3, 11.4, 10.9	12.1, 10.4, 10.4	13.2, 12.4, 11.3

The table shows the average of all cities included in each city category (sampled cities follow those in Table 2).

[a] Taxi drivers' 20-hour working system includes three hours to rest, and one hour per day is assumed to be for maintenance.

[b] The average value in the prefecture that includes each city is obtained from the Japan Federation of Hire-Taxi Associations (2017). Original data for vehicle utilization rates in hours have been modified to account for city-level operations.

[c] Each city's average value is obtained from the results of the National Person Trip Survey (MLIT, 2015), and is the individuals' weighted average. Trips made by private passenger cars in a weekday are considered.

[d] Bösch et al. (2018).

[e] To count the number of cleanings for taxis.

[f] Peak hours are 7:30–9:30 and 17:30–19:30; off-peak hours are 9:30–17:30; night hours are 19:30–7:30. Trips starting or ending in the period are considered.

Table A4
Fares and operating performance (for railways and buses).

Fares and operating performance	Rail [a]				Bus [b]	
	Rapid rail transit in major MAs			Regional rail	Major MAs	Regional MAs and rural
	All	Subway only	Suburban rail only			
Average fare per passenger km (JPY; inclusive of season ticket discounts)	**14.3**	19.0	12.7	**24.5**	**36.8**	**36.0**
Operating revenue per passenger km (JPY)	16.0	21.3	14.1	30.0	39.0	37.8
Operating cost per passenger km (JPY)	**13.1**	17.2	11.6	**32.4**	**38.5**	**43.6**
Operating revenue per revenue vehicle km (JPY)	827.8	1223.6	707.0	NA	557.2	292.5
Operating cost per revenue vehicle km (JPY)	677.4	988.7	582.4	NA	550.2	337.2

[a] Rail indicators are computed from data in the MLIT (2017b) and the JTTRI (2017). The average fare and operating performance are averaged for all lines (operated by public agencies or private companies) in each rail category. The rail category follows the MLIT's (2017b) definition. JR, tourism, freight, and streetcar lines are not included. The fare includes regular fares, and not express fares. The operating cost includes capital depreciation as well as overhead costs. Four rapid rail operators in the regional MAs are not included. Average fare is the fare revenues divided by the passenger-km.

[b] Bus indicators are computed primarily from data in the MLIT (2016, 2018b) and Nihon Bus Association (2017). The operating performance is averaged for all bus lines (operated by public agencies or private companies) in each area. Chartered bus services and streetcar lines are not included.

The national average of bus fare rates is JPY 40.1 per km for operators holding 30 vehicles or more. This value is provided by an official notification system from each bus operator to the government. Note that each operator defines the fare to each zone by utilizing its fare rate, even though the operator uses a zonal fare system.

As regional average fare values are not available in the statistics, they are estimated with the national average value and the following data: the fraction of season-ticket passengers to all passengers in each area (0.25 in the major MAs and 0.31 in other areas; MLIT, 2019a) and the average discount rates for bus commuting and schooling season tickets (33% based on data from JTTRI, 2017; MLIT, 2015).

The computation of operating revenues and costs per passenger-km based on those per revenue vehicle km requires data on the average ridership (passenger-km per revenue vehicle km). First, the fraction of fare revenues to operating revenues (0.942 in the major MAs and 0.951 in other areas for public buses; MIC, 2019) are applied to operating revenues per revenue vehicle km. The obtained fare revenues are then divided by the average fare. Consequently, the computed average ridership is 15.9 in the major MAs and 8.9 in other areas.

The drivers' salaries and overhead labor costs are 56.7% of the total operating costs in the major MAs and 57.0% in other areas. The national average of overhead labor costs is 3.6% of the total operating costs; this value is used to separate the share of labor costs for bus driving.

Table A5
Travel speed.

Travel speed by mode (km/h)	Major MAs			Regional core MAs		Regional large MAs		Regional small MAs	
	Cent.	Near Peri.	Peri.	Cent.	Peri.	Cent.	Peri.	Cent.	Peri.
Taxi[a]	21.8	21.9	22.8	22.7	22.8	22.3	27.9	23.7	27.3
Bus[b]	13.0	13.0	13.0	20.0	20.0	20.0	20.0	20.0	20.0
Urban rail[b]	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Private passenger car[a]	21.8	21.9	22.8	22.7	22.8	22.3	27.9	23.7	27.3

[a] The individuals' weighted averages of private passenger car trips in each city are obtained from the results of the National Person Trip Survey (MLIT, 2015).

[b] The overall (all-day average) travel speeds are obtained from scheduled speeds (in the timetable); bus travel speeds are the network averages of a representative bus operator, while train travel speeds are the averages in a representative rail line.

Table A6
Value of travel time savings.

VTTS by travel attribute (JPN/min)	Non-business travel	Business travel
In-vehicle time (all distances)		
Taxi[a]	24.6	43.4
Bus[a]	24.6	43.4
Urban rail[b]	30.1	43.2
Private passenger car[a]	28.5	43.4
Waiting and transfer time[b]	53.9	68.8
Walking and cycling time for access to stations[b]	32.9	37.8

[a] The VTTSs (in 2017 prices) of taxi and bus passengers and those of private car drivers are obtained from the MLIT (2018a, 2008) and are the national averages.

[b] The VTTSs of urban rail in-vehicle, waiting, and transfer times are obtained from the rail route choice model, and those of walking and cycling are obtained from the access mode choice model to train stations in the Tokyo MA's rail demand forecast model (MLIT, 2017c), in which an average value of commuting and leisure VTTSs is regarded as a non-business value. Waiting and transfer VTTSs are obtained as an average of VTTSs of vertical, horizontal moves for transfer, and waiting times in train stations. In the walking and cycling VTTSs, the height differences in a walking/cycling course are controlled for.

Appendix B. Validation of computed taxi operating costs

See Fig. A1.

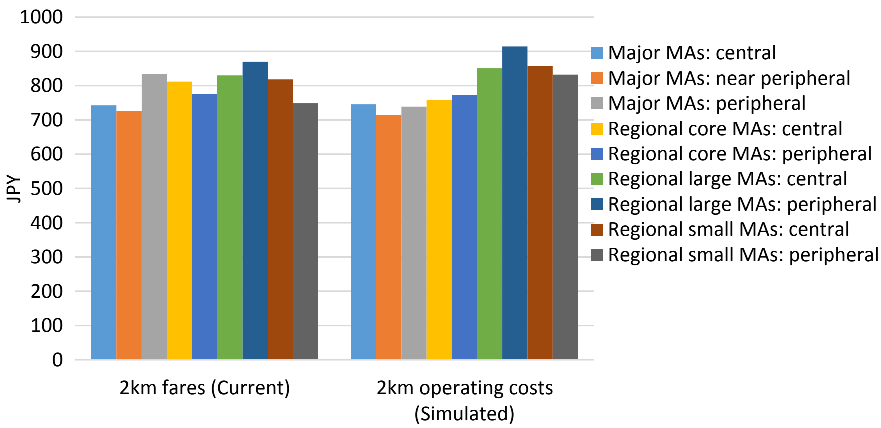

Fig. A1. Current taxi fares and computed taxi operating costs. *Note:* Fares in each city are collected from Taxisite (2018), where a VAT of 8% is included. The computed taxi costs are those per passenger-kilometer (Fig. 1), multiplied by two kilometers and the average occupancy in each city category (Table A3).

Appendix C. Trip costs with and without vehicle automation for non-business travel

See Figs. A2–A4.

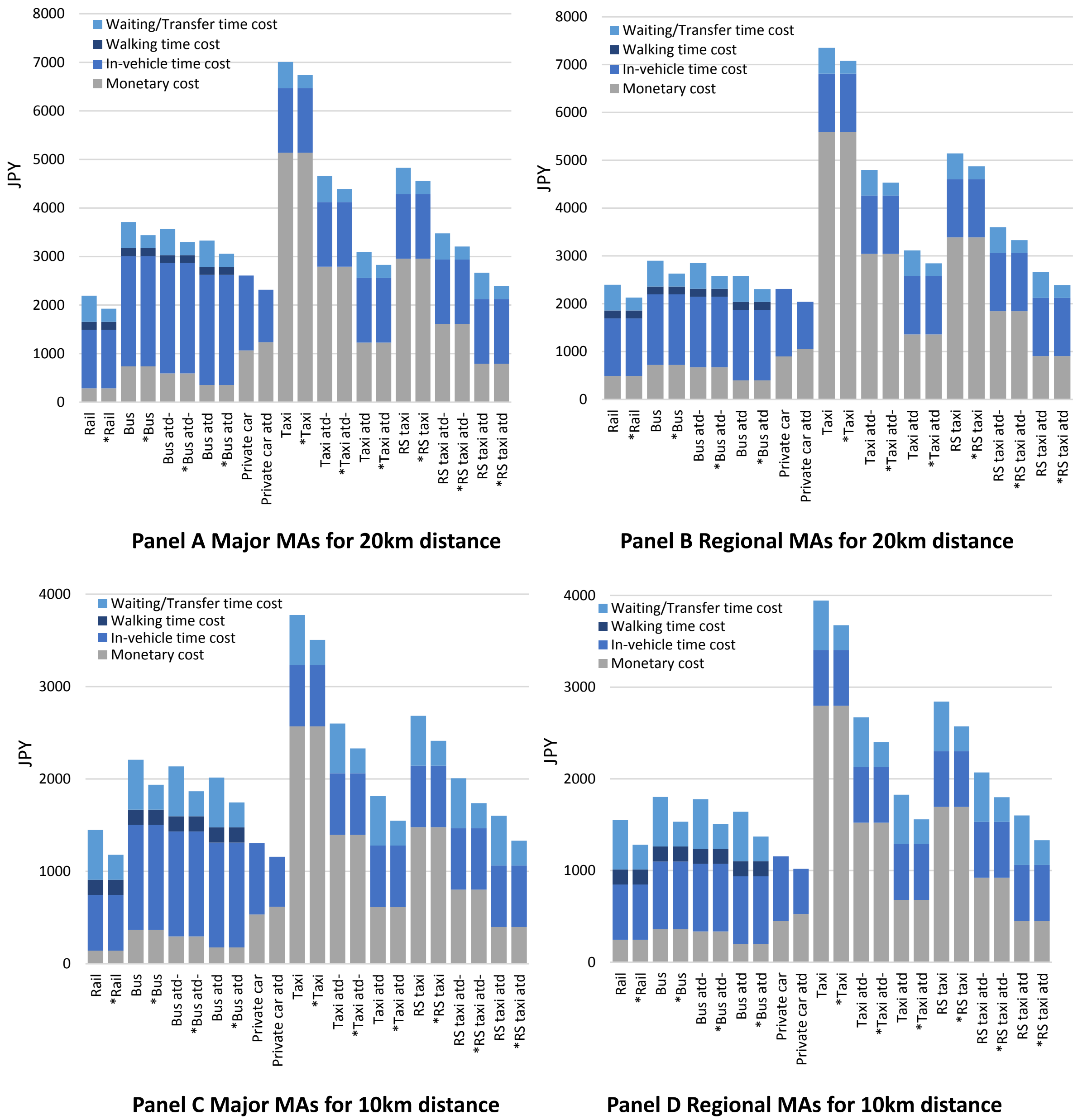

Fig. A2. Trip costs with and without vehicle automation in non-business travel for those living in a 5-min (400 m walk/1250 m cycling) distance from transit stations in trunk lines. *Note:* atd = autonomous; atd- = autonomous transitional (1:1.66 case); RS = ride-sharing. The costs of 5- or 10-min total waiting and transfer times are incorporated in the trips involving rail, bus, or taxi (with and without ride-sharing) stages; * = 5 min; non-asterisk = 10 min. The costs of five-minute walking/cycling times are incorporated in the trips involving rail or bus stages.

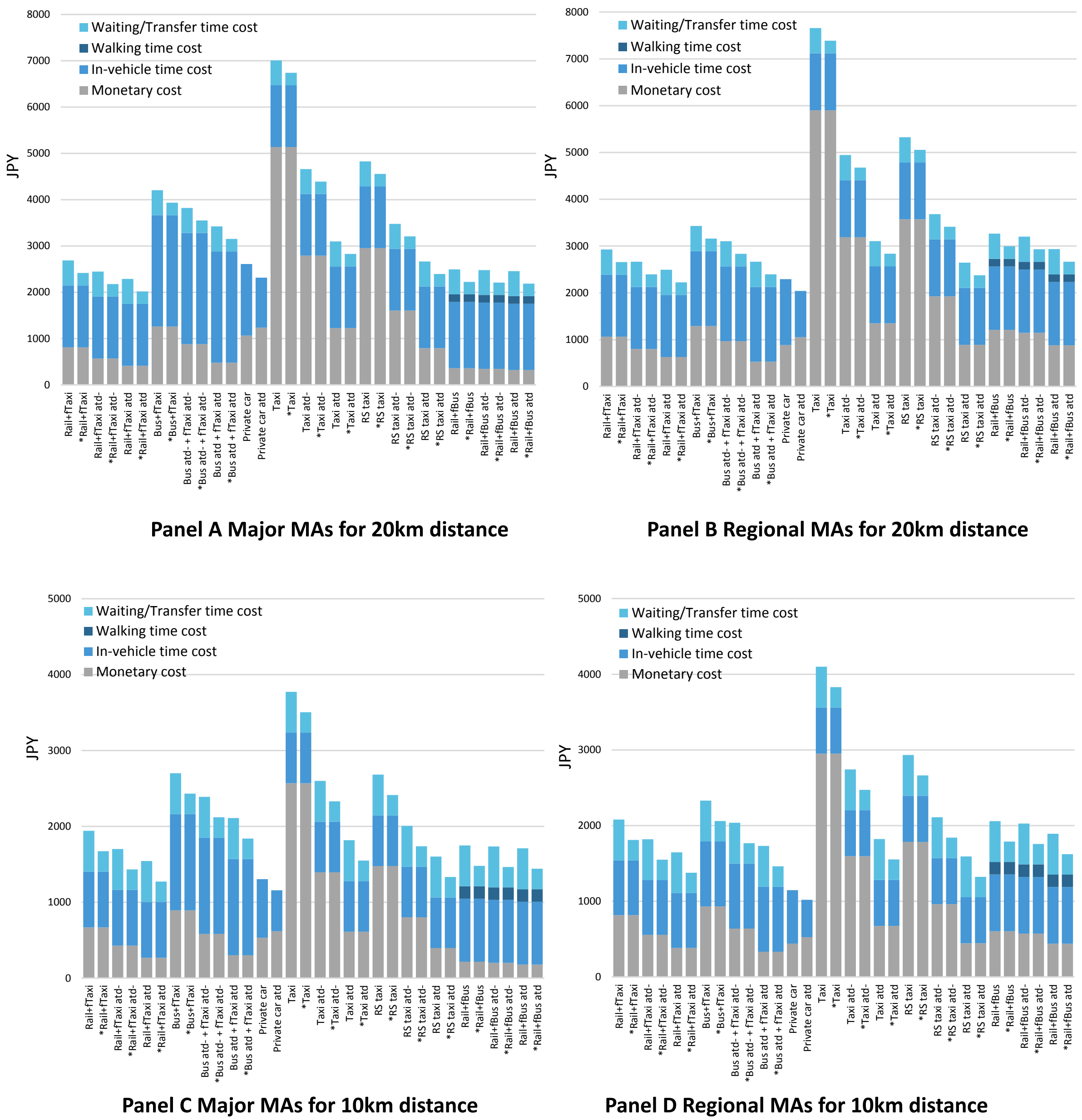

Fig. A3. Trip costs with and without vehicle automation in non-business travel for those living in a two-kilometer distance from transit stations in trunk lines. *Note:* atd = autonomous; atd- = autonomous transitional (1:1.66 case); f = access mode; RS = ride-sharing. The costs of 5- or 10-min total waiting and transfer times are incorporated in the trips involving rail, bus, or taxi (with and without ride-sharing) stages; * = 5 min; non-asterisk = 10 min. The costs of five-minute walking/cycling times are incorporated in rail trips with bus access. The actual length is 10 or 20 km for private car and taxi (with and without ride-sharing) trips, while this is 12 or 22 km for other trips.

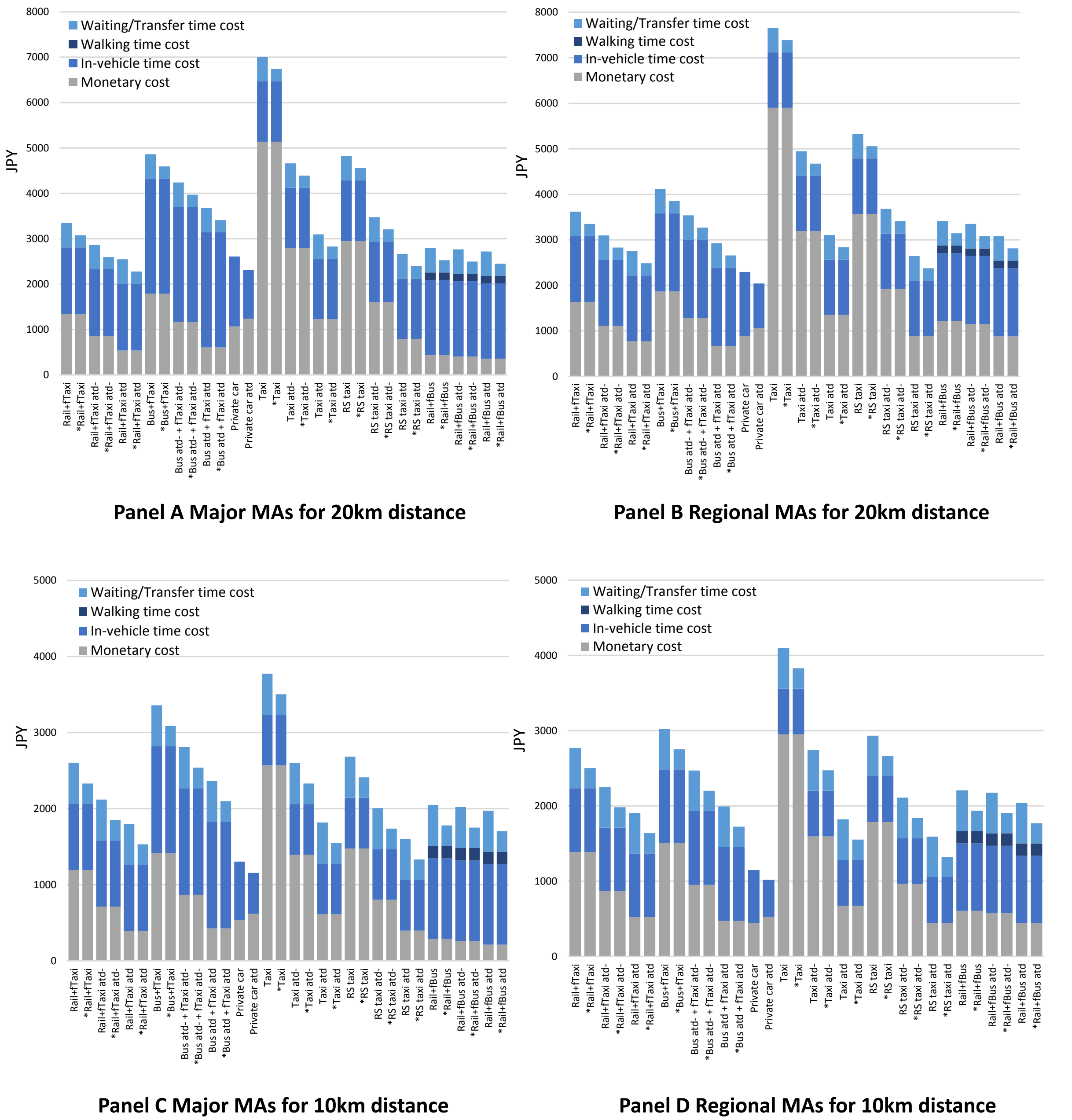

Fig. A4. Trip costs with and without vehicle automation in non-business travel for those living in a four-kilometer distance from transit stations in trunk lines. *Note:* atd = autonomous; atd- = autonomous transitional (1:1.66 case); f = access mode; RS = ride-sharing. The costs of 5- or 10-min total waiting and transfer times are incorporated in the trips involving rail, bus, or taxi (with and without ride-sharing) stages; * = 5 min; non-asterisk = 10 min. The costs of five-minute walking/cycling times are incorporated in rail trips with bus access. The actual length is 10 or 20 km for private car and taxi (with and without ride-sharing) trips, while this is 14 or 24 km for other trips.

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