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Bottom-up development of passenger travel demand scenarios in Japan considering heterogeneous actors and reflecting a narrative of future socioeconomic change

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ABSTRACT

This paper provides a framework and procedure for developing mobility demand scenarios based on daily time use and service intensity of time use, and constructs a passenger travel demand scenario in Japan as a case study. Regarding long-term scenario development, construction of demand scenarios starting from daily life behavior has the potential to capture socioeconomic change transparently, comprehensively, and consistently. We applied this idea to consider the impacts of socioeconomic and technological changes on service demand from the perspective of change in time use. The current status of mobility demand in Japan was analyzed and its structure was reconstructed based on relevant national statistics. Contrasting future passenger travel demand scenarios in Japan, that is, low demand and high accessibility, were developed in accordance with qualitative scenarios and quantitative assumptions of four mega-trends: an aging population, gender equality, tertiary industrialization, and transport technology innovation. This framework enables a systematic and transparent reflection of a narrative of long-term service demand scenario development by considering heterogeneous actors.

1. Introduction

A drastic transition in energy systems, which involves not only decarbonization in supply sectors but also the transformation of systems in end-use sectors, is essential to achieve the long-term targets of the Paris Agreement (UNFCCC, 2015). Previous studies emphasize a faster scale-up of mitigation actions in many energy supply sectors through energy efficiency improvement, fuel switching, and large-scale deployment of negative emission technologies for scenarios that limit global warming to 1.5 ℃ (e.g., Rogelj et al., 2015). Recently, a low energy demand scenario poses an alternative to stringent mitigation scenarios by developing a narrative of future change that focuses on end use and end users based on observable trends (Grubler et al., 2018). Demand-side solutions to mitigate climate change are urgent research questions for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (Creutzig et al., 2018).

In 2016, the transportation sector accounted for 24 % of global carbon dioxide (CO_2) emissions from fuel combustion (IEA, 2018). Although this sector was considered one of the bottlenecks to decarbonization (IPCC, 2014), emerging mobility innovation induced by self-driving vehicles, sharing vehicles, electric vehicles, and mobility-as-a-service, and so on, is creating expectations of disruptive change. Recent studies identified the potential for deep CO_2 emissions reductions from urban passenger transport as a consequence of significant decreases in vehicle travel distances in urban areas (e.g., OECD/ITF, 2019).

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Most global transport-energy models cannot address a potential drastic change in mobility systems because they estimate travel demand in a top-down fashion based on population, GDP, and technology costs (Girod et al., 2013; Yeh et al., 2017). These models calculate future travel demand based on empirical relationships among passenger travel demand, income, vehicle and fuel costs, and value of time. Therefore, existing methodological frameworks used in the global transport-energy models cannot envisage drastic behavioral change in future mobility demand induced by disruptive mobility service developments driven by technology innovation and urban development.

Lowering final energy consumption is a key strategy to navigate the world to rapid decarbonization pathways (Grubler et al., 2018). Energy demand is affected by both socioeconomic and technological factors such as population, income, economic structure, energy efficiency of equipment, and way of using appliances. CO_2 emissions reduction could be achieved by energy demand reduction which is induced by not only end-use technology development thanks to digitalization such as AI, IoT and big data but also socioeconomic change such as urbanization, population aging and gender equality. However, existing literature has not shown consistent end-use demand scenarios yet. In order to better understand energy demand by heterogeneous countries and people, a new concept of bottom-up framework for constructing demand scenarios which explicitly considers both socioeconomic change and technology development is required.

Energy consumption is a resulting event to meet service demand which is eventually generated to fulfill/increase people's utility, not an objective per se. With regard to long-term future scenario development, construction of demand scenarios starting from people's daily life behavior or living activities has a potential to capture socioeconomic change transparently, comprehensively and consistently. Impacts of socioeconomic change of social structure and technological progress on occurrence of society's service demand can be captured from the perspective of society's time use change.

Here, narrative can be used to describe storylines of socioeconomic and technological change in future. In global climate change research, Shared Socioeconomic Pathways have been developed by using narratives of motivating forces, policies, institutional and social conditions, human development, economy and lifestyle, population and urbanization, technology, and the environment and resources to illustrate different socioeconomic development (O'Neil et al., 2017). Narrative is useful not only to assume consistent parameters set for models but also to communicate with policy-makers about scenarios.

This study provides a bottom-up method for constructing demand scenarios, starting from people's daily life behavior. We presents a framework and procedure for developing mobility demand scenarios based on daily time use and service intensity of time use, and constructs a case study scenario of passenger travel demand in Japan. First, the current status of mobility demand in Japan is analyzed and its structure, and mobility demand as a heterogeneous actor, are reconstructed based on relevant national statistics. Second, a narrative of mega-trends in Japan is developed and their assumed impacts are quantified. Third, future passenger travel demand scenarios are constructed in accordance with qualitative scenarios and quantitative assumptions of four mega-trends.

2. Methodology

2.1. Framework for assessing passenger travel demand

Travel needs can be divided into personal movement (e.g., commuting) and obtaining goods or services. The structure of a city affects the relative costs of transportation systems and their availability and accessibility. By contrast, personal characteristics determine heterogeneous travel and time preferences (or habits) and travel budgets. These components all influence travel modal choice and needs. Policy (e.g., regulations) and technological change modify established patterns of activity and spatial-temporal constraints (Gershuny, 2000).

Fig. 1 presents our framework for assessment of passenger travel demand. We mainly focus on travel within daily life, which has a strong relationship with daily life behavior. As shown in Fig. 2, we set 160 representatives to simulate heterogeneous actors that have different personal attributes in terms of region (residence), sex, age, employment status, and occupation. Travel distance by purpose and mode is directly connected to travel time by purpose and mode for each representative actor. Total passenger travel demand is calculated as the sum of the total travel distance of a representative multiplied by the number of representatives.

2.2. National statistics regarding mobility demand

We collected national statistics on population, time use, trip distance, trip rate, and trip time by walk, bicycles, motor transport, rail, and so on. Table 1 presents an outline of national statistics regarding mobility in Japan.

2.3. Reconstruction of current mobility demand in Japan

The current structure of mobility demand in Japan was estimated as follows:

Total travel demand (person-km/yr) = Total travel demand within daily life area (person-km/yr) + Total travel demand outside daily life area (person-km/yr) (1)

Total travel demand within daily life area (person-km/yr) = $\Sigma_{R,\ P,\ M}$ (Travel demand within daily life area $_{R,\ P,\ M}$ (km/yr) × Population $_{R}$ (person)) (2)

Travel demand within daily life area $_{R,\ P,\ M}$ (km/yr) = Trip rate $_{R,\ P,\ M}$ (trip/yr) × Trip distance $_{R,\ P,\ M}$ (km/trip) = Trip rate $_{R,}$

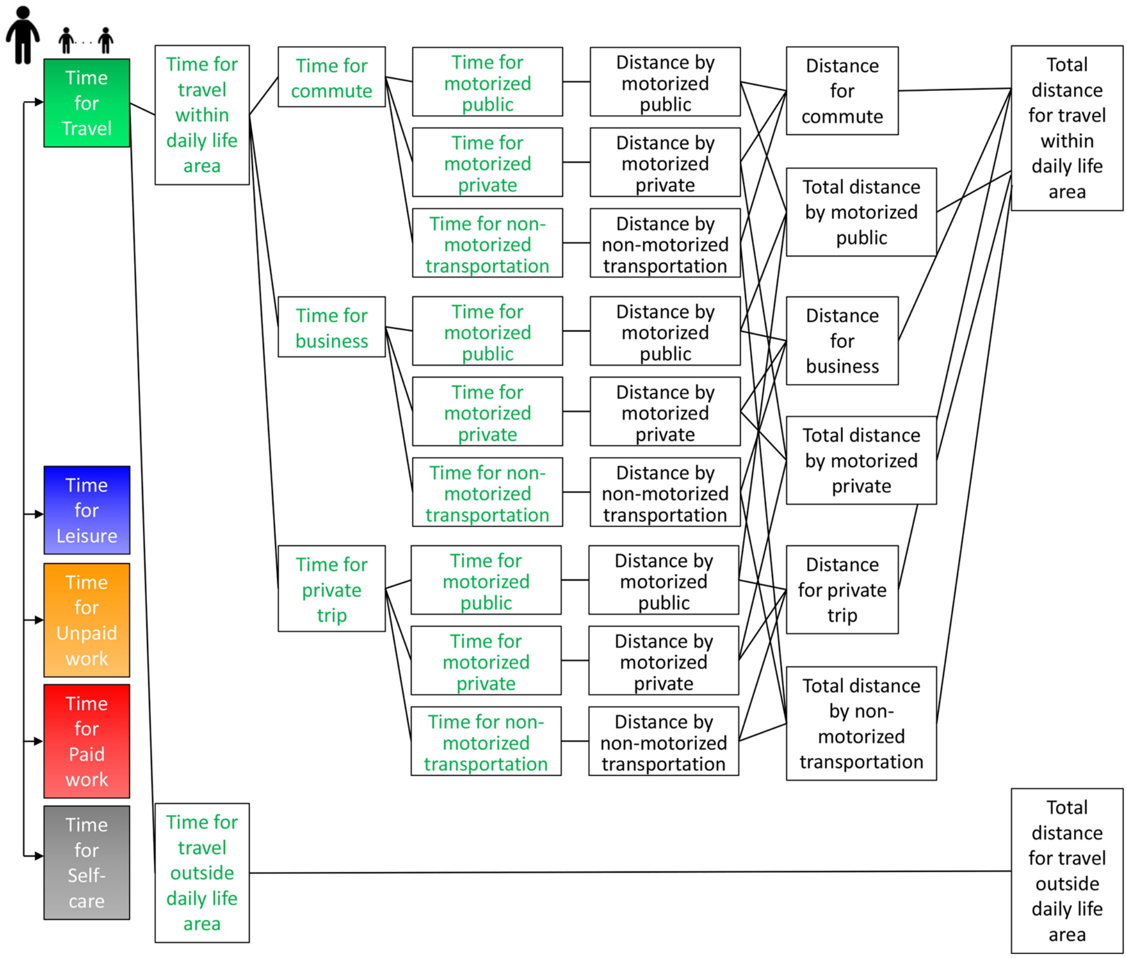

Fig. 1. Framework for the assessment of passenger travel demand.

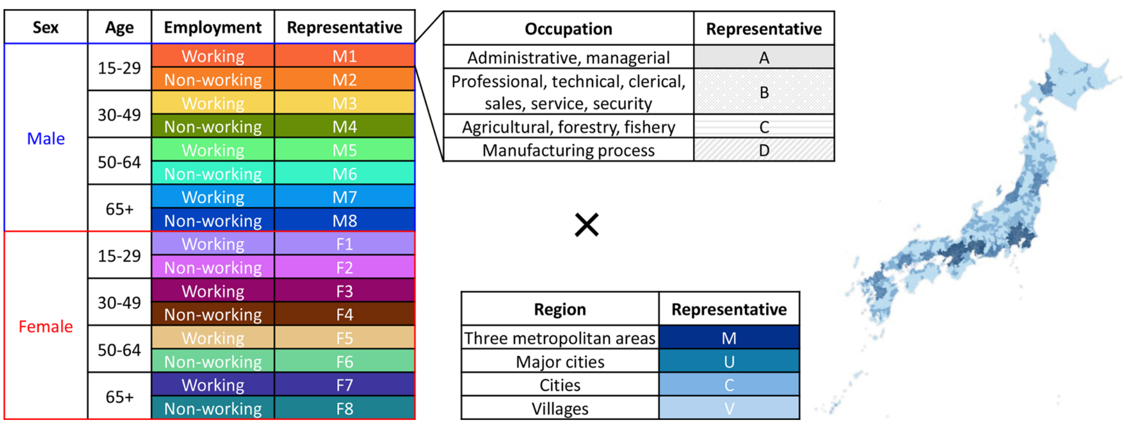

Fig. 2. Personal attributes of representatives.

$$_{P,\,M}\ (\text{trip/yr}) \times \text{Trip time}_{R,\,P,\,M}\ (\text{h/trip}) \times \text{Travel speed}_{R,\,M}\ (\text{km/h}) = \text{Travel time}_{R,\,P,\,M}\ (\text{h/yr}) \times \text{Travel speed}_{R,\,M}\ (\text{km/h}) \tag{3}$$

where R refers to personal attributes (region, sex, age, employment, occupation), P is trip purpose (commuting, work, private trip), and M is travel mode (non-motorized transportation (NMT), motorized private, motorized public).

Although Japan's national statistics cover various dimensions of mobility demand, their attribute resolution is not sufficient. We

Table 1
Japan's national statistics regarding mobility.

Statistics	Year	Target	Data used in this study
Population Census (Statistics Bureau, Ministry of Internal Affairs and Communications (2016))	2015 Oct	All citizens	Population Place of work Commuting employed persons and persons attending school
Survey on Time Use and Leisure Activities (Statistics Bureau, Ministry of Internal Affairs and Communications (2017))	2016 Oct	200,000 people	Time for commuting Time for other travel
Nationwide Person Trip Survey (City Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2018))	2015 Oct–Nov	70 cities (500 households per city) Rank of trip distance Average travel time	Average trip rate
Metropolitan Traffic Census (Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2017))	2015 Nov–Dec	Railways: 2.3 million people Buses: 30,000 people	Population using railways Access/egress traffic to stations Travel time distribution for commuting by railways Inter-block flow by railways
Road Traffic Census (Ministry of Land, Infrastructure, Transport and Tourism (2018))	2015 Autumn	National expressways: 8,687km City highways: 787km National roads: 55,685 km Prefectural roads: 129,003km	Purpose of trip Trip distance Passenger-kilometer Average speed Number of passengers
Survey on Motor Vehicle Transport, Railway Transport, Air Transport (Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2018a), Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2018b), Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2018c))	2016	Business operators	Passenger-kilometer by motor vehicles, railways, aircrafts

therefore assumed distributions among representatives to explicitly identify travel demand, trip rate, trip distance, trip time, travel speed, and travel time for each representative.

We estimated current mobility demand in Japan as follows. First, data directly available from the national statistics is: population by representative; trip rate by trip purpose and travel mode by region, sex, age; travel time by trip purpose by representative; travel demand by region, sex and age. Second, we assumed inter-occupation distribution for trip rate and travel time by travel mode. Third, travel speed by travel mode by region was calculated based on population-weighted average travel demand and travel time. Fourth, Travel demand, trip distance and trip time by trip purpose and travel mode by representative were obtained from trip rate and travel time by trip purpose and travel mode by representative and travel speed by travel mode by region. Finally, travel speed by travel mode by region was calibrated for total travel demand within daily life area by travel mode calculated by Eq. (2) to match that of the national statistics. In addition, we assumed that year-to-year change among the national statistics presented in Table 1 is sufficiently small and all statistics represent socioeconomic characteristics in 2015 − 16.

2.4. A narrative of mega-trends in Japan for future mobility demand scenarios

The following four mega-trends for future mobility demand scenarios in Japan were developed in this study: I Population Aging, II Gender Equality, III Tertiary Industrialization, IV Transport Technology Innovation. Population Aging indicates change in population structure and increase in employment rate for people aged 65 and over in order to compensate decrease of labor population in future. Gender Equality includes increase in employment rate and administrative positions for women and convergence of allocation of time for different living activities between men and women. Tertiary Industrialization represents a shift in the workforce from blue-collar workers to white-collar workers due to the fourth industrial revolution and digitalization. Mega-trends I, II, and III represent socioeconomic change. Mega-trend IV corresponds to technological change in mobility especially that induced by self-driving vehicles. We considered two contrasting scenarios for future mobility demand, that is, mega-trend IV-A (Low Demand) and IV-B (High Accessibility). Low Demand includes decrease of specific trip demand by some representatives thanks to digitalization of living activities. On the other hand, High Accessibility contains increase of usage of motorized private transportation due to the improvement of utility of automobiles.

Table 2 presents scenarios and corresponding quantitative assumptions. We changed applicable terms in Eq. (3) according to the scenarios. For each scenario, we assumed two levels of change of the corresponding term.

3. Results

3.1. Current structure of passenger travel demand in Japan

Fig. 3 shows total passenger travel demand by distance, region, sex, age, employment, purpose, and mode of transportation in

Table 2
A narrative of four mega-trends in Japan for future mobility demand scenarios.

Mega-trend			Scenario	Quantitative assumption: Description	Quantitative assumption: (X, Y, Z) in description for High (H) and Low (L) cases
I Population Aging	a		Change in population structure by region, sex, and age.	Population by region, sex, age in 2050 is calculated based on population projection by the National Institute of Population and Social Security Research (National Institute of Population and Social Security Research (2017), National Institute of Population and Social Security Research (2018)).	–
	b		Increase in employment rate for people aged 65 and over.	Decrease in the non-employment rate for people aged 65 and over by X%. Share of occupation of incremental workers is set as the same as that in 2015-16.	H: 50 L: 20
II Gender Equality	a		Increase in employment rate and administrative positions for women.	Non-employment rates of women aged 30-49, 50-64, 65 and over become X, Y, Z, respectively.	H: (1/3, 1/2, 3/4) L: (3/4, 4/5, 5/6)
	b		Convergence of gender difference of trip purpose by mode.	Difference in trip rate and trip distance between men and women aged 15-29 or 30-49 converge by X. Those between men and women aged 50-64 or 65 and over converge by Y.	H: (1/3, 1/4) L: (1/4, 1/5)
III Tertiary Industrialization			Shift from blue-collar to white-collar workers.	X% of population of Occupation C and D moves to Occupation B. Y% of population of Occupation B moves to Occupation A.	H: (50, 5) L: (30, 5)
IV Transport technology innovation	Common	a	Increase in preference for motorized private transport due to distribution of self-driving vehicles.	Trip rate by motorized private transportation by purpose and mode increases by X%. Trip rates by NMT and motorized public transportation decrease equally to keep the total trip rate constant.	H: (20, 10)
				Trip distance by motorized private transportation by purpose increases by Y%.	L: (10, 3)
		b	Increase in travel speed by motorized private transportation due to efficiency improvement in traffic flow by distribution of self-driving vehicles.	Travel speed by motorized private transportation increases by X % in Region U, C, and V.	H: 20 L: 10
	A Low Demand	a	Decrease in effective travel speed by motorized private vehicles due to waiting time for sharing vehicles.	Travel speed by motorized private transportation decreases by X %.	H: 20 L: 10
		b	Decrease in private trip demand due to increase in online shopping and leisure at home.	Trip rate for private trip by mode decreases by X%.	H: (20, 30, 10)
		c	Decrease in commuting trip demand by employed people due to increase in teleworking for white-collar workers.	Trip rates of commuting trip by mode for Occupation A and B decrease by Y%.	L: (5, 10, 5)
		d	Decrease in commuting trip demand by students due to e-Education.	Trip rate of commuting trip by mode for Non-working aged 15-29 decreases by Z%.	

(*continued on next page*)

Table 2 (*continued*)

Mega-trend		Scenario	Quantitative assumption: Description	Quantitative assumption: (X, Y, Z) in description for High (H) and Low (L) cases
	e	Increase in trip demand by NMT in cities for health improvement.	Trip rates of commuting trip by motorized private and motorized public transportation decrease by X%, and that by NMT increases to keep the total commuting trip rate constant.	H: (10, 20)
			Trip rates of private trip by motorized private and motorized public transportation decrease by Y%, and that by NMT increases to keep the total private trip rate constant.	L: (5, 10)
	f	Increase in trip demand by motorized public transportation and decrease in trip distance in cities due to compact urban design.	Trip rate by motorized private transportation by purpose in Region M and U decreases by X%, and that by motorized public transportation increases to keep the total trip rate constant.	H: (30, 20)
			Trip distances by motorized private and motorized public transportation decrease by Y%.	L: (20, 10)
B High Accessibility	a	Increase in private vehicle ownership due to increase in preference for on-demand trips and shift from trips by motorized public transportation to those by motorized private transportation.	Trip rate and travel demand by motorized public transportation by purpose decrease by X%, and those by motorized private transportation increase to keep the total trip rate and travel demand constant.	H: 50 L: 20
	b	Increase in travel speed due to intelligent transport systems. On the other hand, travel speed by motorized private transportation decreases in city centers due to traffic congestion caused by increase in private vehicles.	Travel speed by motorized public and that by NMT increase by X %. Travel speed by motorized private transportation in Region M decreases by Y%, and that in Region U, C, and V increase by Z %.	H: (10, 30, 10) L: (5, 10, 5)
	c	Expansion of urban areas due to the improvement of utility of motorized private and public transportation on the move.	Trip distance by motorized private transportation and that by motorized public transportation by purpose increase by X%.	H: 20 L: 10
	d	Shift in access/egress traffic from non-motorized to motorized private transportation.	Trip rate and travel demand of NMT by purpose decrease by X%, and those by motorized private transportation increase to keep the total trip rate and travel demand constant.	H: 30 L: 15

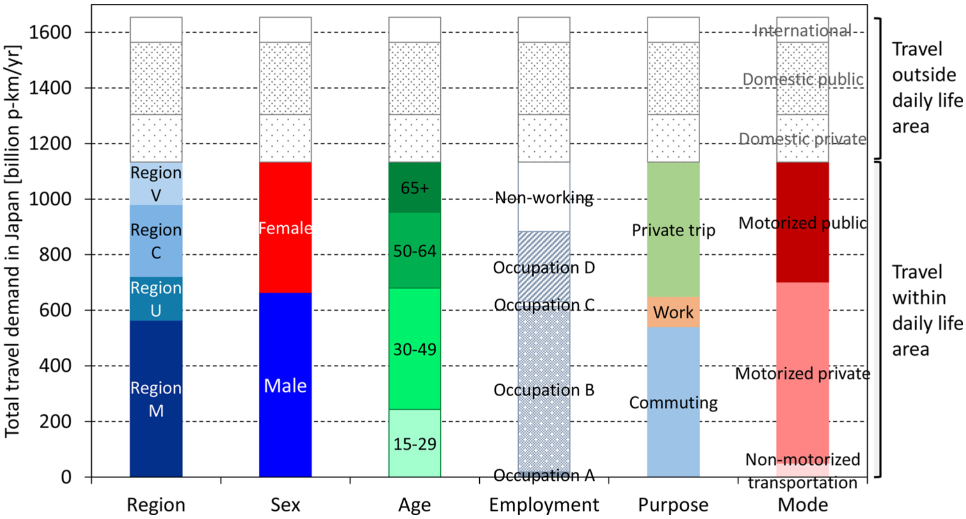

Fig. 3. Total passenger travel demand in 2015–16.

Japan from 2015 to 16. Travel within and outside daily life area are 1133 billion person-km/yr and 521 billion person-km/yr, respectively. People living in three metropolitan areas account for about 50 % of all travel within daily life area. Passenger travel for daily life is about 1.4 times longer for men than for women. Travel demand for commuting, work, and private trips is estimated to be 541 billion person-km/yr, 109 billion person-km/yr, and 484 billion person-km/yr, respectively. Travel by non-motorized, motorized private, and motorized public transportation for daily life are 50 billion person-km/yr, 651 billion person-km/yr, and 432 billion person-km/yr, respectively.

3.2. *Future scenarios of passenger travel demand for daily life in Japan*

Future scenarios of passenger travel demand within daily life area in Japan in 2050 were calculated by a combination of two levels of change of the corresponding term of Mega-trends shown in Table 2. We show four illustrative scenarios: *Population Change Only*, *Socioeconomic Change Only*, *Low Demand*, *High Accessibility*. *Population Change Only* corresponds to Mega-trend I(a). *Socioeconomic Change Only* corresponds to a median case of 16 cases that are a combination of Mega-trends I(a), I(b), II(a), II(b), III. *Low Demand* is a median case of 1024 cases that are a combination of Mega-trends I(a), I(b), II(a), II(b), III, IV(a), IV(b), IV-A(a), IV-A(b, c, d), IV-A(e), IV-A(f). *High Accessibility* is a median case of 1024 cases that are a combination of Mega-trends I(a), I(b), II(a), II(b), III, IV (a), IV(b), IV-B(a), IV-B(b), IV-B(c), IV-B(d).

As shown in Fig. 4, passenger travel by non-motorized, motorized private, and motorized public transportation within daily life area in 2050 are 40 billion person-km/yr, 471 billion person-km/yr, and 377 billion person-km/yr in *Population Change Only*, 44 billion person-km/yr, 494 billion person-km/yr, and 411 billion person-km/yr in *Socioeconomic Change Only*, 88 billion person-km/yr, 356 billion person-km/yr, and 385 billion person-km/yr in *Low Demand*, and 29 billion person-km/yr, 852 billion person-km/yr, and 266 billion person-km/yr in *High Accessibility*, respectively. Travel demand for commuting, work, and private trips in 2050 are 407 billion person-km/yr, 78 billion person-km/yr, and 402 billion person-km/yr in *Population Change Only*, 462 billion person-km/yr, 78 billion person-km/yr, and 409 billion person-km/yr in *Socioeconomic Change Only*, 373 billion person-km/yr, 79 billion person-km/yr, and 377 billion person-km/yr in *Low Demand*, and 545 billion person-km/yr, 98 billion person-km/yr, and 503 billion person-km/yr in *High Accessibility*, respectively.

Fig. 5 shows average distance with respect to average travel time per capita within daily life by mode of transportation in 2015 – 16, and the *Socioeconomic Change Only*, *Low Demand*, and *High Accessibility* scenarios in 2050. Average per-capita travel distance and travel time by motorized public transportation by representative is in the range of 1 – 32 km/day and 1 – 66 min/day in 2015 – 16, 1 – 32 km/day and 1 – 65 min/day in *Socioeconomic Change Only*, 0 – 25 km/day and 0 – 52 min/day in *Low Demand*, and 0 – 22 km/day and 0 – 42 min/day in *High Accessibility* in 2050, respectively. Average per-capita travel distance and travel time by motorized private transportation by representative is in the range of 4 – 46 km/day and 10 – 72 min/day in 2015 – 16, 5 – 42 km/day and 11 – 65 min/day in *Socioeconomic Change Only*, 3 – 36 km/day and 8 – 55 min/day in *Low Demand*, and 9 – 59 km/day and 17 – 103 min/day in *High Accessibility* in 2050, respectively. Average per-capita travel distance and travel time by NMT by representative is in the range of 0 – 2 km/day and 3 – 23 min/day in 2015 – 16, 0 – 2 km/day and 4 – 23 min/day in *Socioeconomic Change Only*, 1 – 4 km/day and 10 – 44 min/day in *Low Demand*, and 0 – 2 km/day and 2 – 14 min/day in *High Accessibility* in 2050, respectively.

Population, average trip rate per capita by purpose and mode, average travel time per capita by purpose and mode, average travel speed by mode, average travel distance per capita by purpose, and mode are provided in Supplementary Table 1.

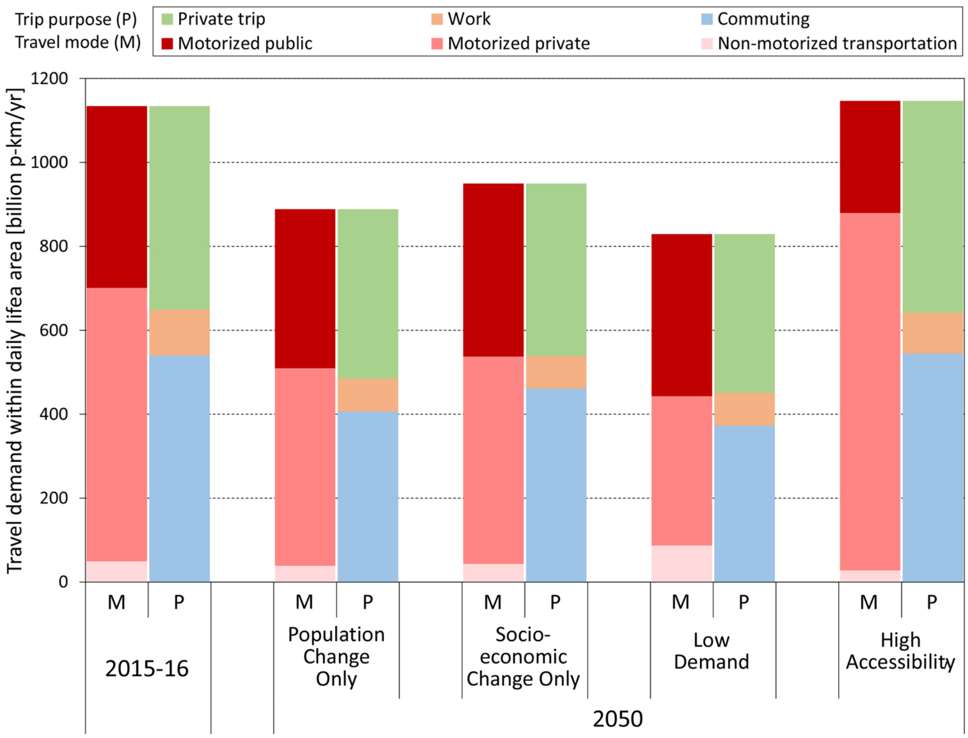

Fig. 4. Total passenger travel demand within daily life area in 2050.

4. Discussion

In *Population Change Only*, travel demand by motorized private transportation decreases by 28 % because the rural population is projected to decrease selectively in 2050. *Socioeconomic Change Only* indicates that travel demand within daily life by motorized private and that by motorized public transportation increase by 23 billion person-km/yr and 34 billion person-km/yr, respectively, compared to those in *Population Change Only* due to an increase in employment rate and white-collar workers. In *Low Demand*, travel demand by NMT doubles and that by motorized private transportation decreases by 45 % compared to 2015 – 16. In contrast, passenger travel demand by motorized private and public transportation in the *High Accessibility* scenario is 2.4 times and 0.7 times as much as those in the *Low Demand* scenario, respectively. Total travel demand within daily life in the *High Accessibility* scenario is as large as that in 2015 – 16.

In 2015 – 16, people living in three metropolitan areas commute longer distances than those living in other regions, mainly using motorized public transportation. In 2050, average distance and travel time within daily life in the *Socioeconomic Change Only* scenario shows little change except for women and those aged 65 and over compared to those in 2015 – 16. *Low Demand* and *High Accessibility* scenarios reflect contrasting behavioral change in terms of mobility demand. In the *Low Demand* scenario, the difference in travel distance and travel time among representatives converges, and travel demand for NMT doubles or triples. In contrast, travel demand by motorized private transportation diverges significantly in the *High Accessibility* scenario.

Although average travel time per capita at the highly-aggregated level differs by only about 10 min/day in these scenarios, heterogeneous characteristics of daily travel time and distance by different representatives can be observed.

5. Conclusions

This study provided a framework and procedure for developing service demand scenarios based on daily time use and service intensity of time use. The current status of mobility demand in Japan was analyzed and its structure, and mobility demand by heterogeneous actors, were reconstructed based on relevant national statistics. Total travel within and outside daily life area are estimated to be 1133 billion person-km/yr and 521 billion person-km/yr in Japan in 2015 – 16, respectively. People living in three metropolitan areas accounts for about 50 %, and motorized private transportation accounts for 58 % of total travel within daily life.

Contrasting future passenger travel demand scenarios in Japan in 2050, that is, *Low Demand* and *High Accessibility*, were developed in accordance with qualitative scenarios and quantitative assumptions of four mega-trends: population aging, gender equality, tertiary industrialization, and transport technology innovation. In the *Low Demand* scenario, total travel demand by motorized private transportation is found to decrease by 45 % in 2050 compared to that in 2015 – 16. Difference in per capita travel distance and travel time among representatives converges in this case. In contrast, total passenger travel demand by motorized private transportation becomes 2.4 times as much in the *High Accessibility* scenario as in the *Low Demand* scenario, and per capita travel demand by

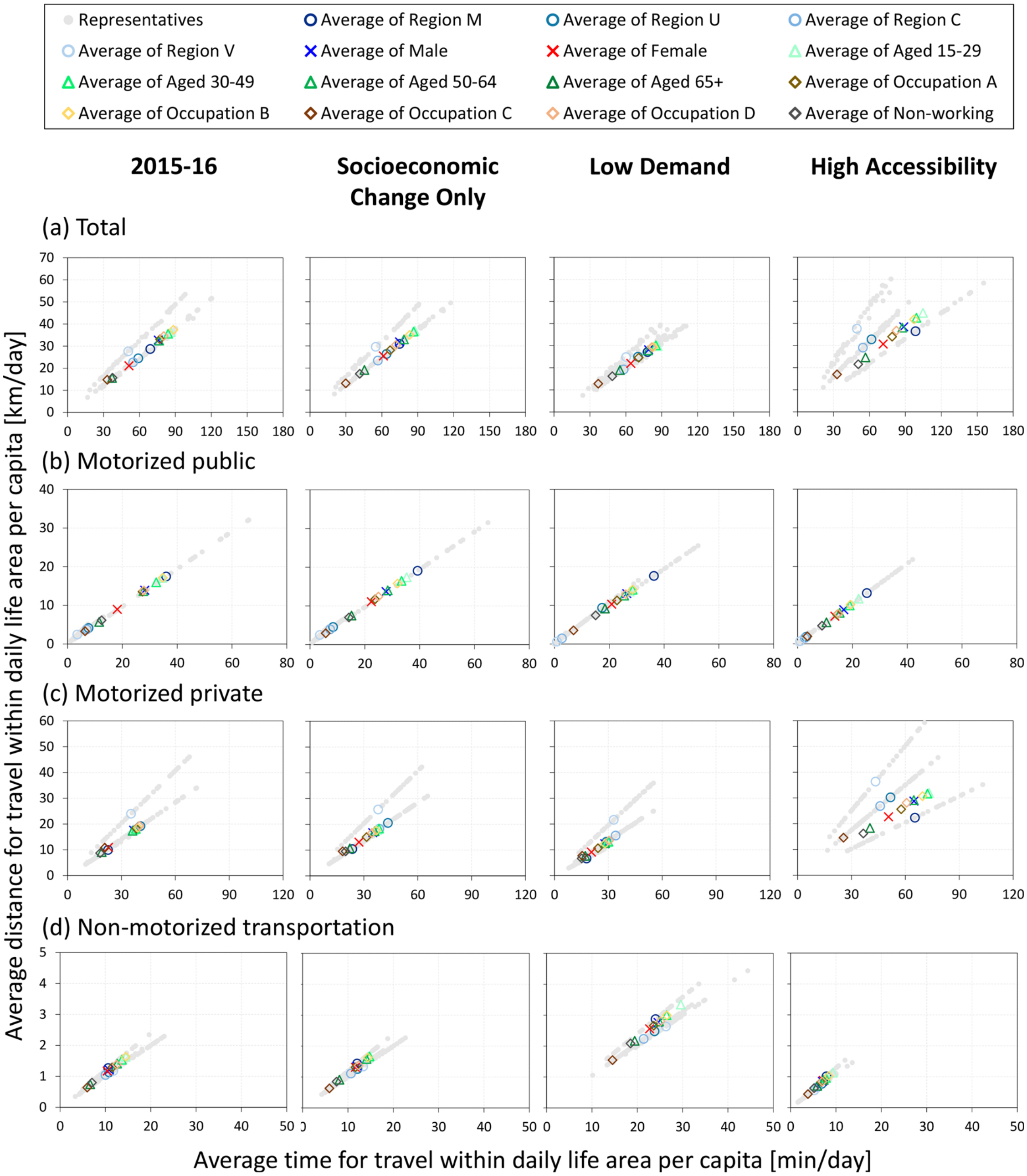

Fig. 5. Average distance and travel time within daily life per capita by (a) all modes, (b) motorized public, (c) motorized private, and (d) NMT for 2015–16, and Socioeconomic Change Only, Low Demand, and High Accessibility scenarios in 2050.

motorized private transportation by representative diverges significantly.

Existing methodological frameworks used in global transport-energy models to estimate future transport demand based on per-capita GDP and service costs cannot envisage drastic behavioral change in future mobility demand induced by disruptive mobility service developments and urban development. By contrast, this framework enables systematic and transparent reflection of a narrative toward long-term service demand scenario development by taking heterogeneous actors into account. Mobility demand can be captured as a part of daily life behavior by using daily travel time and trip rate by purpose, which are explicitly calculated in this study.

Linking global transport-energy models and service demand scenarios obtained from this study can be used to explore an alternative low energy consumption scenarios which consider potential disruptive changes in mobility service to maximize their potentials for deep decarbonization in transportation sector. Further research is needed for quantitative analysis of the relationships among time use, activities, service demand, and life-cycle energy and material demand. In terms of mobility demand scenarios development, vehicle-kilometer demand by motorized private and public transportation will be addressed in the future by considering their operation and capacity. In addition, construction of simpler framework that can be applied to global passenger demand scenarios development is left as an area for future work.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.futures.2020.102553.

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