k平均法を用いた日本におけるダブル連結トラックの走行特性の分析評価に関する研究

Master's Thesis

AN ANALYSIS AND EVALUATION OF DRIVING CHARACTERISTICS OF HIGH CAPACITY VEHICLES IN JAPAN BY K-MEANS CLUSTERING

September 2021

Graduate School of Marine Science and Technology

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1. Introduction

1.1. Trends in Road Freight Transport

Freight transportation is a prerequisite for almost all local, regional, and global trade and production. Freight transportation by road is an indispensable element of the freight task except in the limited circumstances where freight can be transported from door-to-door by rail or water alone (Organization for Economic Co-operation and Development (OECD), 2011). Therefore, road freight transport is an integral part of a supply chain, where it may be used to deliver goods from the place of origin to the destination or may be used at various stages of a supply chain. In almost all cases, road freight transport serves as the first and final links of transportation in a supply chain.

International Transport Forum (ITF, 2019b) estimated that the global freight demand will triple between 2015 and 2050, based on the demand projected at that time, where total freight of 108 trillion t-km was carried in 2015. The increase in freight transport demand will be driven by economic growth and international trade activity (ITF, 2019b). Among the freight transport modes, ITF (2019b) projected that road freight demand will increase 3.5% between 2015 and 2030, and it is estimated to increase 3.2% between 2015-2050. In the past few years, road freight traffic volumes have been increasing across the globe. Since the economic growth has been projected to rise in future, it will have an impact on road freight inevitably, which will continue to grow. ITF (2019b) suggested that the economic growth projections and related traffic growth will require the countries to reassess the capacity utilization of existing transport infrastructure and their ability to accommodate the future demand. ITF (2017b) estimated the required capacity increase will highly pressure the need of transport infrastructure for future trade growth in Asia and Africa regions. The utilization of infrastructure capacity can be improved in ways such as shifting freight modes or rescheduling deliveries to off-peak periods. In addition, the capacity utilization can be improved by increasing road freight transport operation efficiency through the use of high capacity vehicles (ITF, 2019b).

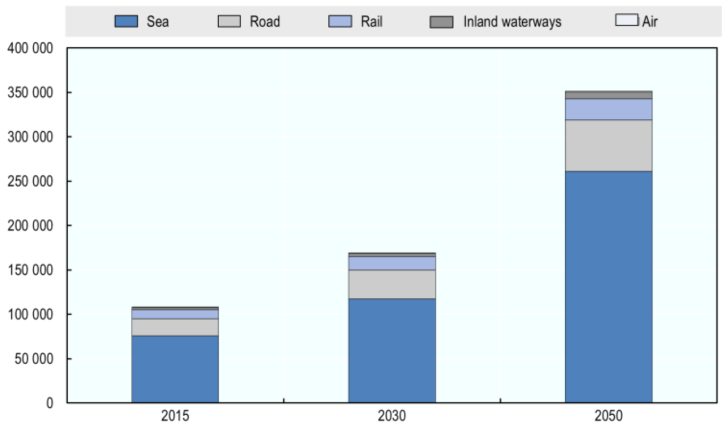


Fig. 1.1 Projected freight transport demand by mode (source: ITF, 2019b)

In recent years, air pollution and global warming have become political priorities (ITF, 2019b). The signing of the Paris Agreement in 2015 at the United Nations Framework Convention on Climate Change (UNFCCC) made the parties to implement their climate commitments. In 2015, the United Nations General Assembly adopted the seventeen Sustainable Development Goals (SDG) as part of the 2030 Agenda for sustainable development. Hence, decarbonizing freight transport and reducing transport CO_2 emissions have become challenging political goals. Studies by ITF (2019a) showed that emissions from transport sector have continued to rise unlike other sectors in both OECD and non-OECD countries.

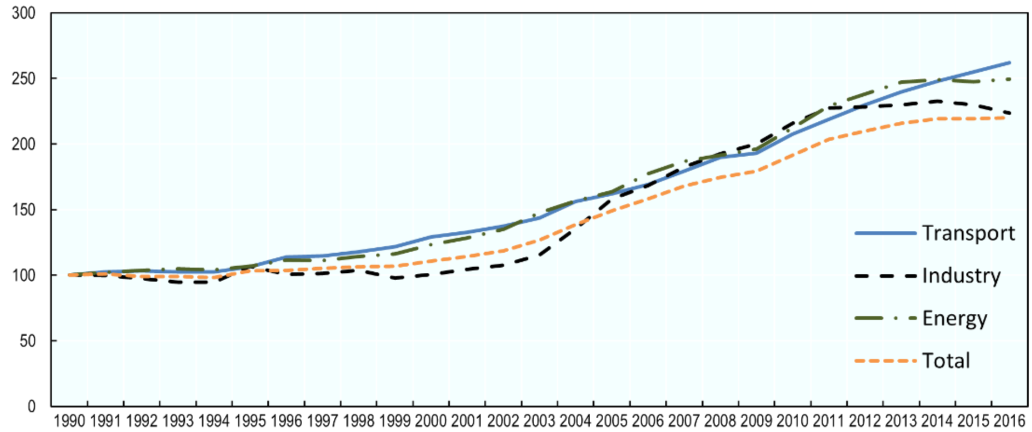


Fig. 1.2 CO2 emissions by sector OECD economies (source: ITF, 2019b)

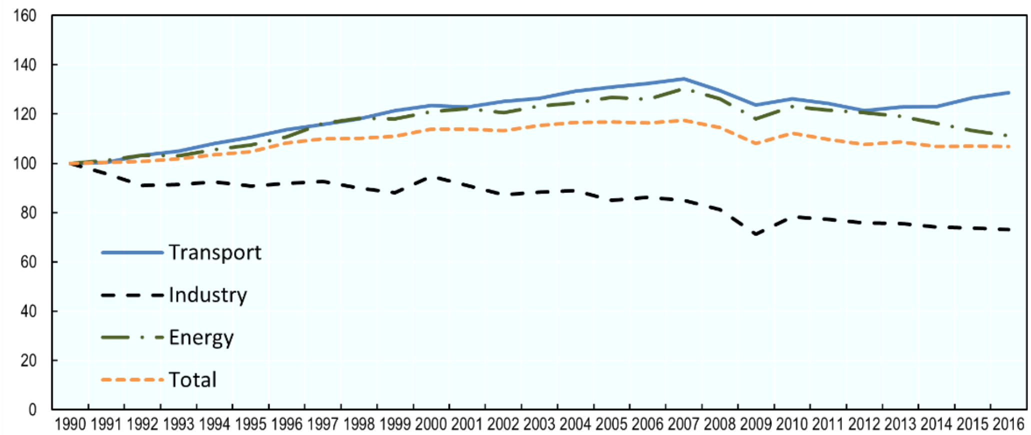


Fig. 1.3 CO2 emissions by sector non-OECD economies (source: ITF, 2019b)

For the freight transport sector to achieve SDGs, ITF (2019a) listed the mitigation measures and potentially disruptive developments. Among the mitigation measures, the freight transport sector can increase their logistics efficiency to combat the climate change. As potentially disruptive developments in freight transport, autonomous vehicles, high capacity vehicles and energy transition for long distance heavy freight will become necessary. Thus ITF (2019b) suggested two sets of approach in decarbonizing freight transport. The first approach deals with logistical, behavioral, and regulatory solutions and management to reduce freight traffic levels, shift to lower carbon transport modes, and improve vehicle efficiency. The second set is concerned with technology and engineering to increase energy efficiency and switching to low carbon energy. A study by Woodrooffee (2017) in the United States and Canada further showed that in the future, emerging technologies which use alternative fuel sources such as electrical power supply could help address the pollution levels and greenhouse gas emissions in the longer term. However, a more efficient use of long combination vehicles could produce positive results in terms of fuel consumption and CO_2 emissions in the short term.

In addition, the Organization for Economic Co-operation and Development (OECD, 2011) estimated that the shortage of truck drivers will have an impact on the future of road freight transport. OECD (2011) predicted that the increased demand for road transport increased the number of truck drivers required in the early part of 21st century. However, it was found that the supply of drivers could not match the demand of the industry. This result was not restricted to any particular region but applicable in countries such as the United States, Canada, Europe, and Australia (OECD, 2011). According to Australian Trucking Association (2003), one of the causes of truck drivers is the average age. Employees in the trucking business are found to be typically older than in other occupations. OCED (2011) again saw the similar data with Canadian trucking industry where truckers aged 55 and over outnumbered those under 30 for the first time in 2004. In the United States, the average age of male truck drivers is getting older than other occupations (ITF, 2017c).

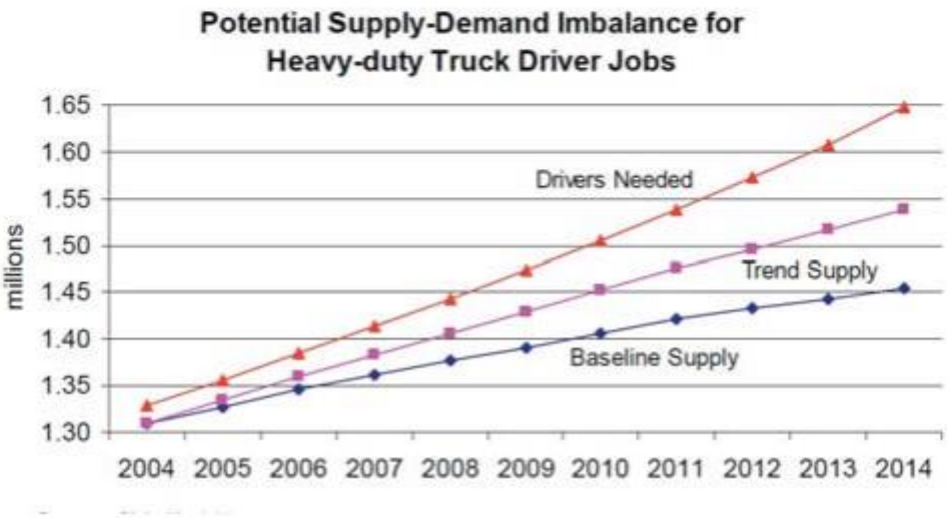


Fig. 1.4 Potential supply-demand imbalance for heavy-duty truck driver in the USA (source: OECD, 2011)

Due to the lack of truck drivers, ITF (2019b) identified high capacity vehicles will become one of the driving factors to reduce the fuel- and labor-related costs per unit of cargo compared to being transported by current freight trucks. In addition, ITF (2017c) the decline in heavy truck labor supply can reinforce the trend towards driverless road freight. With technological developments in vehicle automation, the governments, the logistics industry, original equipment manufacturers (OEM), and IT (information technology) sector look forward to driverless road transport (ITF, 2017a). The concept of transition to driverless road freight ranges from truck platooning to full automation.

Overall, the trends in road freight transport lean towards high capacity transport (HCT) which can provide a smarter, greener and safer road transport, and a more efficient use of transport infrastructure.

1.2. Adoption of High Capacity Vehicles

To address the problems of trade and freight traffic level increase, decarbonization of road freight transport, the declining availability of skilled drivers, and the limitation of existing transport infrastructure to accommodate the growth, ITF (2019a) speculated that high capacity vehicles (HCV) are a potential solution. High capacity vehicles are defined as vehicles with weights and/or dimensions outside that permitted in conventional regulations (OECD, 2011). High capacity vehicles are called “longer and/or heavier vehicles (LHV)” in Europe, “long combination vehicles (LCV) in North America, and “higher productivity vehicles (HPV)” in Australia. Fig 1.5 shows the types of high capacity vehicles deployed in different countries.

Fig. 1.5 HCV (source: OECD, 2011)

From the introduction of HCVs, their impacts on productivity, environment, infrastructure, modal shift, safety in truck operation need to be assessed. ITF (2019b) studies found that vehicle loading can be optimized by using HCVs. In addition, increased average load and logistics efficiency of HCV would lead to increased volume of activity and overall emissions decrease. ITF (2019b) suggested that transport modal shift is possible due to reduced costs generated by the greater efficiency in road freight transport. In terms of operation safety, HCVs operate on the restricted parts of the road that are determined suitable. Their operation sections would be non-urban areas and on divided highway sections. Therefore, OECD (2011) assumed that driver selection, operational controls and higher levels of safety equipment contribute to the safe operation of HCVs.

A study by ITF (2019a) have found that several countries have set up research programs, investigations, and committees to prepare policies and regulations to support introduction and implementation of high capacity transport. The policy study and development for HCT have been ongoing in countries such as Australia and the Netherlands as far as the early 2000s. Since the early 2010s, HCV introduction and regulations have been established in countries such as Australia, the Netherlands, Finland, Denmark, Sweden, Norway, Spain, Germany, Brazil, Argentina (ITF, 2019a). In Japan, high capacity transport has been experimented and adopted in terms of both high capacity vehicles and truck platooning. In FY2016 to FY2018, operational experiments of high capacity vehicles were conducted. In FY2017, a field operational test of truck platooning was conducted.

1.3. Research Purpose

In recent years, Japan has been facing similar above-mentioned issues in their logistics industry (Watanabe et al. 2021). With an increasing demand in freight transportation and a serious shortage of truck drivers, the Ministry of Land, Infrastructure, Transport and Tourism (hereinafter referred to either as the Ministry or MLIT) proposed to introduce high capacity vehicles (HCV) with double trailers of vehicle length over 21 meters to 25 meters. Not only HCVs but also autonomous driving and truck platooning were suggested to address the labor problems and improve the operation efficiency (MLIT, 2019). In October 2016, MLIT set up the council on experimenting HCVs with double trailers. Starting in November 2016, the trials began with 21m trucks. In 2017, experiments with trucks of vehicle length 25m started and were conducted till January 2019. The experiments were run by four logistics companies: Nippon Konpo Unyu Soko Co., ltd, Yamato Transport Co., Ltd, Fukuyama Transporting Co., Ltd, and Seino Transportation Co., Ltd. In January 2019, the Ministry relaxed the vehicle length from 21m to 25m and HCVs with double trailers were fully introduced to operate in Japan.

Fig. 1.6 A 25m HCV in Japan (source: MLIT, 2019)

In this study, research is focused on both literature and data analysis. Reports on HCV status in Japan will be compared and examined to the studies related to HCVs conducted all over the globe through the literature. Primary emphasis will be given to the driver issues and their health and work conditions in Japan because MLIT started plans to introduce HCVs primarily due to the lack of truck drivers in the logistics industry. Since the average truckers are getting older, the solution to the driver shortage issues to the need to improve their working environment have become necessary. The study explores how HCVs can improve the safety and health of truck drivers by making their work environment better through the introduction of the relay transportation system where drivers are exchanged at a facility instead of one driver driving the whole trip.

High capacity vehicle movement data from the MLIT trial experiments are studied. Since the truck movement data are unlabeled, the author finds his interest in the underlying patterns of the data. Therefore, the running characteristics of HCVs will be analyzed by applying the clustering algorithm, which is one of the unsupervised machine learning techniques. The purpose of clustering is to differentiate how the driving characteristics can differ in various locations and which factors cause different truck movement behaviors. The clustered results will be visualized by using the geographic information system (GIS).

1.4. Thesis Structure

In this study, chapter 1 discusses the background and trends in freight transport and the challenges of road freight transport. In addition, the adoption of high capacity transport and their timeline is discussed. The chapter then explores the purpose of the study carried out in this paper.

Chapter 2 mainly discusses the literature related to high capacity vehicles and their impacts. The following aspects are focused: economic impacts, environmental impacts, modal shift, emerging technology in transport, safety in truck operations and their impact on transport infrastructure. Moreover, deployment status of high capacity vehicles in Japan is discussed in detail.

Chapter 3 deals mostly with the theoretical background of the methodology applied in this paper. It introduces a brief on machine learning, explores K-means clustering algorithm and evaluation methods, and explains the data collection method and an overview of how the research will be carried out throughout the paper.

In chapter 4, findings in terms of various driving characteristics of high capacity vehicles are explored. Calculated analysis results are discussed and evaluated using the literature.

The contents of chapter 5 are concerned with conclusions and suggestions. Brief conclusions on the literature and findings are discussed. Then, suggestions by the author on how the research can be continued and future research considerations will be presented.

2. Literature on High Capacity Vehicle Status and Their Impacts

In recent years starting from the 2000s, there has been several assessments, research programs and studies to support the introduction and implementation of high capacity transport (ITF, 2019a). The studies and implementations have been introduced mostly in OECD countries such as Canada and the United States in North America, Australia, European countries, and Japan. In each country, the weight and vehicle length restrictions are different. In Europe, the general allowance can be summarized as 25.25m long vehicles with a total weight of 60t (ITF, 2019a) although the allowable weight and length can differ in some countries. Table 2.1 summarizes the implementation scenario of HCV in OECD countries, which is compiled by the author sourcing from ITF (2019a) and OECD (2011).

Table 2.1 Examples of HCV introduction in OECD countries

Country	Year	Current Situations and Regulations
Canada		HCVs are referred to as LCV. The regulations limit the vehicle length to 25 meters and gross masses between 53.5 and 62.5 tons are permitted. Depending on the types of LCVs, vehicles length may be allowed up to 38m.
The United States		At the beginning LCVs were allowed only on limited routes in the late 1950s. In 1991, 21 states allowed the use of at least one form of HCV. In 2009, LCVs were allowed in some states but not on interstate road networks.
Australia		HPVs of 26m in length and 68.5t are allowed to operate. In remote areas, HPVs also known as double and triple road trains up to 53.5m and 125t have been widely used for many years.
Sweden	Since 1998	Sweden has fully adopted 25.25m and 60t HCVs for a long time. On designated road networks, vehicles up to 74t are allowed to operate.
Finland	2013	HCVs were fully introduced in 2013, limited to 25.25m and weight from 60t to 76t without special restrictions. In 2019, the vehicle length was further relaxed to 34.5m although there was no weight relaxation.
The Netherlands	2013	Full scale introduction of HCVs allowed to operate vehicles of 25.25m and 60t
Denmark	Since 2008	Field tests of 25.5m and 60t have been conducted since 2008. They are on the long-term trials.
Germany	2017	HCVs were authorized with limitations of 25.25m and 40t.
Japan	2019	HCVs of length 25.25m are relaxed to operate on allowed expressways. There is still restrictions of weight.

With the introduction and implementation of HCVs in above countries, both OECD (2011) and ITF (2019a) identified their impacts on the following factors: economic and productivity, environment and decarbonization, modal shift, and safety, infrastructure and technology issues.

2.1. Economic Impacts

In terms of economic impacts of HCVs, the following will be covered: productivity and road haulage costs.

OECD (2011) examined and found that the prospective economic impact on HCVs is to be productivity benefits. Since HCVs can transport a larger weight and volume of cargo in one trip than a normal truck, the loading capacity can be optimized in transport operations (ITF, 2019a). As the loading capacity is limited either by weight or volume of the shipment depending on cargo type, transport operations of specific commodities can be optimized. In such cases, the use of HCVs can produce impacts on high-density cargo due to the increase of weight limits in HCVs as well as the low-density commodities due to in the increase in dimensions of vehicles (ITF, 2019a). Therefore, depending on the needs of the commodities, the application of HCVs could increase logistics efficiency in transport of large volumes of either weight- or volume-limited cargo on specific routes.

As HCVs can transport a larger amount of cargo in one trip than a normal truck, the number of required trucks and freight trips can be reduced. ITF (2019a) listed fuel costs, capital, labor costs make up the three major costs of road haulage. ITF (2019b) estimated that HCVs could increase transport costs per truck by 5-12% but at the same time, the number of trucks required to carry the same amount of cargo will be reduced by 10-50%. Thus, costs per unit load of cargo in road haulage decreases (Christidis and Leduc, 2009). Both Vierth et al. (2008) and Christidis and Leduc (2009) wondered whether it could lead to a shift in modal choice from rail and/or inland waterways to road freight. With the reduction in freight trips and trucks, HCVs bring major benefits in terms of more efficient use of the vehicle, reduction in fuel consumption per unit cargo, and reduction in labor costs per unit cargo (ITF, 2019a). How the number of trips and trucks required can be reduced is shown in European Modular System (EMS) as an example in Fig 2.1.

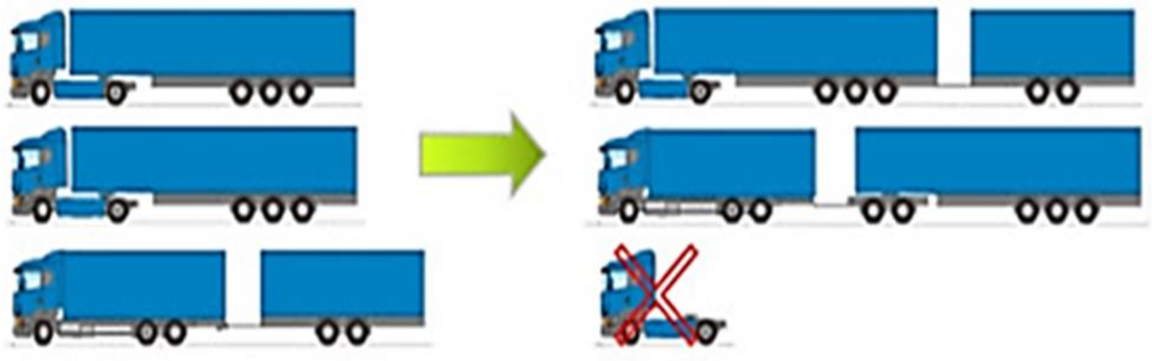


Fig. 2.1 EMS (source: ITF, 2019b)

2.2. Environmental Impacts

Decarbonization of road freight transport has become an important issue due to the signing of the Paris Agreement in 2015 (ITF, 2019a). Suggested by McKinnon (2018), there are two major approaches to decarbonize the road freight transport either through logistical, behavioral, regulatory management or through technology. As the methods to reduce carbon emissions by increasing energy efficiency and alternative energy sources are the long-term approach, freight movement traffic, modal shift and vehicle loading improvement can help reduce carbon emissions in the short term. In this case, HCVs become a potential solution in two ways by improving vehicle loading and reducing the freight traffic.

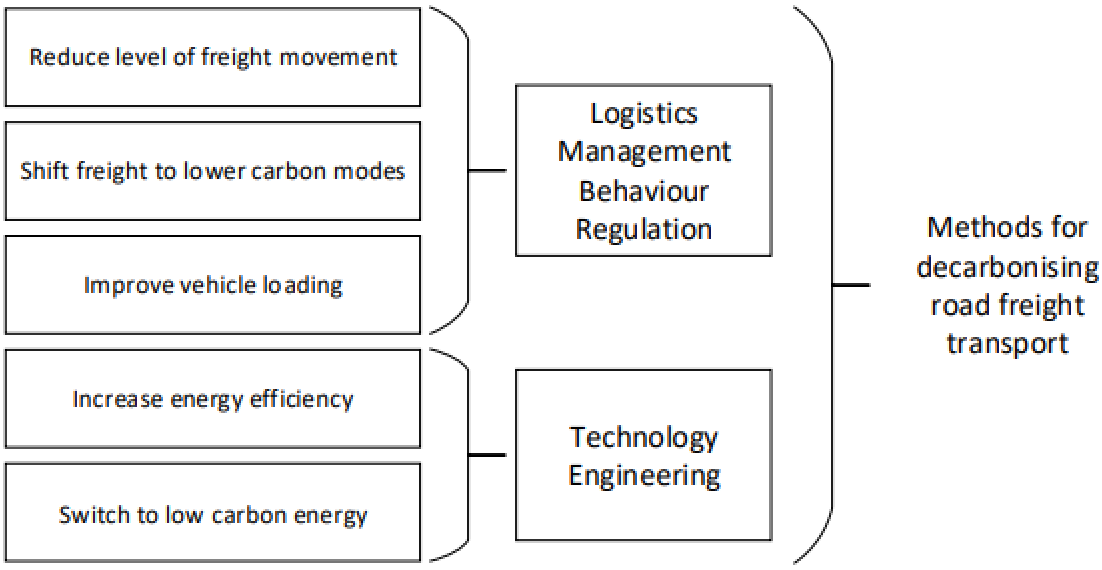
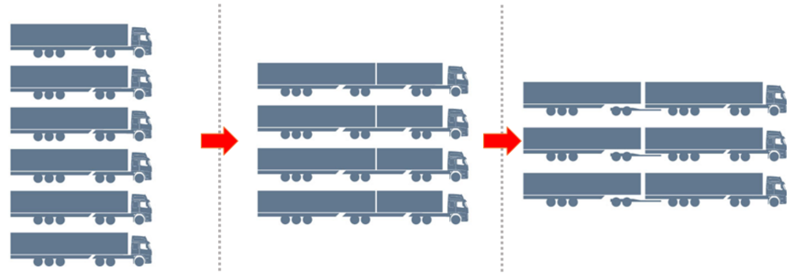


Fig. 2.2 Methods to decarbonize road freight (source: ITF, 2019a)

ITF (2019a) proposed that by improving vehicle loading of HCVs, the energy efficiency per unit of cargo can be increased from 10% to 20% in terms of carbon reduction. The vehicle loading improvement methods include increased logistical collaboration between shippers, delivery consolidations, and relaxation of just-in-time shipment deliveries. In addition, it is suggested to relax weight and dimension restrictions on road freight transport so that HCVs can be adopted more widely to increase vehicle utilization. As a result of improved vehicle loading, this can in turn reduce the number of freight traffic required to transport the same amount of cargo.

In terms of reduced freight movement, Woodrooffee (2017) studied the emission comparison between Canadian B-train (25m) and US tractor semi-trailer of length (12-16m), and Canadian B-trains have 68% better emission efficiency. Pettersson et al. (2017) estimated CO2 emissions from HCVs and their impacts in Sweden for 40-year timespan (between 2018 and 2058), assuming the GDP growth and development of energy efficient vehicles in future. The study found that significant reduction in CO2 emissions can be achieved if LHVs (74t/34m) are allowed. In 2015, DUO2-CAT projected began in Sweden. DUO-trailer is a tractor with double trailers of vehicle length 32m (DUO2, 2019). The project demonstrated substantial increase in vehicle loading efficiency, greater amounts of savings in fuel consumption, reductions in CO2 emissions, reduction in the number of trucks and drivers required.

3 HIGH CAPACITY VEHICLES CAN REPLACE 6 REGULAR TRUCKS, REDUCING CO2 BY UP TO 27%



Vehicles (and drivers)	6	4	3
Vehicle length	16.5 m	25.25 m	32 m
Load per vehicle	100 m³	150 m³	200 m³
Fuel consumption	3.5 ml/m³km	3 ml/m³km	2.5 ml/m³km
CO_2 emissions	100%	85% = -15%	73% = -27%
Road use	499 m	368 m	296 m

Source: Cider L , Larsson L, HCT DUO2-project Gothenburg-Malmoe in Sweden, 2019

Fig. 2.3 DUO2 project (source: DUO2, 2019)

ITF (2019b) estimated that now HCVs still have a very moderate decrease of 3% in CO2 emissions compared to the current ambition scenario.

2.3. Modal Shift

ITF (2019a) stated that transport policies on national levels have promoted modal shift away from road to rail or inland waterways for several years to reduce the volume of freight traffic on road infrastructure. With the adoption of HCVs, OECD (2011) raised the issues of HCV impact on rail freight such as whether diversion of freight to road could affect rail lines and whether the rail freight mode would sustain due to their relative safety and emission performance although HCVs could produce better improvements in safety and emission standards compared to normal freight trucks.

In Europe, studies have been done to quantify the actual and potential diversion of freight movement from rail and multimodal transport services to HCVs. When considering modal choice, costs, time, reliability, and flexibility are considered. Although HCVs are beneficial in terms of transport operating costs, their impacts on decarbonization compared to other modes show a significantly less decrease (ITF, 2019b). Vierth et al. (2008) concluded that both rail and road modes in Sweden have different competitive advantages as both freight traffic volumes continues to grow. A study by ITF (2019a), in the Netherlands, HCVs operating on the roads have increased regularly between 2001 and 2016. HCVs are found to take over freight volumes of regular trucks, not from rail and inland waterways, which are immensely utilized in the country and all modes of transport showed performance growths with inland water transport experiencing the largest growth.

Studies by ITF (2019a) focused on independent freight modes and multimodal transport cases where there is a combination of trucks and rails were not considered. In multimodal transport scenarios, HCV utilization can benefit both transport modes as they improve efficiency and reduce operating costs.

ITF (2019a) studies found that HCVs do not have negative effects on rail freight volumes and HCV adoption will not lead to disruptive scenario for rail and other transport modes.

2.4. Safety, Infrastructure and Technology Issues

With the introduction and implementation of HCVs on road networks, OECD (2011) considered vehicle types and axle masses and characteristics of the existing infrastructure for operational applicability. ITF (2019a) suggested that HCVs ought to be adapted to the current existing infrastructure, and their impacts on primary and other road infrastructure need to be studied such as bridges, pavements, tunnels, expansion joints, and safety barriers.

In terms of operational safety, studies have been conducted in several countries. Matuszkova et al. (2018) studied the maneuverability of longer and heavier vehicles in Czech by simulations. The results showed the possibility and safe operational ability in interchange junction but there could be difficult maneuvering at intersections or roundabouts as LHVs could possibly overlap the traffic lanes. Jagelčáka et al. (2019) also carried out the study on LHV possibility in Slovakia and concluded that EMS LHV combinations provide high flexibility to deploy the vehicles on the roads.

In terms of infrastructure, the needs to improve the transport infrastructure have been considered in Japan. MLIT (2019) found the parking restraints for HCVs of length over 21m and suggested to designate parking spaces for HCVs and implement measures such as markings and warning signs to prevent other vehicles from parking in HCV designated areas. MLIT (2019) also proposed to utilize the parking reservation system to secure parking capacity for HCVs. In terms of maneuverability of HCVs in Japan, MLIT found the effect of passing and turning is the same as large truck as the HCV turning radius is operatable within the vehicle restriction.

2.5. Current Status of High Capacity Vehicles in Japan

Road freight transport is the most common mode of freight movement in Japan. Motor vehicles cover about 91% of the total freight transportation movement while coastal vessels are responsible for about 7% of the freight transport. Rail and air transport modes carry the remaining 1~2% (Statistics Bureau of Japan, 2021). Therefore, road freight transport plays a critical role in Japanese logistics industry as shown in Fig 2.4.

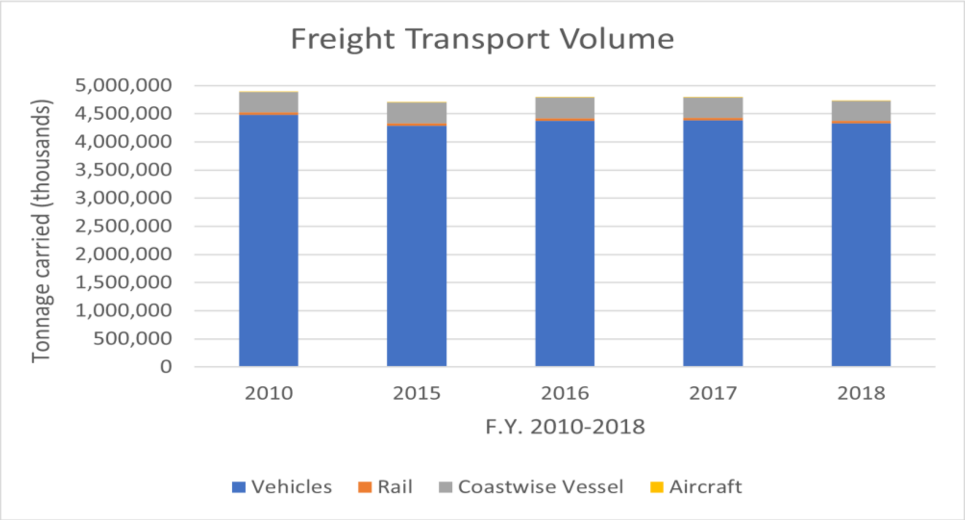


Fig. 2.4 Total freight transport volume by mode (source: Japan Statistics Bureau, 2021)

However, the statistics also show that truckers in Japanese trucking are getting older. Statistics Bureau of Japan (2021) find that the average age of Japanese truck drivers is found to be over 45. Large-sized truck drivers for business are aged average 48.6, small-sized or regular-sized truck drivers being 46.6, and the average age for private truck drivers is 47.7. Since about 40% of truck drivers are aged over 50 years old, and almost 70% being over 40 years old, trucking in Japan is severely under-staffed (MLT, 2019). To promote labor saving, MLIT started experimenting high capacity vehicles with double trailers which can transport freight capacity of two regular trucks with only one vehicle as well as truck platooning and autonomous driving.

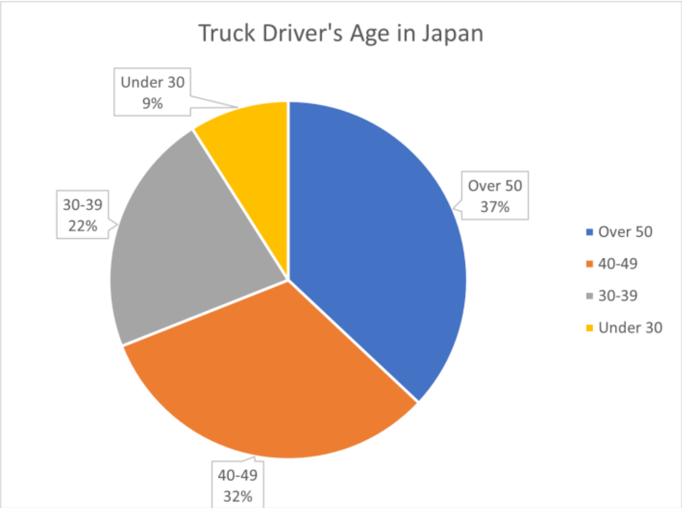


Fig. 2.5 Age of truck drivers in Japan (source: MLIT, 2019)

On 14 September 2016, the council for experimenting high capacity vehicles with double trailers was established by MLIT. The Ministry then called for participants to take part in the driving experiments. On 22 November 2016, Nippon Konpo Unyu Soko Co., Ltd first started their driving experiments with 21m long trucks. On 17 March 2017, Yamato Transport Co., Ltd and Fukuyama Transporting Co., Ltd began experimental driving with 21m long trucks. Later in October 2017, trial runs were relaxed to 25m trucks with Fukuyama Transporting

Co., Ltd starting the experiments on 16 October, which was later followed by Yamato Transport Co., Ltd experimenting on November 1st. In February 2018, Nippon Konpo Unyu Soko Co., Ltd began the trial driving of 23m long trucks. Finally in March 2018, Seino Transportation Co., Ltd started their experimental driving of 25m long trucks.

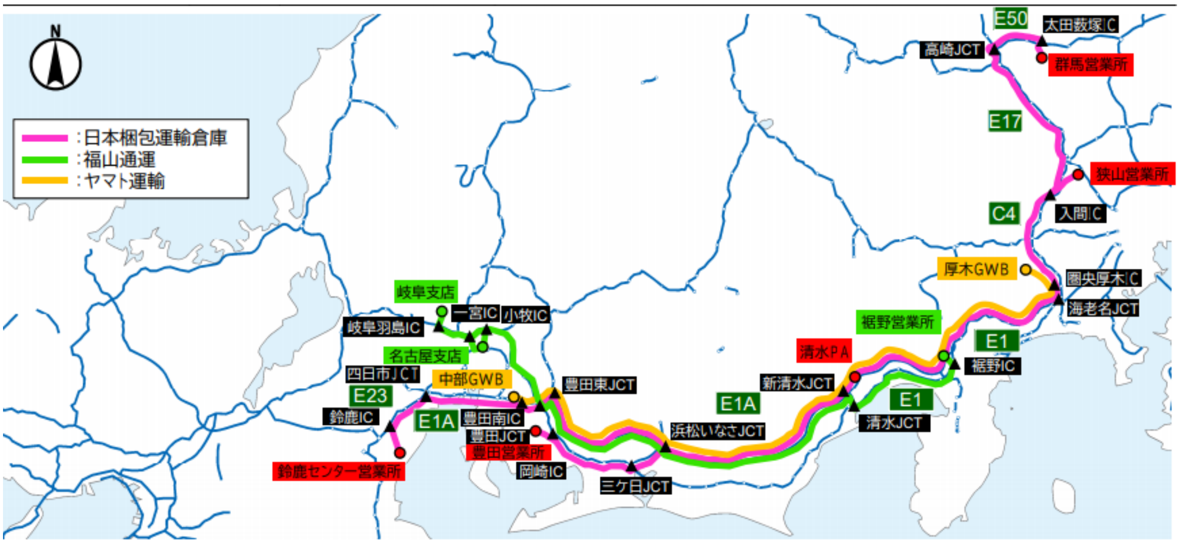


Fig. 2.6 21m HCV experiment route (source: MLIT, 2019)

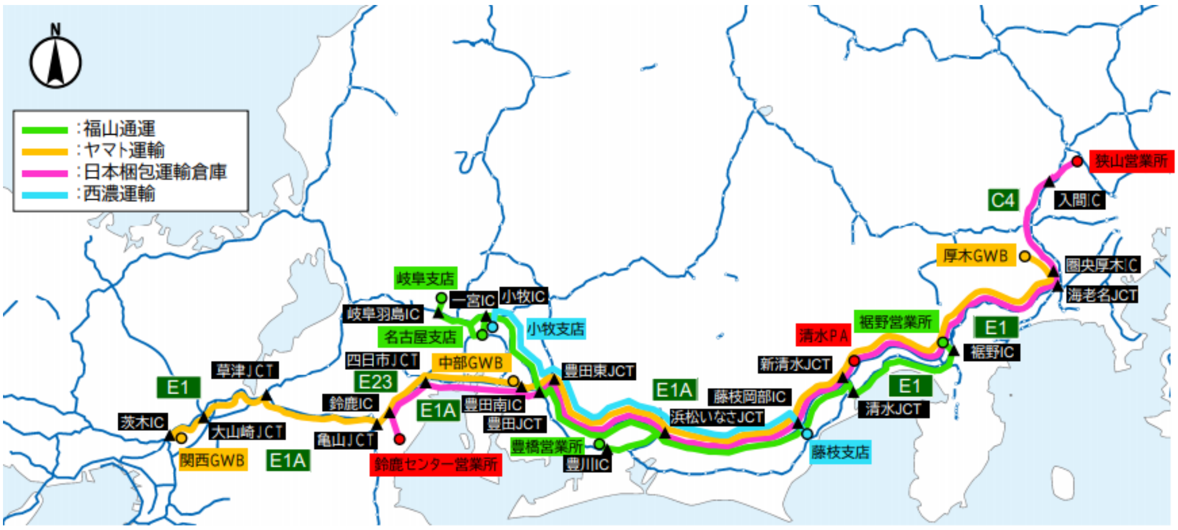


Fig. 2.7 25m HCV experiment route (source: MLIT, 2019)

On January 29, 2019, the Ministry finally announced the relaxation of the special vehicle length from 21m to 25m and it was made possible to transport two normal heavy trucks with one vehicle. As a result, the full-scale introduction of high capacity vehicles with double trailers came into effect. The Ministry (2019) started to allow the operation of HCVs of 25m along the Shin Tomei Expressway between Ebina section and Toyota Higashi section. As the needs of the logistics companies grew, MLIT (2019) in August approved the expansion of HCV operation routes from Tohoku region to Kyushu region along the Pacific coastline. The approved operation routes include the Tohoku Expressway, the Tomei Expressway, the

Ken-O Expressway, the Meishin and Shin-Meishin Expressways, Sanyo Expressway, and Kyushu Expressway. The expansion route is as shown in Fig 2.8.

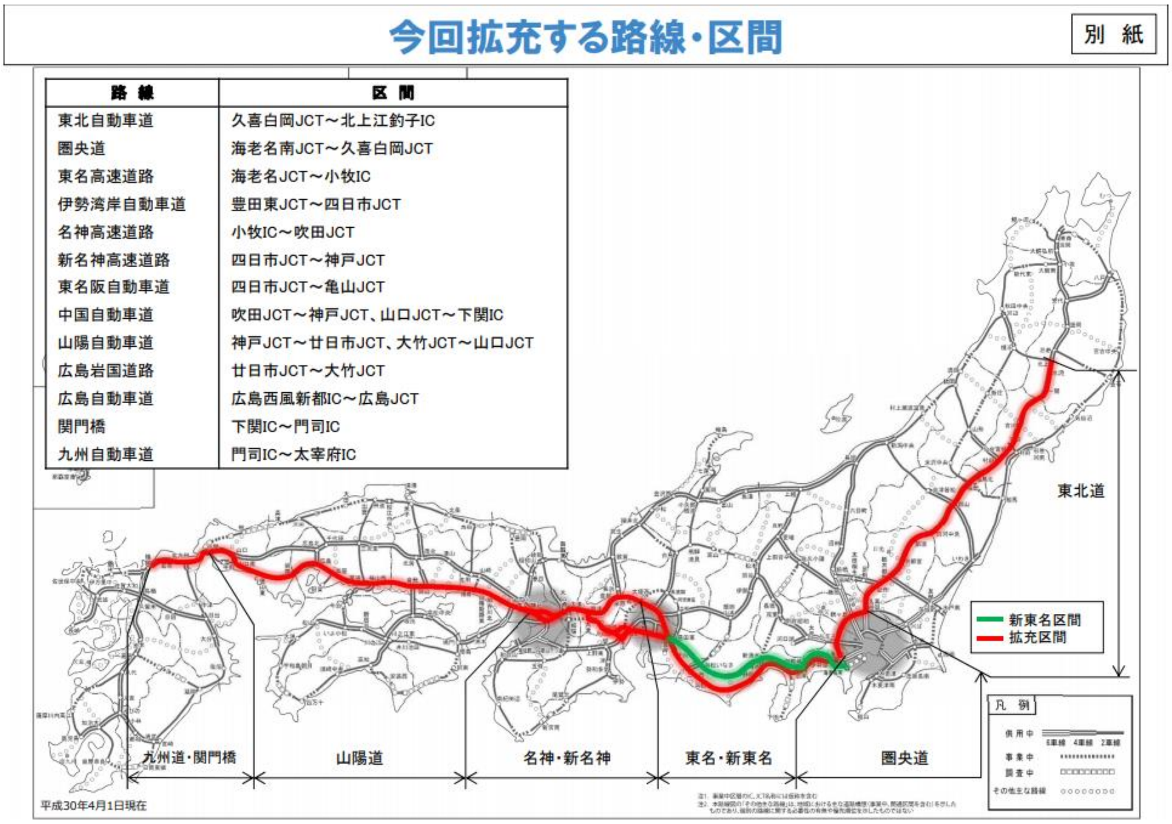


Fig. 2.8 Expansion routes for HCV operation (source: MLIT, 2019)

From a supply chain point of view (Japan Automobile Manufacturers Association (JAMA), 2020), logistics for automobile part suppliers and production plants is linked by wide-area transportation using expressways. In Japan, logistics is tended to high-frequency and low-volume transportation as the production systems are established based on JIT approach (just in time). Therefore, the expansion of the routes is closely related to the locations of automobile manufacturing plants for the distribution of automobile parts with HCVs.

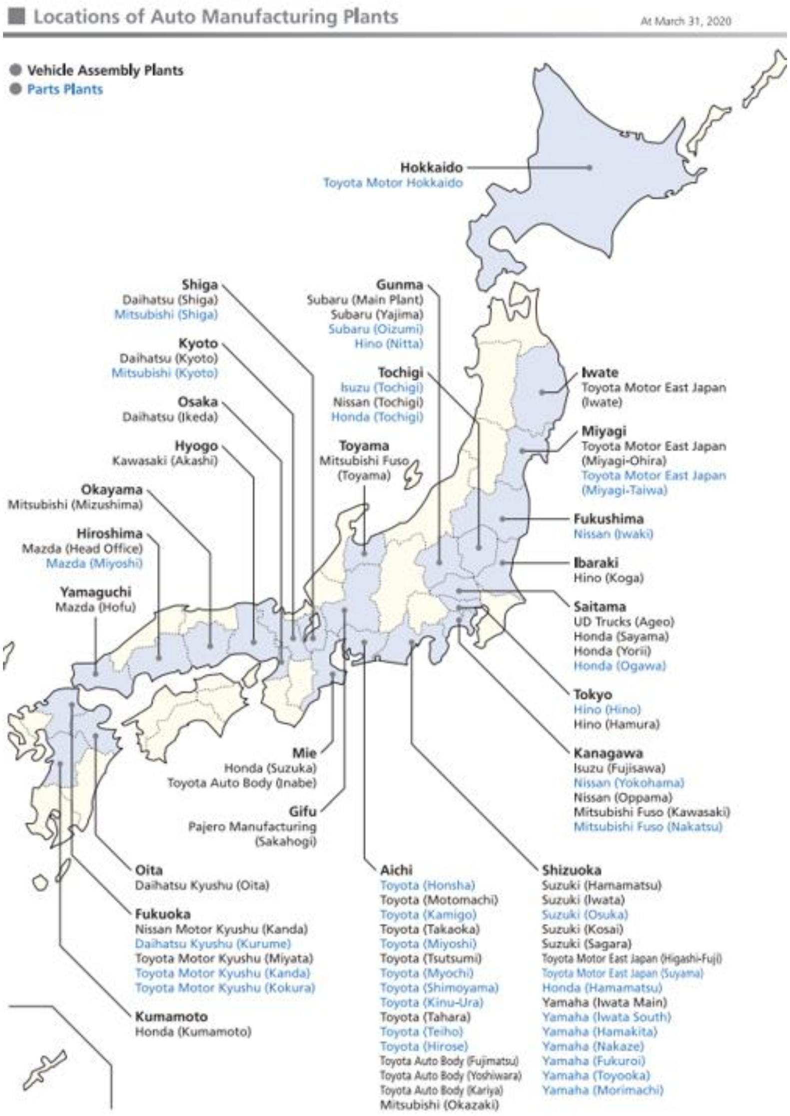


Fig. 2.9 Automobile manufacturing plants (source: JAMA, 2020)

Although high capacity vehicles have already been fully introduced in Japan, they are still regarded as special vehicles. Since a trailer is attached to the back of the truck, an HCV is regarded as a towing vehicle and a towing license is required to operate an HCV. In order for drivers to drive an HCV, they need to satisfy the condition of more than five years of experience of driving heavy trucks. In addition, the drivers must be trained for a minimum of 2 hours or more before they are permitted to drive an HCV.

2.5.1. Economic Impacts on Driver Requirement and Vehicle Loading

As the Ministry anticipated to address the problem of driver shortage in trucking by introducing HCVs, a positive result was produced in terms of driver requirements. Since both 21m and 25m long HCVs were experimented, a comparison of driver requirement in terms of different vehicles could be studied. It was found that HCVs could reduce the number of truck drivers required to 0.23 driver per 1000 t-km for a 21m HCV from 0.35 person per 1000 t-km for a normal 12m freight truck. In the case of an HCV over 21m, it was found to be further reduced to 0.18 driver per 1000 t-km (MLIT, 2019). Therefore, the reduction in the number of drivers required was found to be reduced about 50% for vehicles over 21m compared to normal freight trucks when they carry the same capacity.

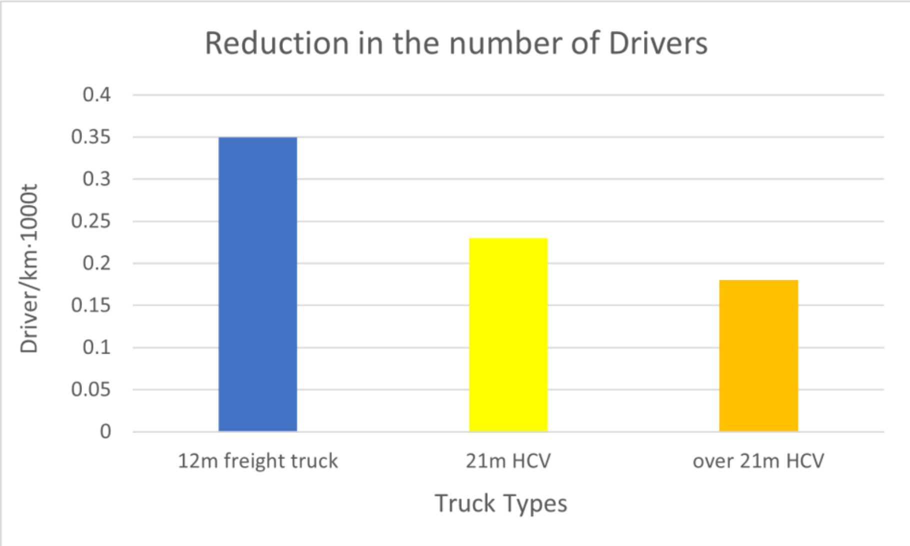


Fig. 2.10 Reduction in driver requirement (source: MLIT, 2019)

Compared to a normal freight vehicle of 12m which can carry 13 tons in Japan, HCVs of both 21m and 25m can carry almost twice cargo capacity that of the normal truck. An HCV of 21m can carry 24.1 tons of cargo (85.38% of the normal freight truck). In the case of a 25m HCV, the cargo carrying capacity is doubled as they can accommodate 25.9 tons of cargo compared to a 12m truck.

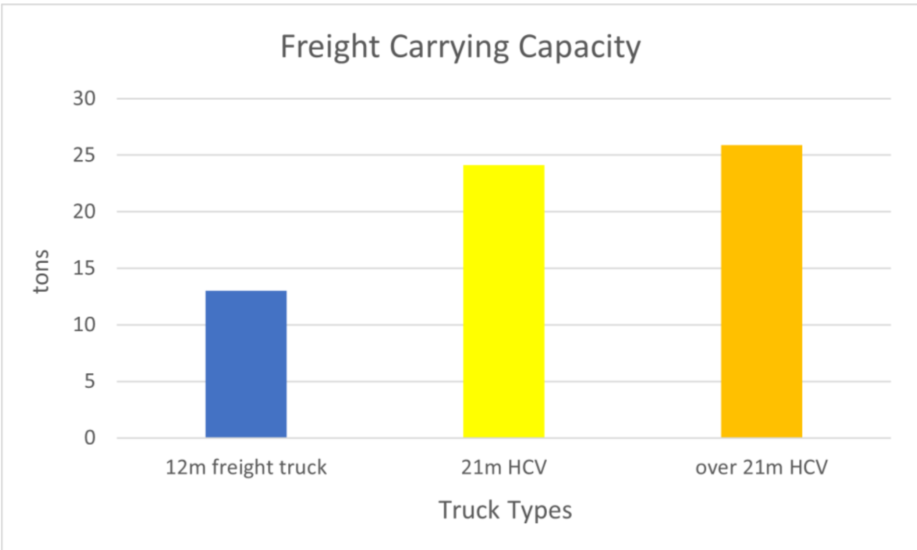


Fig. 2.11 Increase in freight carrying capacity (source: MLIT, 2019)

2.5.2. Working Environment Improvement through Relay Transportation

In addition to labor shortage problems, MLIT also aimed to improve working efficiency and their work environment by introducing the relay transportation system. The relay transportation is the system where the drivers would be exchanged at service areas or parking areas (SA/PA) to drive a truck instead of one driver driving the whole trip.

In the case of one driver driving the whole trip, truckers would need to spend their break time at the lodging house at SA/PA whereas in the relay transportation system, drivers would be able to return home daily. MLIT (2019) saw that an average driver would spend 280 hours of rest at home and 90 hours of rest at a lodging house in the direct transportation without driver exchange, but a driver would have 370 hours of rest on average at home in the relay transportation. About 40% increased rest time was found in the relay transportation. MLIT interview results with relay transportation drivers found that 70% of truckers were in favor of being able to return home daily, felt physically comfortable due to little fatigue, and in favor of increasing the transfer service.

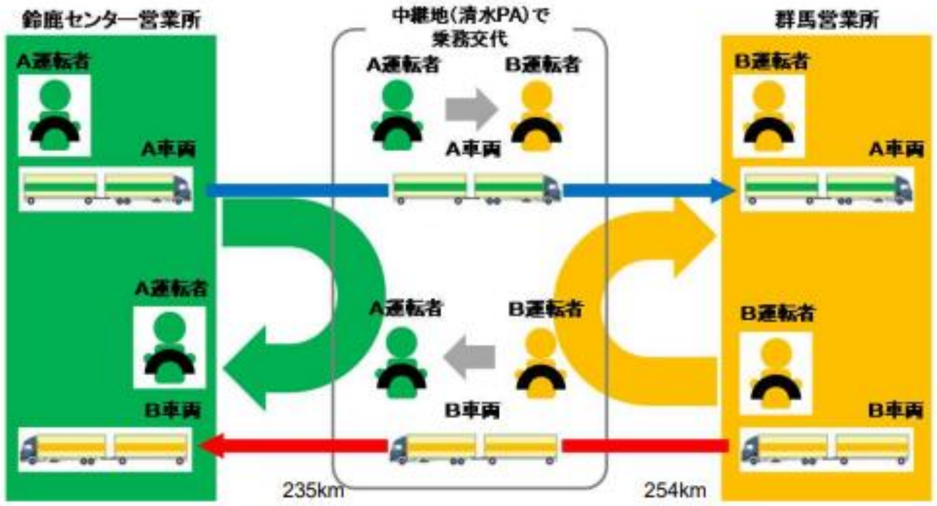


Fig. 2.12 Relay transportation (source: MLIT, 2019)

According to Nemoto (2021), the relay transportation is effective for long-distance trips and could become a factor that will bring in young people to trucking because young drivers can spend time with their family at home. As the driver’s working hours are reduced, wages can be reduced. Therefore, it is important to increase the added value of logistics so that the wages can increase. In this case, Nemoto (2021) believed that it is important to improve the truck loading rates and to train the sales drivers who will actively visit shippers to pick up their cargo.

2.5.3. Environmental Impacts on CO2 Emissions and Fuel Consumption

In addition to labor saving and improving their work environment, HCVs had better impact on the environment in terms of CO2 emission and fuel consumption. The experiments by MLIT (2019) found that CO2 emission could be reduced about 40% when an HCV over 21m was used instead of a normal freight truck of 12m. MLIT saw the reduction in CO2 emissions to 39.1kg-CO2 per 1000 t-km in a 21m HCV from 56.6kg-CO2 per 1000 t-km. Emissions were further lowered to 32kg-CO2 per 1000 t-km when an HCV over 21m was used.

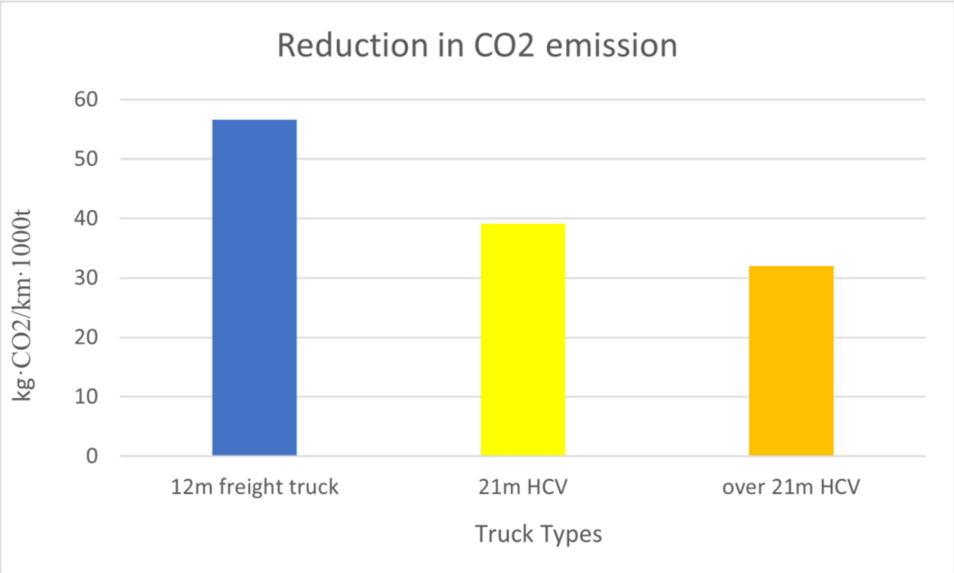


Fig. 2.13 Reduction in CO2 emissions (source: MLIT, 2019)

In terms of fuel consumption, HCVs consumed less than about 44% (12.2L per 1000 t-km in an HCV of vehicle length over 21m) and 14.9L per 1000 t-km (about 31%) in an HCV of 21m, compared to 21.6L per 1000 t-km in a 12m freight vehicle.

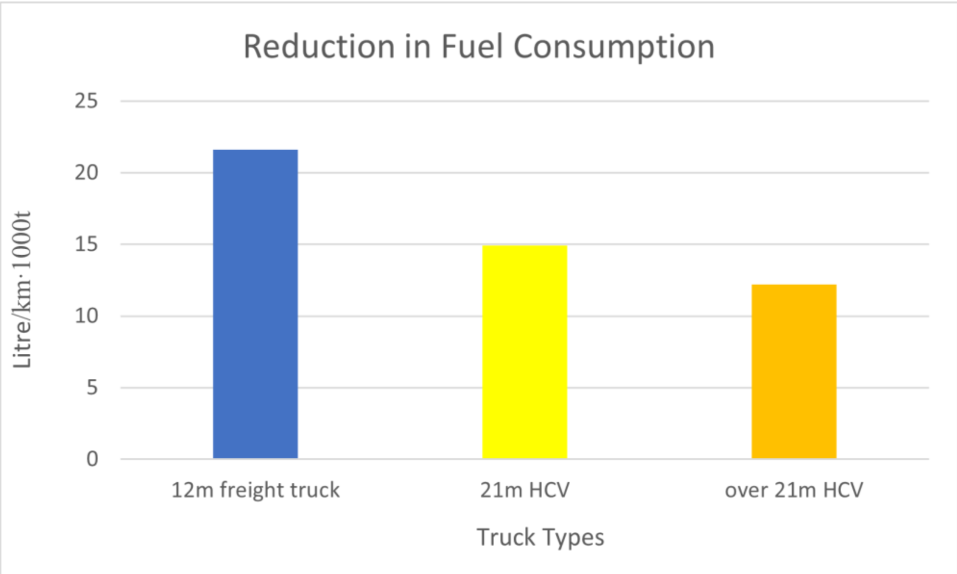


Fig. 2.14 Reduction in fuel consumption (source: MLIT, 2019)

3. Theoretical Study on Methodology

3.1. Experiments and Vehicle Movement Data

3.1.1. Vehicles used in Experiments

The truck movement data used in this study were obtained from the results of the high capacity vehicle experiments conducted by the Ministry of Land, Infrastructure, Transport and Tourism and the Chubu Regional Development Bureau. The experiments that produced the data were conducted in October and November 2017 and from March to July 2018. There were total 151 experimental runs operated by four logistics companies.

The vehicles and the tractor and trailer types used in the experiments are different to each company. Tables 3.1 and 3.2 and Fig 3.1 show their attributes.

Table 3.1 HCV attributes of each company (source: MLIT, 2019)

Company Name	Length(m)	Height(m)	Width(m)	Axles in Tractor	Axles in Trailer	Max. Load Capacity(t)
Fukuyama Transporting	24.975	3.79	2.49	4	2	26.3
Yamato Transport	24.995	3.78	2.49	4	2	26.3
Nippon Konpo Unyu Soko	22.965	3.79	2.49	4	3	27.8
Seino Transportation	24.790	3.79	2.49	4	3	26.3

Table 3.2 Trailer types in experiments (source: MLIT, 2019)

Company Name	Maker	Trailer type
Fukuyama Transporting	Nippon Trex	Dolly type full trailer (dolly non-separable type)
Yamato Transport	Nippon Trex	Dolly type full trailer (dolly non-separable type)
Nippon Konpo Unyu Soko	Hanama Works	Center axle type full trailer
Seino Transportation	Toho Vehicle	Semi-trailer (dolly separation type)

Fig. 3.1 Types of trailers in experiments (source: MLT, 2019)

3.1.2. Equipment used in Experiments

The truck movement data were recorded by using GPS (global positioning system) loggers, accelerometers, and heart rate sensors. Smartphones installed with a GPS logger, a 3-axis gyro sensor, and a rolling moment sensor were equipped in the front and the rear of each truck. The equipment measured the following of each tractor and trailer: their location, 3-axis and combined accelerations, and rolling and pitching.

The combined acceleration can be calculated from 3-axis accelerations as follows:

$$c = \sqrt{x^2 + y^2 + (z - 9.8)^2} \tag{1}$$

where c is the combined acceleration,

x is the x-axis acceleration,

y is the y-axis acceleration,

z is the z-axis acceleration.

To measure the driver stress conditions and truck speeds, the drivers in the experiments wore the wristwatch heart rate monitors equipped GPS functions. This device logged location information and heart rates of the driver, and the truck speed. In addition, the equipment recorded the date and time of the experiments, the operating company, and their trip ID and driver ID. The devices used in the experiments can log the data to the shortest time interval of one second. Fig 3.2 shows how the equipment are installed on an HCV.

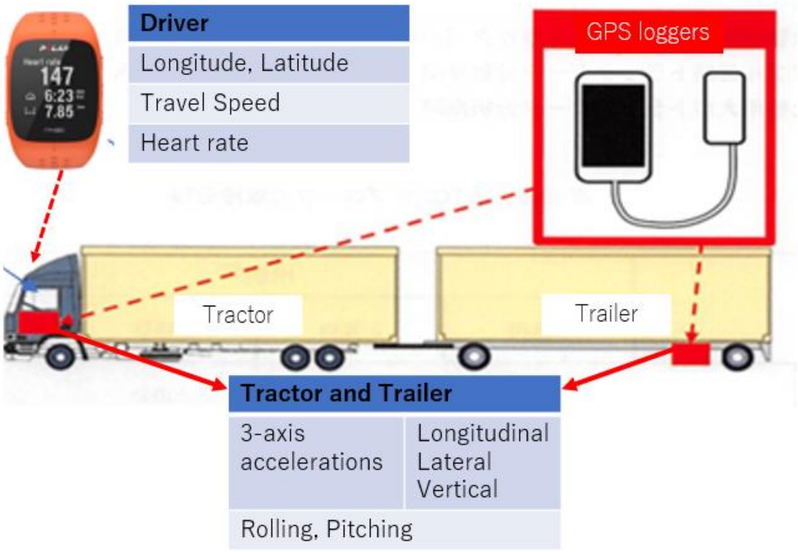


Fig. 3.2 Data logger on an HCV (source: Watanabe and Hyodo, 2020)

3.1.3. Data Description

Combining all the data from the above devices, total 940736 GPS data points were generated in the experiments. The final dataset becomes available in a comma-separated value format (csv). Table 3.3 lists the variables measured in the experiments.

Table 3.3 Variables measured in HCV experiments

Item	Description	Unit
year	Experiment date (year)	
month	Experiment date (month)	
day	Experiment date (day)	
H	Experiment time (hour)	
M	Experiment time (minute)	
S	Experiment time (second)	
tract.accx	Tractor x-axis acceleration	m/s^2
tract.accy	Tractor y-axis acceleration	m/s^2
tract.accz	Tractor z-axis acceleration	m/s^2
tract.pit	Tractor pitching	degree
tract.rol	Tractor rolling	degree
tract.y	Tractor latitude	
tract.x	Tractor longitude	
trail.accx	Trailer x-axis acceleration	m/s^2
trail.accy	Trailer y-axis acceleration	m/s^2

trail.accz	Trailer z-axis acceleration	m/s^2
trail.pit	Trailer pitching	degree
trail.rol	Trailer rolling	degree
trail.y	Trailer latitude	
trail.x	Trailer longitude	
drive.y	Latitude	
drive.x	Longitude	
drive.hr	Heart rate	bpm
drive.velo	Velocity	km/h
trp	Trip ID of each company	
tract.acc	Tractor 3-axis combined acceleration	m/s^2
trail.acc	Trailer 3-axis combined acceleration	m/s^2
comp	Operating company	
drv.id	Driver ID	
trp.comp	Trip and company ID	

From the above table 3.3, the dataset is available as (940736 rows x 31 columns). From this point onward, the companies will be anonymously abbreviated as "A", "B", "C" and "D" for the research purposes. The summaries of each company's data are described in the following table 3.4.

Table 3.4 Data summary of each company

Company	No. of data points	No. of drivers	No. of trips
Company A	224611	1	32
Company B	317824	11	61
Company C	276259	2	30
Company D	122042	2	28

In the above dataset, the driver information of the company C and company D is found to be missing. The driver ID of the company C trip ID 17 is missing for 3901 data points. The driver ID of the company D trip ID 19 is missing for 1153 data points.

3.2. A Brief Introduction to Machine Learning

Machine learning is defined as the study of computer algorithms that teach machines and computers to learn from existing data to make predictions on new data without being explicitly programmed (Gupta, 2019). Machine learning algorithms can be divided into three major categories: supervised learning, unsupervised learning, and reinforcement learning.

Supervised machine learning algorithms model the relationships and dependencies between the target prediction output and the input variables. The output values are predicted based on the relationships the computer learns from the original dataset. Supervised machine learning algorithms are used in classification and regression problems.

Unsupervised machine learning algorithms are used when the computer deals with unlabeled data. They are primarily used when there are no output results to validate the efficiency of the learning process. By unsupervised learning, the computer learns to extract features and discovers underlying patterns. When the learning process is complete, the data can be labeled. Unsupervised machine learning algorithms are applied in clustering, anomaly detection and association mining.

Reinforcement machine learning is an area of machine learning that allows intelligent agents to automatically determine the ideal behavior and take actions in an environment to maximize its performance. The applications of reinforcement learning algorithms can be found in self-driving vehicles, robotic hands and so on.

In this study, unsupervised machine learning is applied to analyze and evaluate the driving characteristics of high capacity vehicles in Japan. Clustering is one of the unsupervised machine learning techniques, defined as the process of grouping similar entities together (Gupta, 2019). The process is to split the dataset into groups based on their similarity. The purpose of the algorithm is to find similarities in the dataset, which will detect and give insights on the underlying patterns of different groups. Among the clustering algorithms, the commonly used techniques include centroid-based clustering (partition-based clustering), density-based clustering, hierarchical clustering, distribution-based clustering, and fuzzy clustering.

3.3. K-Means Clustering

K-means clustering is one of the centroid-based clustering algorithms which clusters data of similar features into K clusters with the help of Euclidean distance (Prasad, 2020). In the algorithm, K means the number of clusters to which the dataset will be clustered and assigned. To initiate the algorithm, K needs to be defined first. Then the algorithm is initialized by placing K centroids randomly in the dataset. In the clustering process, the cluster centroid is recalculated as a mean of all data points in the corresponding cluster, using the Euclidean distance between the data points and centroids at each iteration. This process is repeated, and the centroid locations are updated after every iteration until no further changes occur.

According to Gupta (2019), K-means clustering is a relatively simple algorithm to apply. The algorithm is also applicable to large datasets. In addition, it can be generalized to implement in clusters of various shapes.

In terms of visual analytics of movement data, Andrienko et al. (2013) suggested that the usefulness of partition-based clustering such as k-means clustering depends on the properties of the data and the analysis target and found it reasonable to group the data based on their numeric attributes such as speed, duration, the number of stops and so on.

Steps of K-means clustering algorithm can be mathematically simplified as follows.

Firstly, let the Euclidean distance between x and y be defined as

$$dist(x, y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \tag{2}$$

where n represents the number of data points,

$x = (x_i, \ldots, x_n)$,

$y = (y_i, \ldots, y_n)$

Then, a centroid for each cluster needs to be selected. For the number of clusters k, let the cluster be defined as $C_1, \ldots, C_k$ with the corresponding centroids $c_1, \ldots, c_k$. Minimizing the distance between the data points and the cluster is the same as minimizing the square of the distance. Thus, the distance will be redefined as $dist^2(x, y)$.

For each element x in the dataset S, it will be assigned to their nearest centroid. The minimum distance value needs to be calculated. Let this value be defined as j. Mathematically it can be expressed as

$$C_j = \{x: \min_n dist^2(x, c_n) = j\} \tag{3}$$

In the case the centroids do not belong to the dataset S, the new centroid needs to be selected for each cluster and the cluster center is updated as follows:

$$c_j = \frac{1}{m_j}\sum_{x \in C_j} x \tag{4}$$

where c_j is the centroid j,

m_j represents the number of data points in j-th cluster.

By the above, the K-means clustering algorithm iterates continuously to cluster again and update the centroids at each iteration. The clusters and centroids are updated until no further changes occur. Therefore, the sum of squared errors value needs to be minimized. The termination conditions can be defined as follows:

$$SSE = \sum_{j=1}^{k}\sum_{x \in C_j} dist^2(x, c_j) \tag{5}$$

where SSE stands for the sum of squared errors.

In this context, Wierzchoń and Kłopotek (2018) defined SSE as the optimization criterion function. The points, at which the partial derivatives of the function are equal to zero, are the condition to terminate the iteration threshold. Once the iteration is terminated, the resulting clusters become the final clustering result of the K-means clustering algorithm.

3.3.1. Elbow Method

One of the disadvantages of K-means clustering is the requirement to define the K value. Therefore, it is difficult to see whether the pre-input K value is the correct or appropriate value. One of the methods to calculate the optimal number of K value is called the Elbow method (Dabbura, 2018). The method provides the optimal number of clusters based on the sum of squared distances between data points and their assigned clusters' centroids. K value is decided at the point where the sum of squared distance becomes linear and flattens to form an elbow curve. The point at which the elbow shape gets formed is called the elbow point and is taken as the optimal K value for the clustering algorithm.

Tibshirani et al. (2001) proposed the gap statistic to estimate the number of clusters. The method is designed to be able to virtually detect the cluster by calculating the sum of squared errors. The sum of squared errors can be mathematically calculated as

Let d_{ij} be the squared Euclidean distance between the data points i and j in a cluster.

$$d_{ij} = \left(d_i - d_j\right)^2 \tag{6}$$

The sum of distances between all points in a cluster can be defined as

$$D_r = \sum_{i=1}^{n_r-1} \sum_{j=i}^{n_r} d_{ij} \tag{7}$$

where D_r is the sum of distances between all points in a cluster,

n_r is the number of points in a cluster r

The average internal sum of squares is the average distance between points inside a cluster. Mathematically it can be defined as

$$W_k = \sum_{r=1}^{k} \frac{1}{n_r} D_r \tag{8}$$

where k is the number of clusters,

W_k is the sum of squares.

To obtain the optimal number of clusters, the sum of squares value decreases as the number of clusters increases and at one point, the graph will start to smooth out. This point is taken as the Elbow point.

3.3.2. Silhouette Analysis

Although the number of clusters k is known, such k is not always the proper value to cluster (Wierzchoń and Kłopotek, 2018). It is important to measure the accuracy or goodness of the clustering algorithm (Bhardwaj, 2020). One of the methods to apply in identifying the goodness of clustering is optimization of criterion function characterizing the properties of mixtures of the probability distributions (Wierzchoń and Kłopotek, 2018).

Among the optimization methods, one of the applications to evaluate the cluster quality is called the Silhouette analysis. The silhouette coefficient or score introduced by Rousseeuw in 1987 shows which objects lie well within the cluster and which objects are in an intermediate position (Kaufman and Rousseeuw, 2005). Thus, the silhouette analysis is the comparison of within-cluster cohesion and between-cluster separation. The silhouette analysis is applied when the data are assumed to have been already clustered into k clusters.

The silhouette coefficient can be expressed mathematically as follows:

For data point i in the cluster C_i,

$$a(i) = \frac{1}{|C_i| - 1} \sum_{j \in C_i, i \neq j} d(i,j) \quad (9)$$

where a(i) is the mean distance between data point i and all other data points in the same cluster,

d(i,j) is the distance between data points i and j in the cluster C_i.

Therefore, a(i) measures cohesion, meaning how well the data point is assigned to its cluster so the smaller value implies the better assignment.

Next, the mean dissimilarity of data point i to the cluster C_k, is defined for each point i in the cluster C_i,

$$b(i) = \min_{k \neq i} \frac{1}{|C_k|} \sum_{j \in C_k} d(i,j) \quad (10)$$

where b(i) is the smallest mean distance of data point i to all points in any other cluster, of which i is not the member,

Thus, the silhouette value s(i) of a data point can be defined as

$$s(i) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}}, \text{ if } |C_i| > 1 \quad (11)$$

$$s(i) = 0, \text{ if } |C_i| = 1 \quad (12)$$

The equation can be rewritten as:

$$s(i) = \begin{cases} 1 - \frac{a(i)}{b(i)}, & if a(i) < b(i) \\ 0, & if a(i) = b(i) \\ \frac{b(i)}{a(i)} - 1, & if a(i) > b(i) \end{cases} \tag{13}$$

From the above definition, the silhouette score is found to lie between

$$-1 \leq s(i) \leq 1 \tag{14}$$

The silhouette coefficient defines how well the objects are clustered. On approach to +1, it means the objects are appropriately clustered and they match with each other in their cluster. When the value approaches to 0, the clusters become indifferent, meaning the objects could overlap each other from another cluster. As the coefficient gets close to -1, the objects are not well clustered and could be assigned in the wrong cluster.

3.4. Computation

Applying the above-mentioned data and clustering algorithm, the calculations are carried out in the following computation environment. Spyder 1.4.1 IDE (integrated development environment) is the primary IDE where the computations are mostly done. Python 3.8.3 is used as the main programming language. Moreover, the following python packages are applied in computation processes: pandas 1.18.5 for data frame manipulation and analysis, matplotlib 3.2.2, seaborn 0.11.0 and plotly 4.14.3 for data visualization, and yellowbrick 1.2 and sklearn 0.23.1 for machine learning purposes.

To convert the clustered truck movement data from the csv format to visualize on the map and for spatial analysis purposes carried out in this study, QGIS 3.10.13 A Coruna version and ArcGIS Pro 2.4.0 version are applied.

3.5. Methodology Overview

Using the available dataset, the raw data will be processed first. Then the processed data will be evaluated for the optimal clustering k value and the cluster quality before the data are fed into the k-means clustering algorithm. The resultant clusters are then visualized in GIS. Finally, each cluster and their attributes will be analyzed. The step-by-step flow of research conducted in this study is summarized as follows.

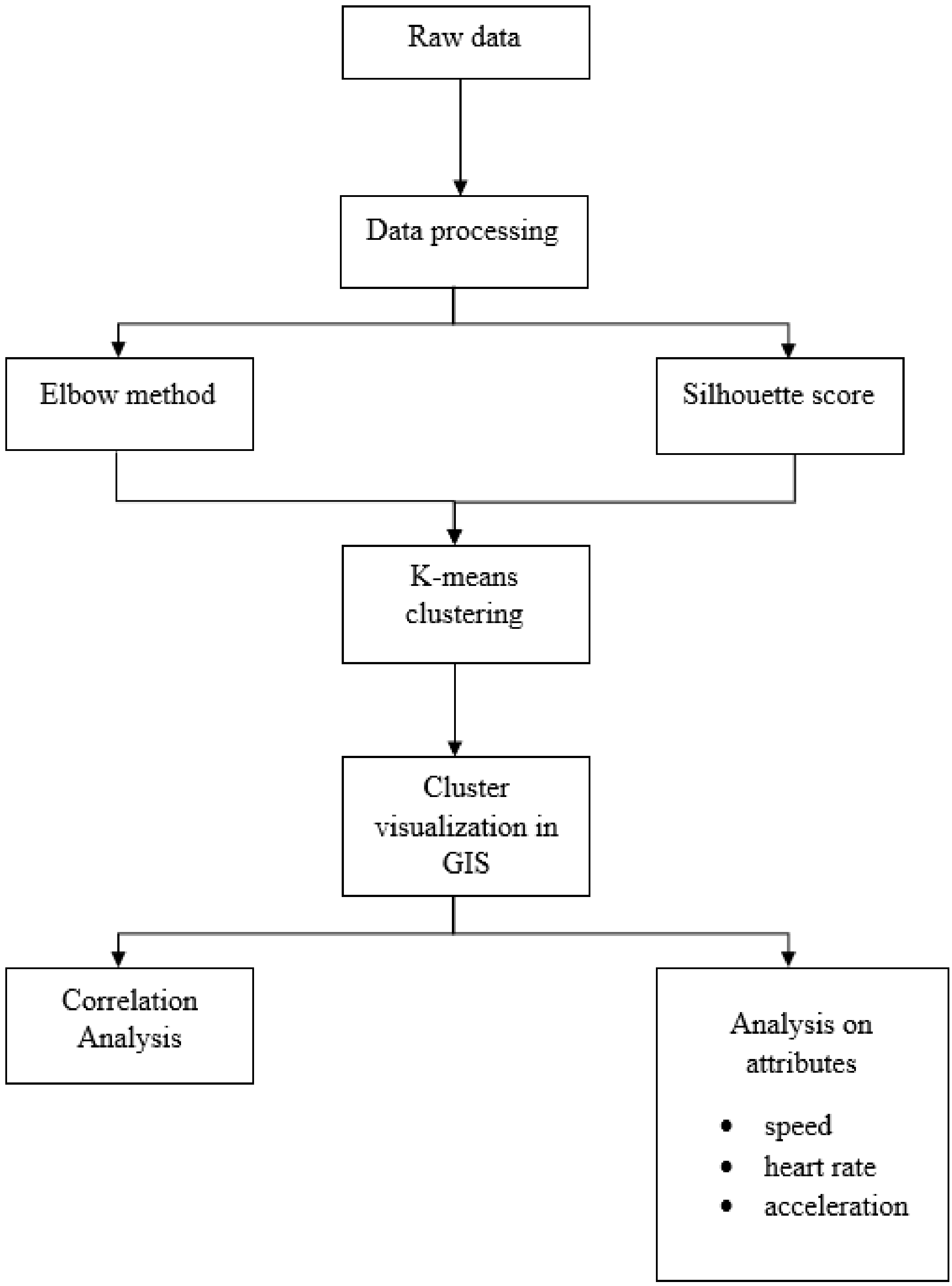


Fig. 3.3 Research steps

4. Analysis on Clustering Results

4.1. Selecting K Value

In this chapter, the driving characteristics of high capacity vehicles are analyzed by applying k-means clustering algorithm. Before k-means clustering algorithm is applied, the optimal number of clusters is calculated first and then the cluster quality is evaluated as explained in chapter 3: 3.3.1. and 3.3.2. However, before the above evaluation methods are applied, the variables related to the driving characteristics are selected first. Among 30 variables recorded by the equipment in the experiments, particular variables applicable to driving characteristics such as 3-axis and combined accelerations, rolling and pitching, geographic location, truck speed, and the driver's heart rate are selected. The total number of selected variables are 20.

Table 4.1 Selected variables in the computation

Accelerometer		**GPS logger**	**Heart rate monitor**
Tractor	**Trailer**		
x-axis acceleration	x-axis acceleration	tractor latitude	heart rate
y-axis acceleration	y-axis acceleration	tractor longitude	truck speed
z-axis acceleration	z-axis acceleration	trailer latitude	
combined acceleration	combined acceleration	trailer longitude	
rolling	rolling	driver latitude	
pitching	pitching	driver longitude	

According to the computation steps described in chapter 3.3.1. and 3.3.2, the Elbow method and Silhouette coefficient are calculated using the selected variables. The results of the sum of squared errors and Silhouette coefficient are summarized in Table 4.2. The results are then visualized in graph forms.

Table 4.2 Cluster Evaluation Result

k	Silhouette score	Sum of squared errors
1		744367549
2	0.556874	395074983.1
3	0.323486	283813666.8
4	0.323332	241812637.2
5	0.266859	211148434.7
6	0.262763	191879501
7	0.215114	179268000.6
8	0.217078	168621301.4
9	0.22392	158921253.7
10	0.199782	152987357.8
11	0.191731	147722261.4

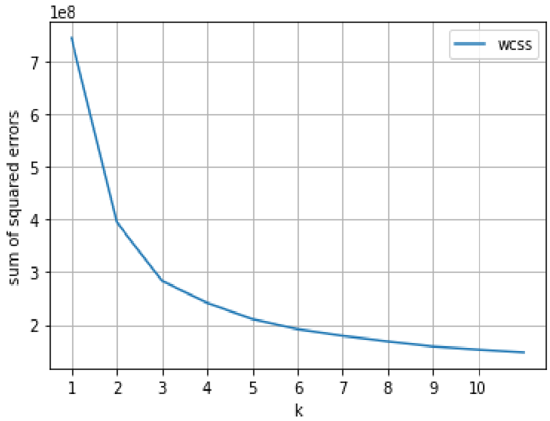


Fig. 4.1 Elbow curve

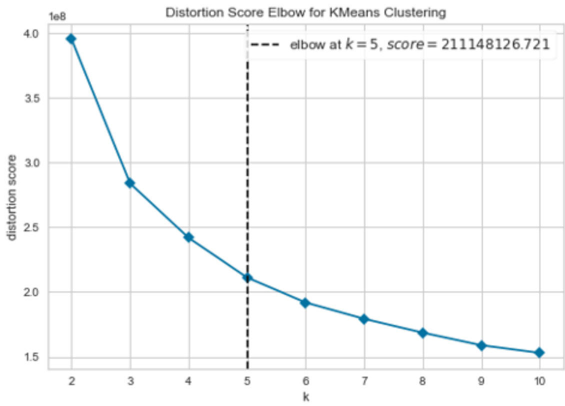


Fig. 4.2 Elbow curve (yellow brick)

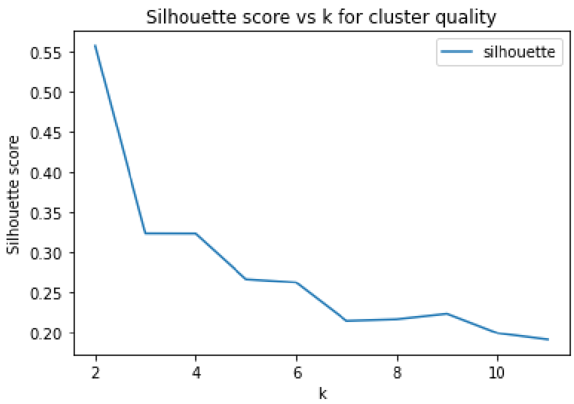


Fig. 4.3 Silhouette score

From the above figures, the Elbow point lies at cluster k=5. Figure 4.1 is calculated using the Elbow curve calculation steps as described in chapter 3.3.1 while Figure 4.2 is directly calculated with the Python package. The numerical result is slightly different. Comparing the clusters with Silhouette coefficient (0.266859), the cluster quality for k=5 is found to be relatively lower than that of lower k values whose Silhouette coefficients are higher.

4.2. Cluster Description

Once the k-means clustering is completed, the resultant dataset is converted to geographic information system file format (shp) by converting the location information to the coordinate reference system (CRS) to EPSG 4326 (WGS 84). Figure 4.4 shows the raw experimental data points after conversion before each cluster is selected. The experiments cover the routes along the Pacific coastline of Japan from Atsugi-shi in Kanagawa Prefecture to Ibaraki IC in Osaka Prefecture. Each company route and each trip is different to each other as their origin and destinations are dependent on the location of their logistics facilities.

Fig. 4.4 Truck movement data point

After data processing and applying k-means clustering with k=5, the resultant clusters are grouped as in Table 4.3 and visualized in the following figures from Fig 4.5 to Fig 4.10.

Table 4.3 Number of data points in each cluster

Cluster	Number of data points
1	266845
2	351355
3	85633
4	142174
5	94729

Fig. 4.5 Overall Clusters

Fig. 4.6 Cluster 1

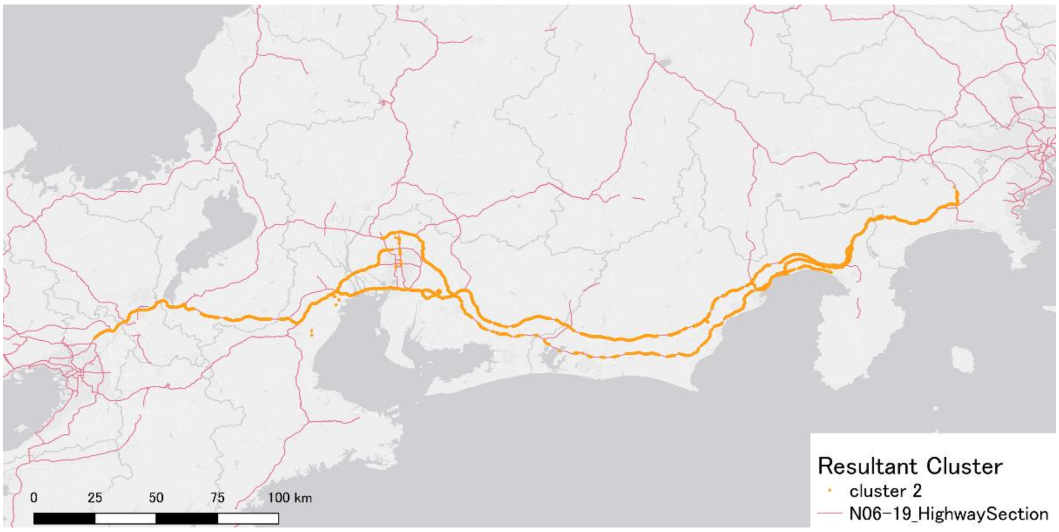


Fig. 4.7 Cluster 2

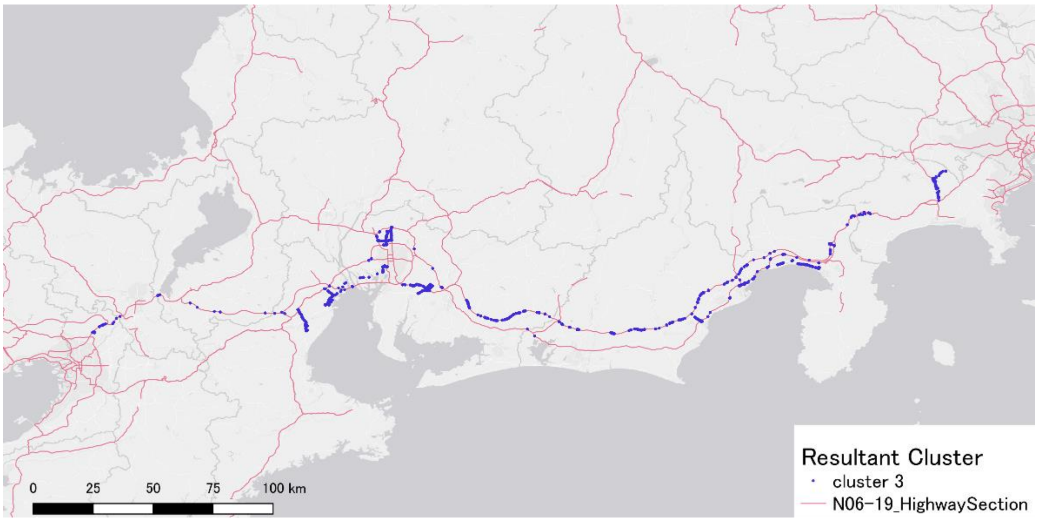


Fig. 4.8 Cluster 3

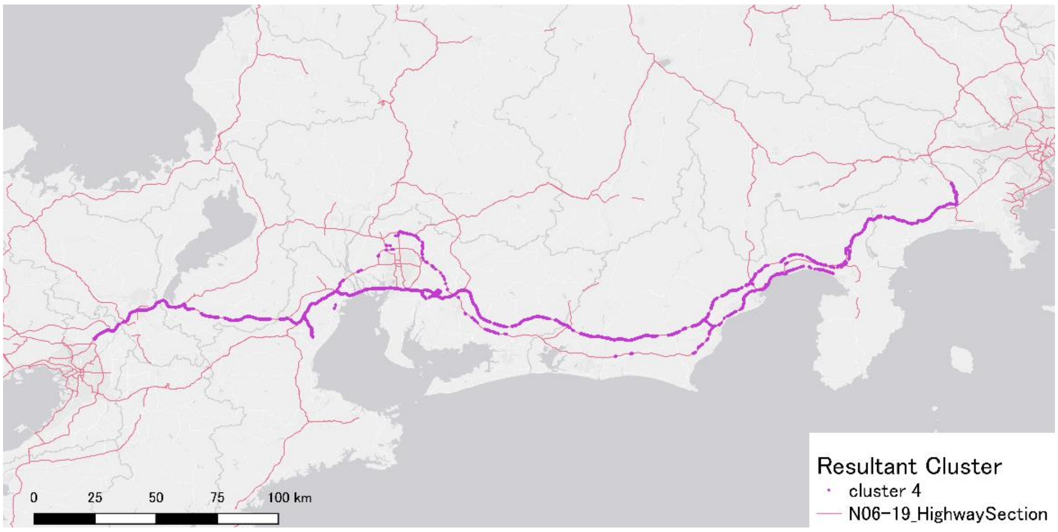


Fig. 4.9 Cluster 4

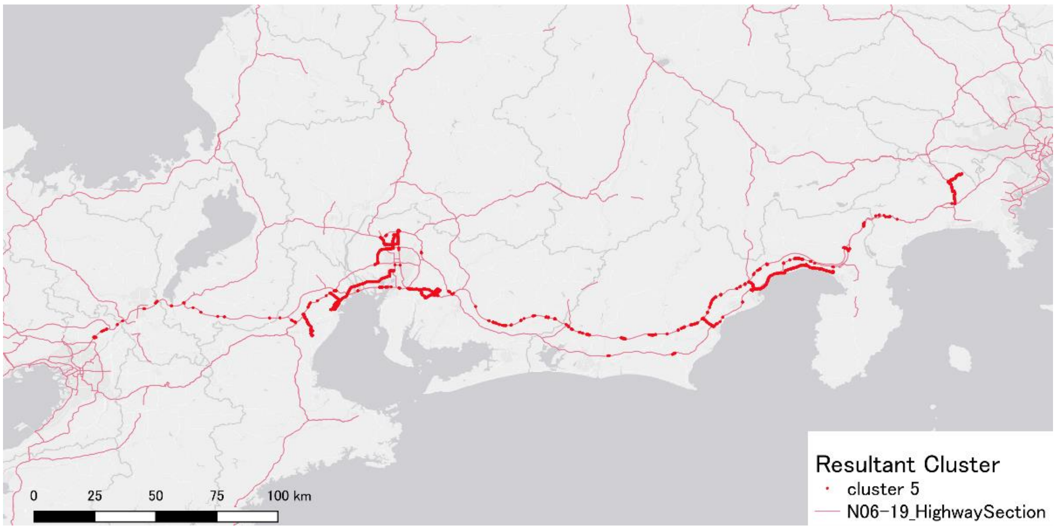


Fig. 4.10 Cluster 5

Figure 4.4 shows the major clusters that are dominant on each section throughout the trips. From Table 4.3 and the above figures, the clusters 1 and 2 are the most dominant among the clusters. Clusters 1, 2 and 4 are present throughout all the trips and on expressways. Comparing the driving characteristics on the Tomei Expressway, cluster 1 is found to be more significant than cluster 2. However, cluster 4 characteristics are exhibited on almost all expressways except the Tomei Expressway and the Kinki Expressway. Cluster 3 is mostly concentrated near the places of origin and destination such as logistics facilities, service areas or parking areas (SA/PA) on the Shin-Tomei Expressway, and on urban roads. The characteristics of cluster 5 are detected highly concentrated on urban road networks near Nagoya area and SA/PAs on the Shin-Tomei Expressway as well as on Kinki Expressway.

4.3. Tractor and Trailer Behavior

Watanabe and Hyodo (2020) conducted the study on the driving characteristics of HCVs by aggregating the GPS data points and expressway interchange and/or junction points (IC/JCT). By aggregation, their research showed the average values of running characteristics and their relation to each other in vicinity of IC/JCTs. Inspired by their study, the correlation analysis is done in this research to discover the relationships of truck driving characteristics.

Table 4.4 Correlation of tractor behavior in each cluster

k		tract_accx	tract_accy	tract_accz	tract_pit	tract_rol
k=1	tract_accx	1				
	tract_accy	0.0370278	1			
	tract_accz	-0.195025	-0.313352	1		
	tract_pit	0.0451925	-0.6538	0.2018247	1	
	tract_rol	0.5597547	-0.037209	-0.039227	0.0926866	1
k=2	tract_accx	1				
	tract_accy	0.1912988	1			
	tract_accz	-0.194936	-0.219978	1		
	tract_pit	-0.152041	-0.727099	0.2246493	1	
	tract_rol	0.5457235	0.2206421	-0.086648	-0.300483	1
k=3	tract_accx	1				
	tract_accy	0.2321047	1			
	tract_accz	-0.110691	-0.203013	1		
	tract_pit	-0.270245	-0.825771	0.1101324	1	
	tract_rol	0.7435942	0.2189269	-0.073779	-0.269253	1
k=4	tract_accx	1				
	tract_accy	0.2280772	1			
	tract_accz	-0.131833	-0.126051	1		
	tract_pit	-0.244423	-0.771488	0.082552	1	
	tract_rol	0.6110554	0.3050282	-0.006419	-0.433659	1
k=5	tract_accx	1				
	tract_accy	0.0856481	1			
	tract_accz	-0.107125	-0.165892	1		
	tract_pit	-0.049486	-0.799949	0.0849396	1	
	tract_rol	0.6510143	0.0365247	-0.022985	-0.047411	1

Table 4.5 Correlation of trailer behavior in each cluster

k		trail_accx	trail_accy	trail_accz	trail_pit	trail_rol
k=1	trail_accx	1				
	trail_accy	-0.032159	1			
	trail_accz	0.2843439	-0.219372	1		
	trail_pit	-0.045152	-0.121736	-0.002359	1	
	trail_rol	0.1704655	0.0623679	-0.048636	-0.159039	1
k=2	trail_accx	1				
	trail_accy	-0.128507	1			
	trail_accz	0.1134532	-0.120457	1		
	trail_pit	-0.055806	-0.106283	-0.033436	1	
	trail_rol	0.2449499	0.051824	-0.055945	-0.19863	1
k=3	trail_accx	1				
	trail_accy	-0.157419	1			
	trail_accz	0.0181075	-0.118976	1		
	trail_pit	-0.009675	-0.37088	0.0606422	1	
	trail_rol	0.4634201	-0.014013	-0.079933	0.0114756	1
k=4	trail_accx	1				
	trail_accy	-0.123584	1			
	trail_accz	0.0490716	-0.10708	1		
	trail_pit	-0.016909	-0.11571	-0.014237	1	
	trail_rol	0.290209	0.0258486	-0.022224	-0.071587	1
k=5	trail_accx	1				
	trail_accy	-0.155682	1			
	trail_accz	0.0655973	-0.11434	1		
	trail_pit	-0.030732	-0.358855	-0.002226	1	
	trail_rol	0.3806412	0.0544319	-0.071086	-0.093527	1

As shown in the tables 4.4 and 4.5, calculation results show correlation coefficients of tractor and trailer behavior between 3-axis accelerations and rolling and pitching. From the tables, it can be seen in each cluster that tractor pitching is highly correlated to tractor y-axis acceleration (longitudinal acceleration). Tractor pitching and y-axis acceleration has strong negative correlation, meaning the increase in y-axis acceleration leads to the truck pitching backward. In all clusters, tractor rolling has strong positive correlation to tractor x-axis acceleration. The tractor is likely to roll to the right side with the increase in x-axis acceleration (lateral). However, the similar trailer behavior is not detected in all clusters. Their correlation is visualized in the following pair plot.

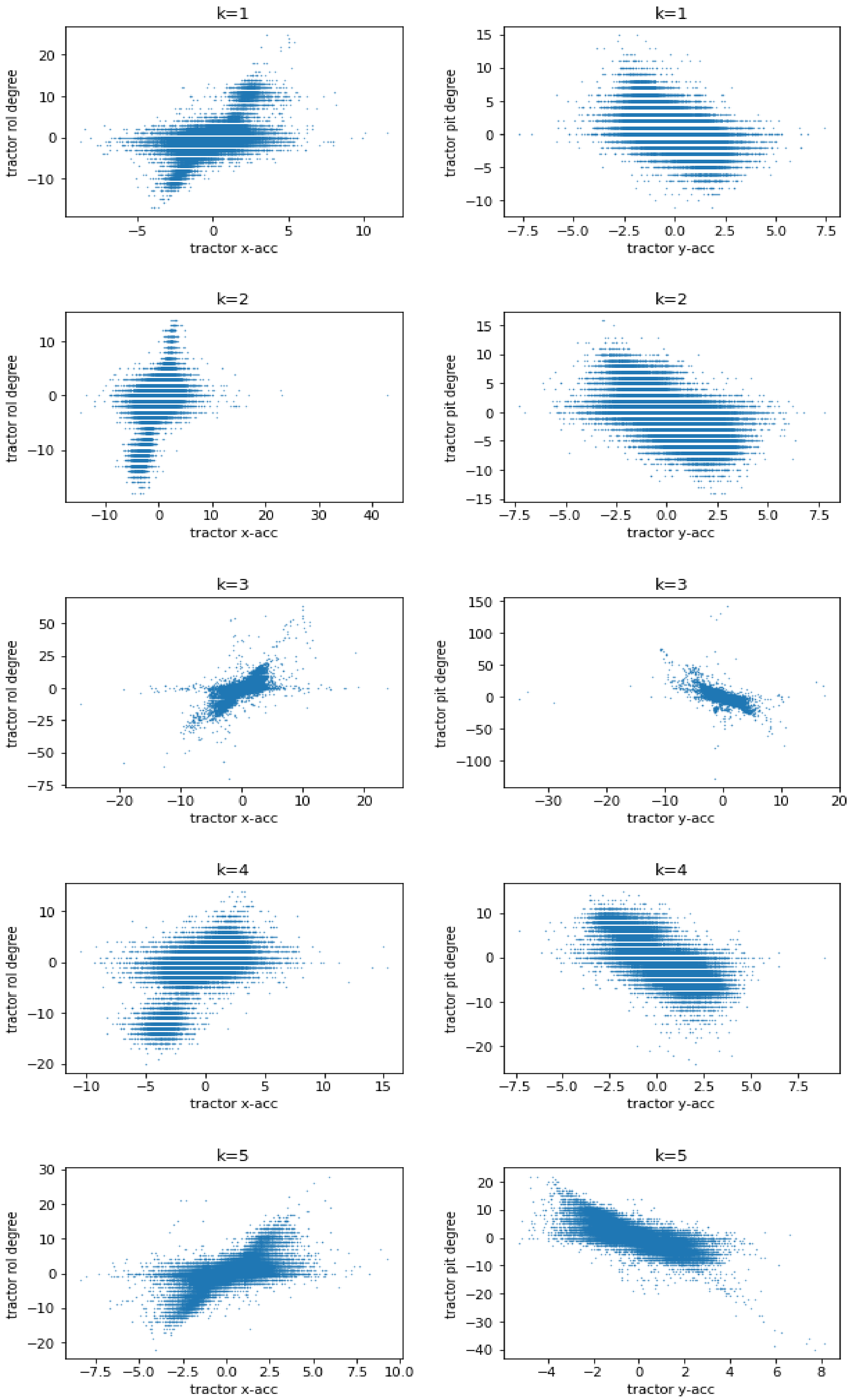


Fig. 4.11 Pair plot of tractor behavior

From Fig 4.11, the tractor x-axis acceleration and their rolling degree is not linear while in some clusters, their y-axis acceleration and pitching relation appears to be in linear form.

A linear regression is performed to calculate their goodness of fit between y-axis acceleration and pitching. The results are as follows.

k=1	$pit = -1.348 * accy + 0.53079$ $R^2 = 0.42745$	(15)
k=2	$pit = -1.69187 * accy - 0.42138$ $R^2 = 0.52867$	(16)
k=3	$pit = -3.38914 * accy + 0.1011$ $R^2 = 0.6819$	(17)
k=4	$pit = -2.14182 * accy - 0.40443$ $R^2 = 0.59519$	(18)
k=5	$pit = -2.45047 * accy + 0.36643$ $R^2 = 0.63992$	(19)

4.4. Comparison of Truck Speed and Heart Rate

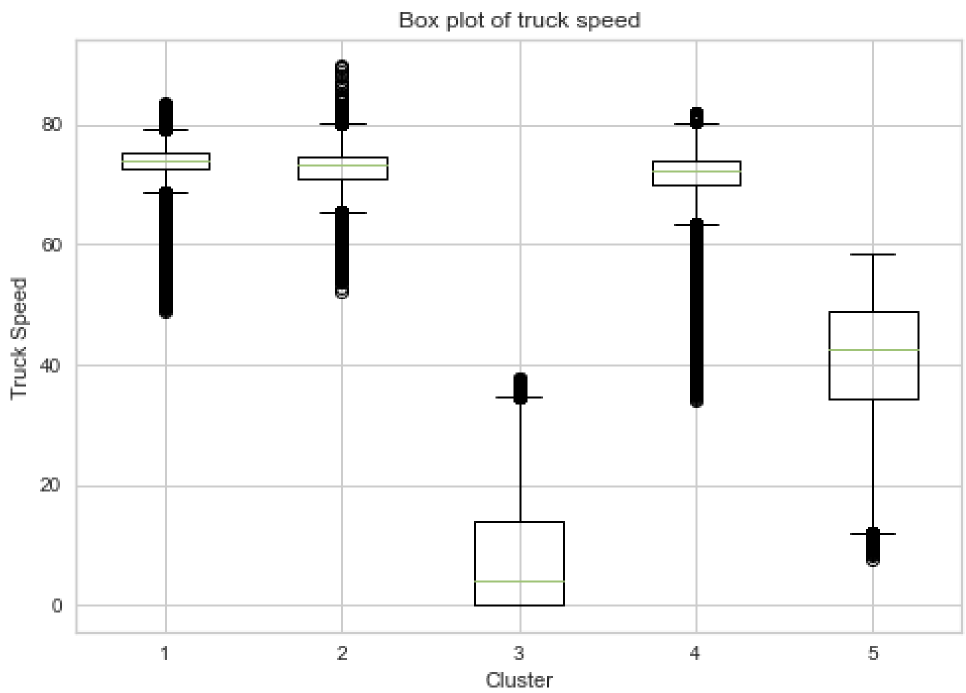


Fig. 4.12 Box plot of truck speed

Two of the most distinct truck driving characteristics after clustering is applied are truck speed and the driver heart rates. Figure 4.12 shows the behavior of HCV speed after clustering. As clusters 1, 2 and 4 are present throughout the trips and mostly on the expressways, their truck speed is higher than the rest clusters averaging 72 km/h. Since the cluster 3 is heavily concentrated in areas of logistics facilities and SA/PAs which are the places of arrival and departure, trucks run the slowest. The main presence of cluster 5 is on the urban road networks, they run slower than clusters 1, 2 and 4 with an average speed of 41 km/h.

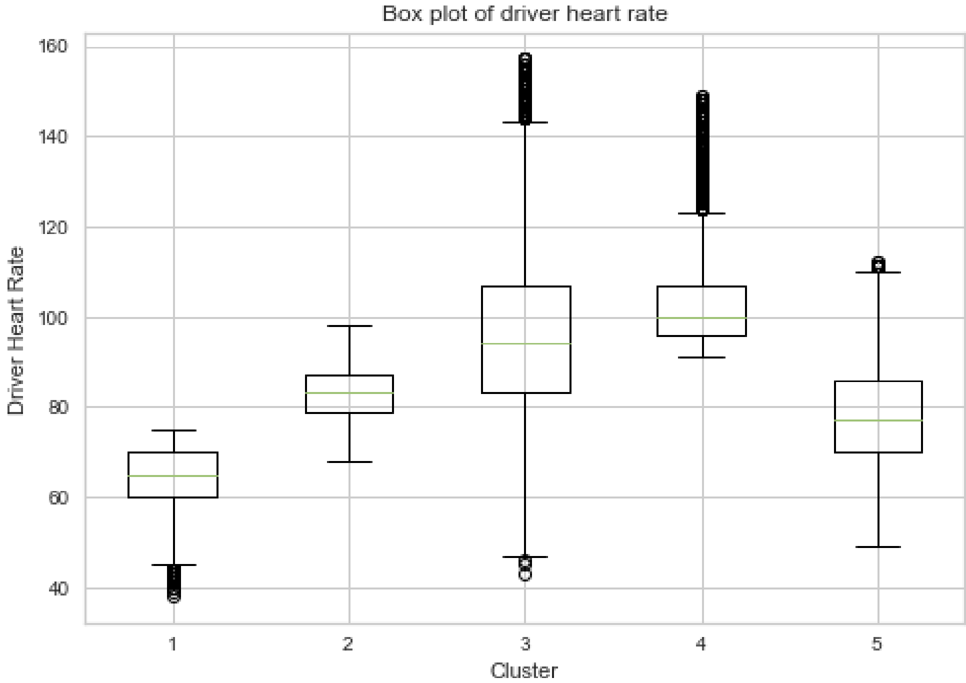


Fig. 4.13 Box plot of driver heart rate

Since clusters 1,2 and 4 are exhibited mostly on the expressways, their truck speed values almost similar. However, the driver's heart rates are found to be different to each other. Drivers tend to experience lower average heart rates (64.59 bpm) in cluster 1 than in cluster 2 (82.92 bpm). In cluster 4, the heart rates the drivers suffer average 102.55 bpm higher than both clusters 1 and 2 although their major presence is on the expressways. As cluster 3 behavior is concentrated in logistics facilities and SA/PAs, the drivers exhibit high average heart rates of 95 bpm. In cluster 5 which is mainly on urban roads, the drivers experience the average heart rate around 77 bpm. In both clusters 3 and 4, their average heart rates are detected to be the highest among all clusters. Thus, they have high outlying heart rates over 140 bpm in cluster 3 and 120 bpm in cluster 4. The outliers are visualized in GIS as follows.

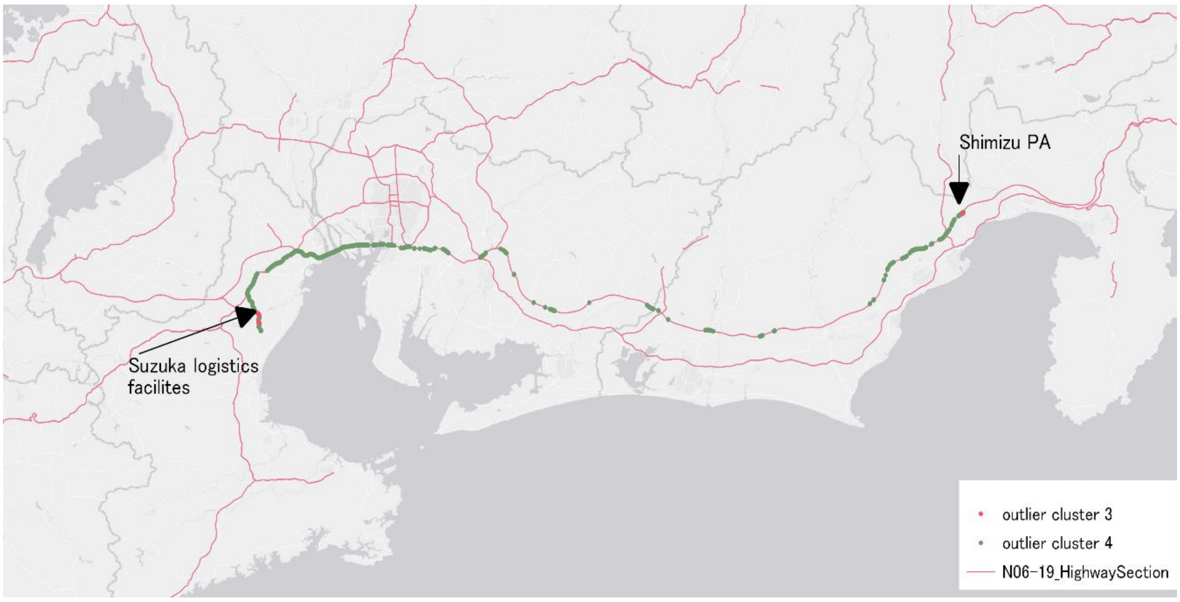


Fig. 4.14 Outlying heart rate locations

The outlying heart rates in cluster 3 are in vicinity of logistics facilities, and in cluster 4 on the Shin-Tomei Expressway and the Shin-Meishin Expressway near the origins and destinations of the trips. The outliers in heart rates detected in both clusters are found to be suffered by drivers of company C. All the company C's experimental routes are run along the Shin-Tomei, Isewangan and Shin-Meishin Expressways, and most of their trips start from the Shimizu PA in Shizuoka Prefecture to their logistics facilities in Suzuka-shi of Mie Prefecture. Therefore, how high heart rates the company C drivers tend to experience in each trip is studied by comparing to the drivers of other companies. The result shows that the average company C driver is likely to suffer higher heart rates than those of the rest companies. Hence, to compare how the average heart rates are different, near the logistics facilities where HCVs depart and arrive, the logistics facilities of each company will be selected to study how HCV behaviors, speed, and driver's stress in each facility's vicinity.

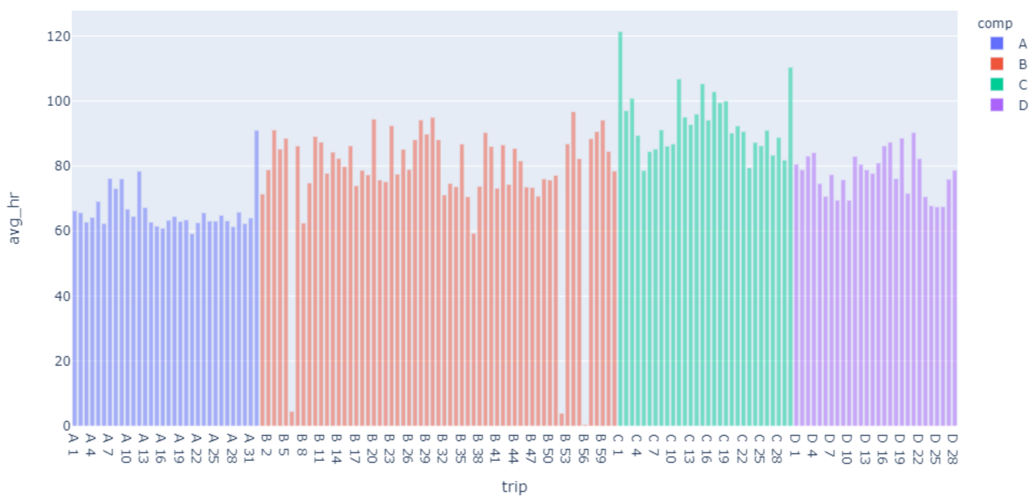


Fig. 4.15 Average heart rate by trip

4.5. Heart Rate Distribution by Buffer Analysis

Soma and Hyodo (2020) studied the driver stress and their relation to the high accelerations of longer and heavier vehicles for the safety of truck operation. In their study, heart rate variability analysis (RRI analysis) of high heart rate and stress related to the vehicle acceleration are focused. In this study, driver heart rate in outliers and in the logistics facilities of the cluster 3 will be studied using the geographic information system.

To spatially analyze the driver heart rates and HCV characteristics in logistics facilities, buffering technique is applied. Buffers are areas or zones around a geographic feature within a specified distance or time of that feature. Buffering is commonly used for proximity and location analysis in the geographic information system. Buffers can be created around a geographic feature such as a polyline, a point, or a polygon with a defined radius (ESRI, 2021).

Before buffer analysis is carried out, the following logistics facilities are selected in this study. As the radius needs to be specified for buffer creation, a 200m radius is defined to create a buffer. A 200m radius is selected in order to cover the overall logistics facility base and the truck operations within the base. For buffer analysis, the coordinate reference system must be set in the way that the distances are measured in actual distances, not in angular degrees. Therefore, CRS is again converted to EPSG 3857 (WGS 84 pseudo-Mercator projection) which measures the distance in meters.

Table 4.6 Selected logistics facilities in study

Comp ID	Facility	Location	Prefecture
1	Susono	Susono	Shizuoka
1	Nagoya	Nagoya	Aichi
2	Kansai	Ibaraki IC	Osaka
2	Chubu	Toyota-Higashi	Aichi
2	Atsugi	Atsugi	Kanagawa
3	Shimizu	Shimizu PA	Shizuoka
3	Koucho	Suzuka	Mie
3	Misonocho	Suzuka	Mie
4	Yokkaichi	Yokkaichi	Yokkaichi
4	Yaizu	Yaizu	Shizuoka
4	Numazu	Numazu	Shizuoka
4	Fuji	Fuji	Shizuoka
4	Komaki	Komaki	Aichi

Fig. 4.16 Buffer of logistics facilities

From buffer analysis, it is found that the average company C driver tends to experience higher heart rates at their logistics facilities, where their heart rates range as low as 60bpm to over 150 bpm. The highest heart rate of 157bpm is recorded at Shimizu PA. In all three of their facilities, the driver exhibits high heart rates, whose average is over 100bpm. At Shimizu PA, the average heart rate is the highest which is 113.54bpm among not only company C facilities but also the rest of the companies' facilities. At their facilities in Mie Prefecture, the Misonocho facility's average is 103.61bpm and 109.56bpm for the Koucho facility. The distribution of heart rates is as shown in Fig 4.17.

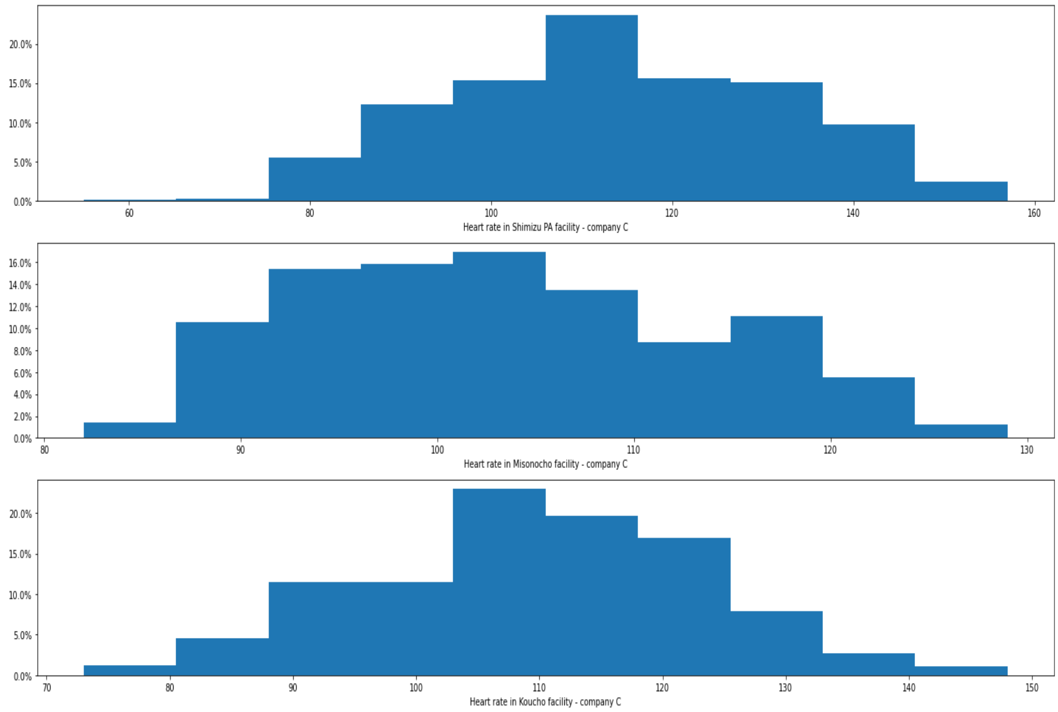


Fig. 4.17 Driver heart rate in company C facilities

Fig 4. shows the driver heart rate distribution in company A's logistics facilities and they are found to be lower than company C. Here, the heart rate drivers suffer range from 51bpm in Susono-shi logistics facility to 119bpm and the heart rate distribution is found to be normal. In Nagoya, over 70bpm heart rate accounts for one quarter of the total distribution. Their average heart rate in Susono-shi facility is 76.903 bpm, and 82.427bpm in Nagoya.

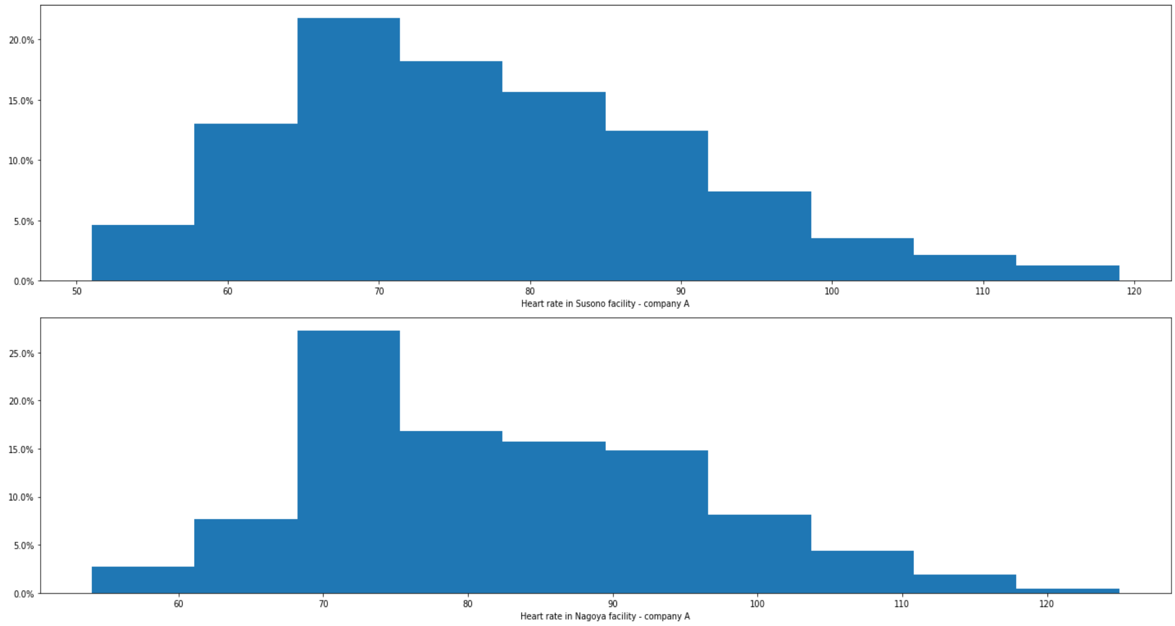


Fig. 4.18 Driver heart rate in company A facilities

Among the companies in the experiments, the company B accounts for the most number of experimental trips. At their Chubu logistics facility in Toyota-Higashi area in Aichi Prefecture and Kansai facility in Osaka Prefecture, their drivers' heart rate is mostly to be in normal distribution. At Atsugi logistics facility, the drivers tend to exhibit higher heart rates cver 100 bpm, which accounts for almost 60% of the total distribution. The Atsugi facility heart rate distribution is not normal compared to the other two facilities.

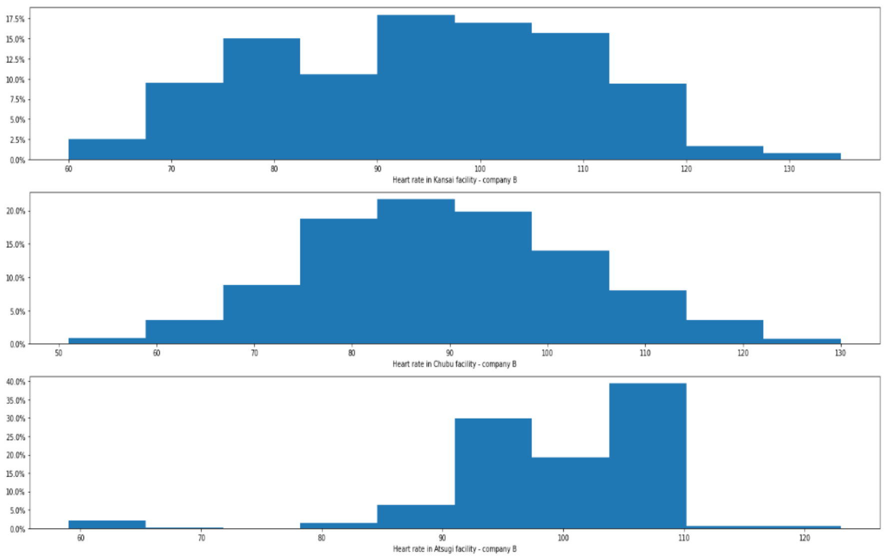


Fig. 4.19 Driver heart rate in company B facilities

In the logistics facilities of company D, the drivers are likely to experience slower heart rates compared to the above 3 companies. Their Komaki facility in Aichi Prefecture's driver heart rate tends to be in normal distribution with an average of 91.388bpm. In Yokkaichi facility, the drivers are likely to experience high heart rates, averaging 96.143bpm. Among 3 of their Shizuoka Prefecture facilities, the drivers experience the lowest stress in Fuji-shi facility with 75-80bpm accounting for almost 50% of the total distribution. In Yaizu facility, 60% of the total heart rates the drivers suffer range from 65 to 95bpm while the drivers tend to show higher heart rates in Numazu logistics facilities, averaging 98.116bpm.

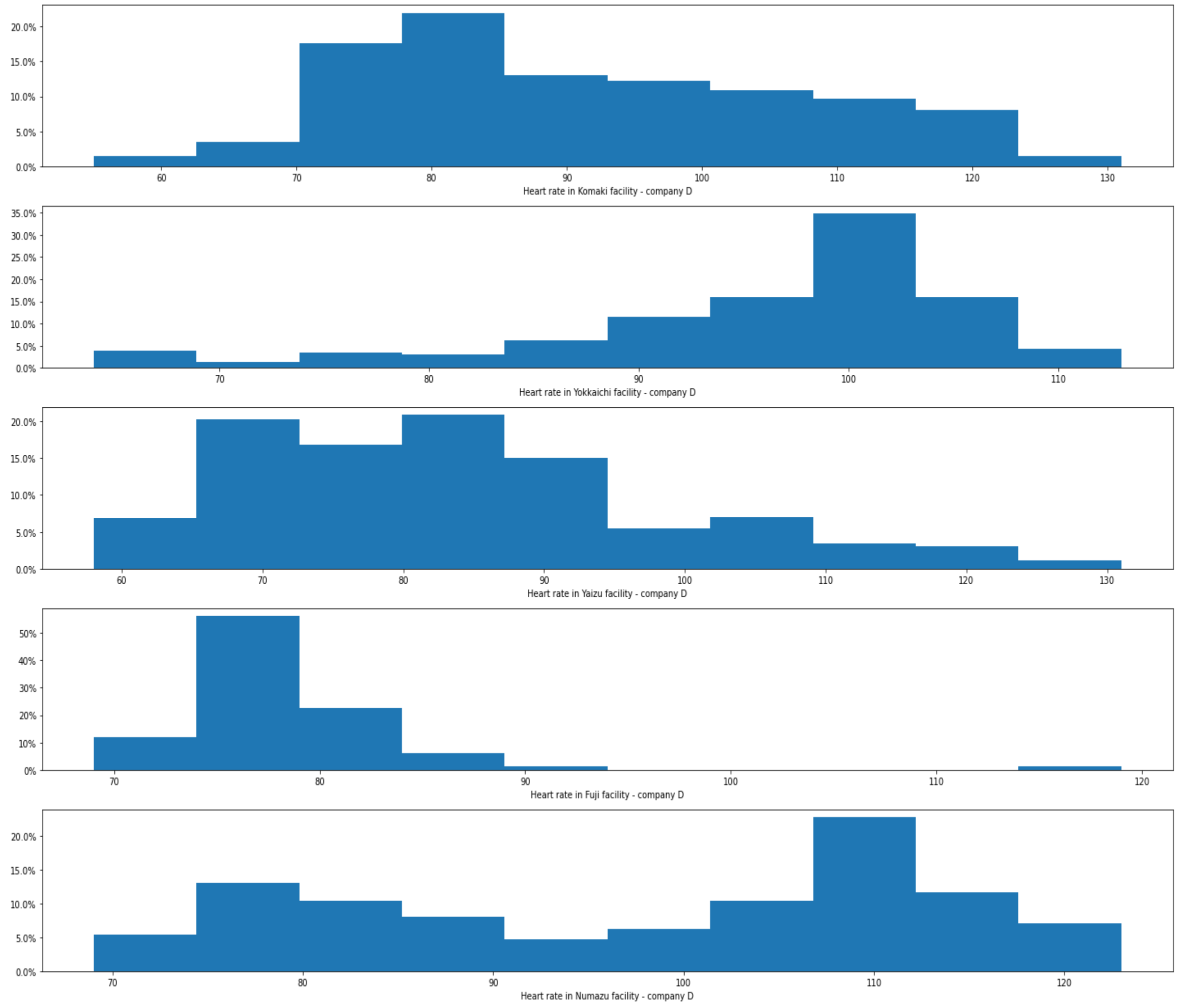


Fig. 4.20 Driver heart rate in company D facilities

From the above findings, the patterns the drivers experience and show their heart rates tend to be different from each facility. Thus, it is important for the drivers and logistics operators to be aware of safety of HCV operations in their surroundings and logistics facilities.

4.6. Findings on Rolling and Pitching

Weight transfer or load transfer on vehicles can occur due to the change in load borne by different wheels of the vehicles during acceleration or the change in the center of mass due to cargo shifting or sloshing on vehicles. These moments can be caused and observed as rolling and pitching of vehicles. As HCVs carry cargo, high rolling and pitching moments of both tractors and trailers can have impacts on and damage the cargo carried. In this study, high rolling and pitching characteristics of both tractors and trailers of HCVs on the Japanese expressways and normal roads will be studied. The below figures show the rolling and pitching moments of HCVs in experiment trips.

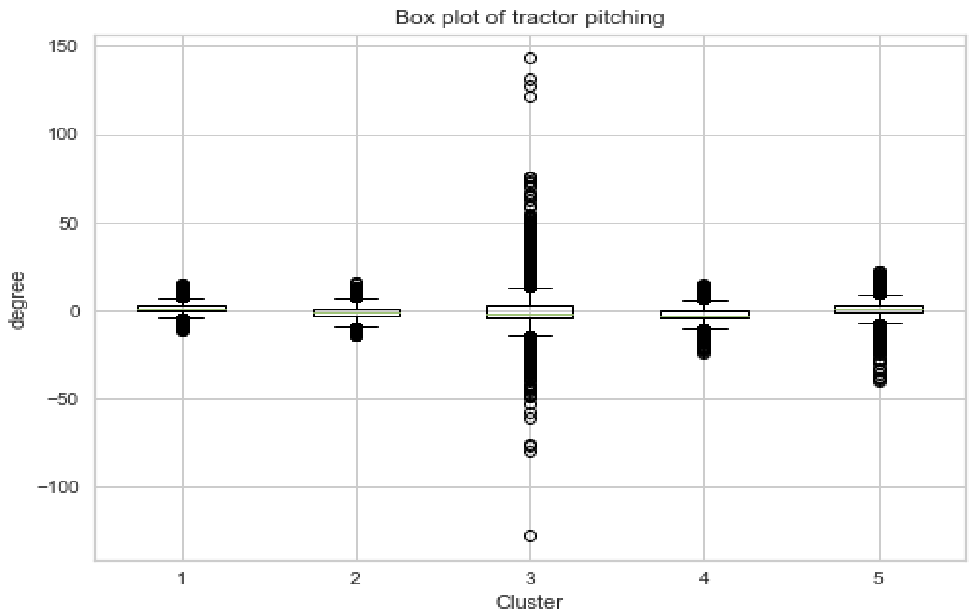


Fig. 4.21 Tractor pitching

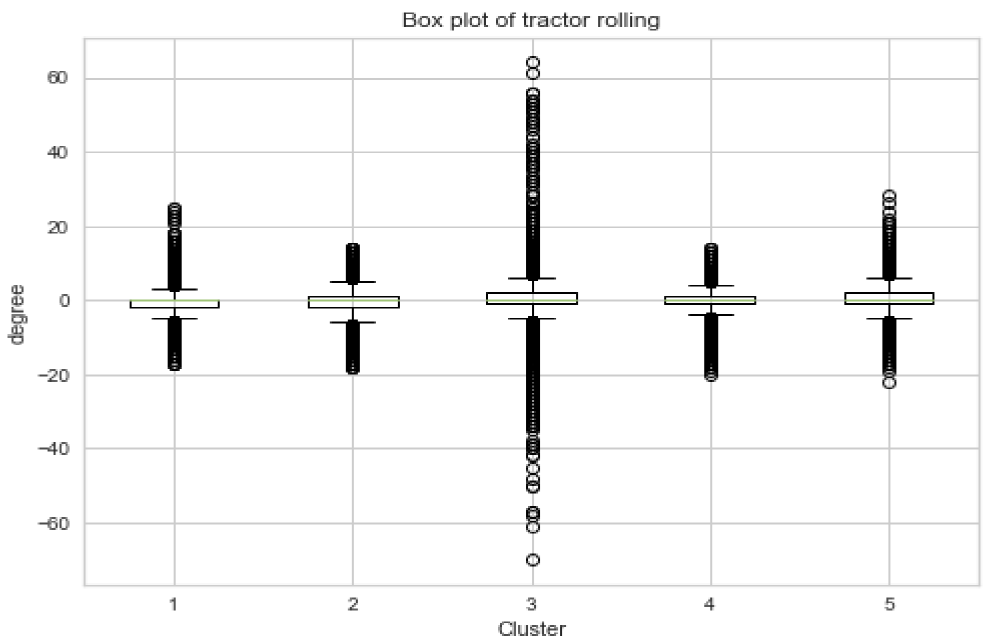


Fig. 4.22 Tractor rolling

From the above figures, cluster 3 has the highest outlier rolling and pitching moments of tractors. Calculating the outliers of tractor rolling and pitching values gives the following results for all the clusters. Total of 653 outlying points are detected in tractor behavior in all clusters.

Table 4.7 Summary of tractor behavior

Tractor pitching		Tractor rolling	
Backward	Forward	Left	Right
outlier < -15 minimum = -128	outlier > 14 maximum = 143	outlier < -6 minimum = -70	outlier > 7 maximum = 64

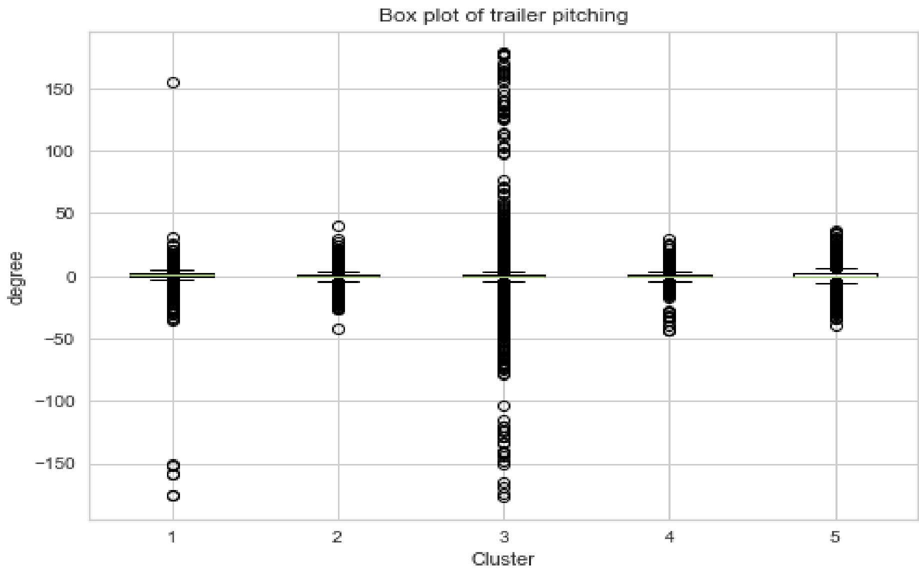


Fig. 4.23 Trailer pitching

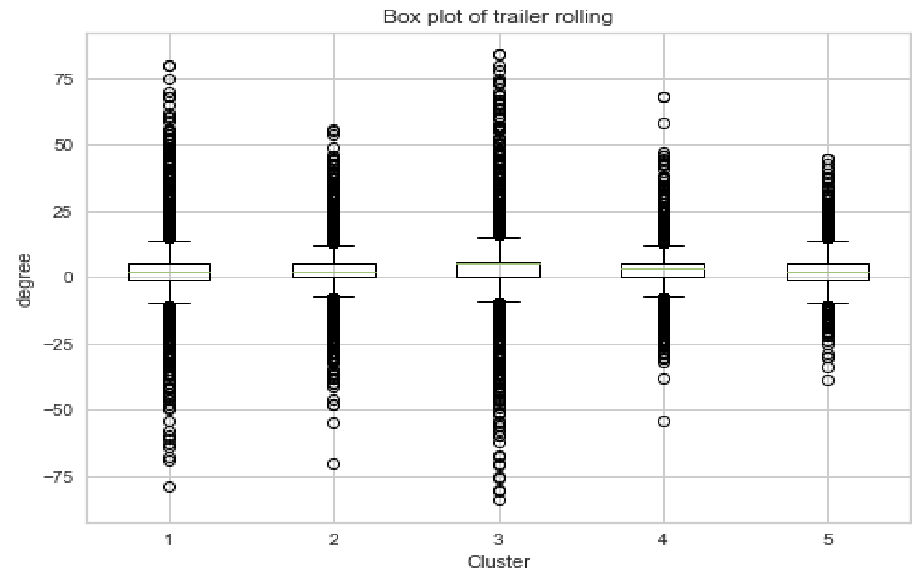


Fig. 4.24 Trailer rolling

Compared to the tractors, the trailers are found to move more freely than tractors in HCVs. Thus, the trailers outlying values tend to be higher than those of tractors. While pitching of both tractors and trailers exhibit the similar behaviors, the rolling degrees of trailers in all clusters range a lot more than tractors whose maximum degrees do not exceed 30° except in cluster 3. The number of outlying high trailer rolling and pitching moments is 2795, which is 4 times higher than tractors.

Table 4.8 Summary of trailer behavior

Trailer pitching		Trailer rolling	
Backward	Forward	Left	Right
outlier < -4 minimum = -177	outlier > 4 maximum = 178	outlier < -9 minimum = -84	outlier > 15 maximum = 84

Fig. 4.25 High tractor rolling/pitching points

Fig. 4.26 High trailer rolling/pitching points

Comparing the high rolling and pitching locations of both tractors and trailers in GIS, HCV tractors' high movement behaviors are mostly detected only in a few parts of the trips such as Ibaraki IC in Osaka Prefecture, logistics facilities of company C in Suzuka-shi in Mie Prefecture, some IC/JCTs of Shin-Meishin Expressway, Kita-Nagoya, Yokkaichi and Yaizu logistics facilities of company D, and on a few parts of Tomei-Expressway such as Gotemba and near Atsugi-shi on Ken-O Expressway. In the case of HCV trailers, they have higher freedoms of movements than tractors. As a result, trailers exhibit their high rolling/pitching movements throughout the trips. However, their behaviors are distinct throughout IC/JCTs on the Shin-Tomei Expressway, Isewangan Expressway and Shin-Meishin Expressway. In addition, some of their behaviors are also present on the First Tokai Expressway up to Kita-Nagoya. In logistics facilities of company C in Suzuka-shi, both tractors and trailers' movement behaviors are found to be strong, which in turn influence the drivers' maneuverability of HCVs.

4.7. Evaluation on Truck Transport Environment

Shipping environment study is important for evaluating logistics service quality. Logistics and distribution processes are made up of storage events and transportation events connected by handling events, shipments may suffer shock which have potentials to damage products and packaging (Goodwin and Young, 2011). Shipping environment can be evaluated by measuring shock and vibration levels, and truck speeds in the process (Watanabe et al., 2016). Acceleration as well as vibrations is important in cargo transport as it may affect cargo conditions in case cargo is detached or damaged (Vlkovský, 2017)..

In this study, HCV experiments run along the major expressways of Tomei and Shin-Tomei. Although these expressways are commonly known as the Tomei and Shin-Tomei Expressways, they are officially designated as the First Tokai Expressway and the Second Tokai Expressway. Since the majority of HCV traffic run through these two expressways, it is important to evaluate the truck transport environment on the said expressways. The highway lane data are obtained from the National Land Numerical Information section of the Ministry of Land, Infrastructure, Transport and Tourism as highway time series data which are available in two GIS formats: polylines for highways and points for IC/JCTs on the highways. The coordinate reference system of the above data is in Japanese Geodetic Datum 2011 (JGD2011 or EPSG:6668). In order to cover the driving characteristics of HCVs on the expressways, buffer analysis is done. As buffering technique requires the CRS in the actual distance unit, JGD2011 distance is measured in angular degrees. Thus, the CRS of the expressways is converted first to EPSG 3857 (WGS 84 pseudo-Mercator projection) whose measurement unit is distance in meters. As the number of lanes on both Tomei and Shin-Tomei Expressway has up to 6 lanes, each of which is 3.6m wide, it is essential for buffers to cover all the lanes so that the driving characteristics cannot be missed. Hence, the 20m radius is applied to buffer both the expressways. The result of the buffer is visualized in the following Fig 4.27.

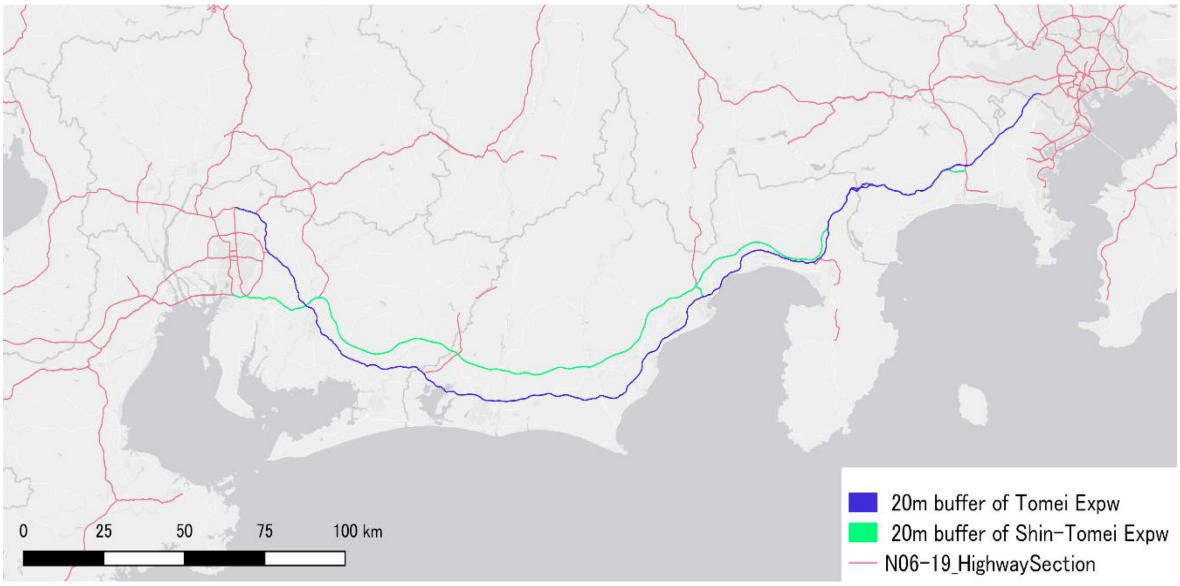


Fig. 4.27 Expressway buffers

The buffer on the Shin-Tomei Expressway in Fig 4.27 includes both the Shin-Tomei section and the Isewangan sections since they are on the sections of the Second Tokai Expressway. Therefore, the Shin-Tomei section is further divided between the Ebina IC and the Toyota-Higashi IC as shown in Fig 4.28.

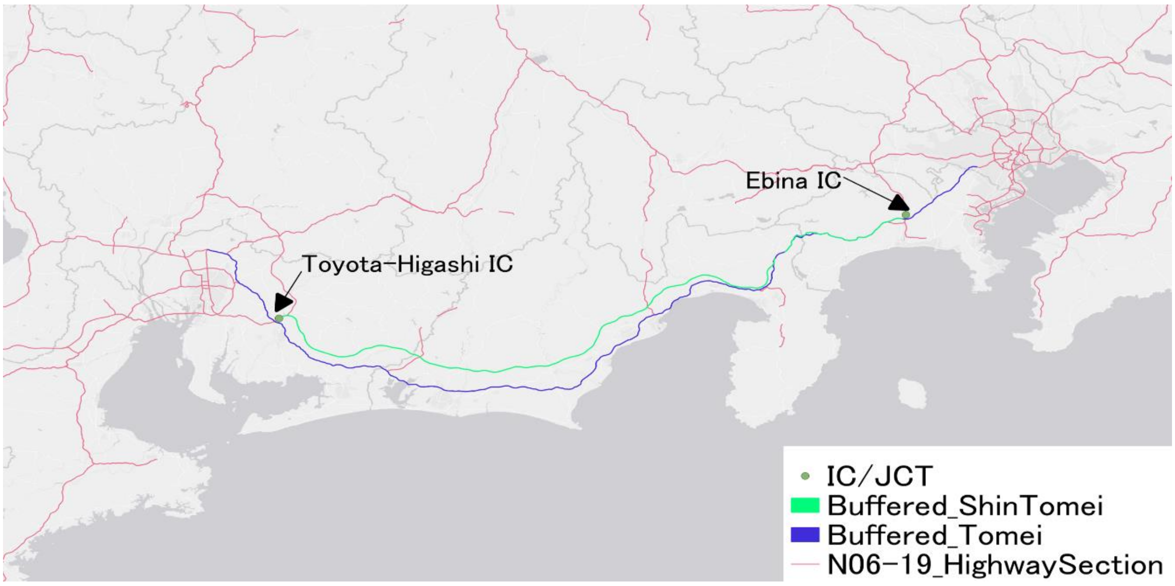


Fig. 4.28 Expressway buffers after Shin-Tomei section division

Watanabe et al. (2019) studied the shipping environment status on major economic corridors in Southeast Asia by the route survey and using small-sized shock logger and GPS logger. In this study, HCV transport environment analysis on the Tomei and Shin-Tomei Expressways will be evaluated using the average HCV speed and the average resultant accelerations of both tractors and trailers since they are the major routes on which the experimental trips were run.

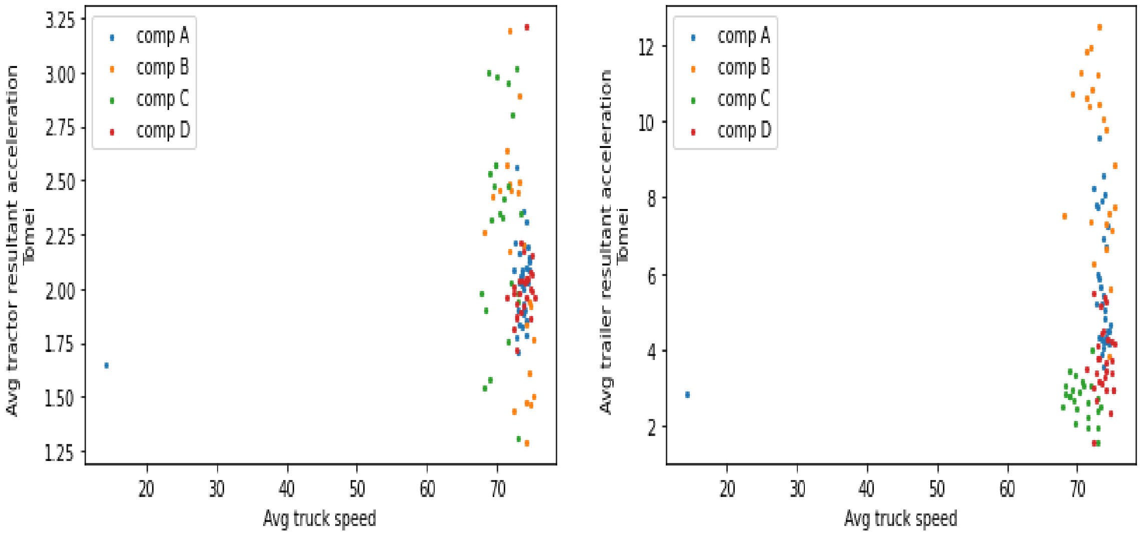


Fig. 4.29 Avg accelerations vs avg speed on Tomei Expressway

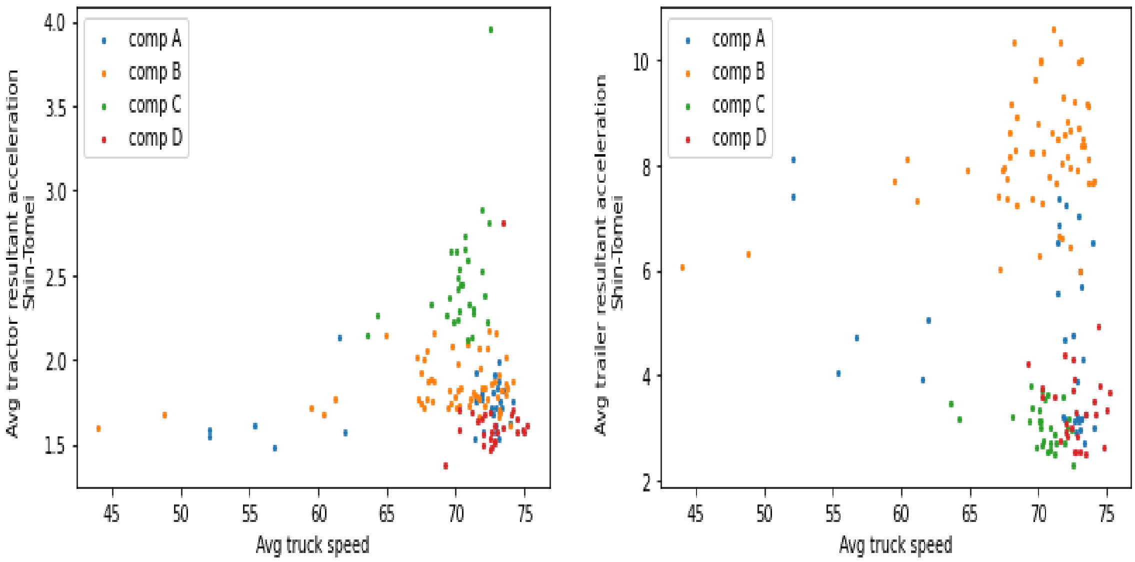


Fig. 4.30 Avg accelerations vs avg speed on Shin-Tomei Expressway

From the above findings in both figures 4.29 and 4.30, the relationship between the average travel speed of HCVs and the average resultant accelerations of both tractors and trailers does not appear to be strong.

In all 4 cases, the resultant tractor/trailer acceleration seems to depend on the type of vehicles and trailers used in the experiments. In the case of tractor accelerations, company C produces the highest average accelerations vs the travel speed. The rest three companies' results appear to be in the similar situation to each other. When comparing the trailer average accelerations, the acceleration behavior of company B's HCV trailers are found to be the highest among all the trailers. While company C and D trailers produce the low average accelerations, company A's trailer accelerations are found to have no relation to the average

HCV speed. The similarity of shipping environment evaluation of HCV tractor and trailers is detected on both expressways.

Once the shipping environment analysis and acceleration behavior in truck transport are known, the logistics operators can make use of the knowledge to safely secure the cargo and improve the packaging conditions as well as they can evaluate the vehicle route planning to ensure the optimal safe and secure transport operations.

5. Conclusions

Road freight transport is an integral transportation mode of any supply chain. Economic developments and the estimated economic growth in future will be accompanied by the increase in freight movement. To accommodate the growth in freight traffic volumes, logistics efficiency is required in terms of improving vehicle loading and the upgrade of existing logistics infrastructure. In this case, high capacity vehicles play an important role in improving vehicle loading and reducing the road haulage costs. As transportation is one of the major sources of greenhouse gas emissions, decarbonization of road freight can be contributed with the introduction of high capacity vehicles as HCVs can reduce the number of vehicles required to transport the cargo. With the reduction in the number of required trucks to carry the same amount of cargo, the number of driver requirement can be reduced with the help of HCVs. Therefore, the adoption of HCVs has risen as the trend in OECD countries.

As HCVs have been trialed and adopted in several OECD countries, they have shown significant positive impacts on vehicle productivity and road transport cost reductions. In addition, they are found to be able to contribute to decarbonization of road freight transport as the number of required trucks can be reduced by 10~50%. Although the road freight haulage costs and CO2 emissions can be reduced with the adoption of HCVs, they have little affects on transport modal shift in EU countries. Most of the rail freight and inland water transport freight have not shifted to road freight, and HCVs can only take over the freight share of normal trucks. In terms of safety and maneuverability, HCVs exhibit their safety and applicability on expressways although difficulty driving near intersections and roundabouts can occur. To summarize, the adoption of HCVs for road freight can be applied under most circumstances in developed countries.

The driving reason of high capacity transport adoption in Japan is mainly due to the shortage of truck drivers. Thus, the Japanese government conducted the experiments of high capacity vehicles with double trailers and trials in truck platooning, and HCV impacts on the driver requirement, work condition, fuel consumption and CO2 emissions have been assessed. Positive results were produced in the HCV experiments. They finally led to full-scale introduction of high capacity vehicles of vehicle length over 21m to operate on the expressways.

In this research, the HCV experimental data are used to study for clustering analysis. In this study, k-means clustering is applied to cluster the driving characteristics of HCVs. Before k-means clustering algorithm is applied, the calculation of the optimal number of clusters is done by the Elbow method and the quality of clusters is evaluated by the Silhouette analysis. Once the optimal k value and the cluster quality have been assessed, the HCV driving characteristics are clustered into different groups. In this study, k=5 is selected to group the truck running characteristics into 5 clusters.

The author believes that selecting different k values would produce the different results. So, it is suggested to test clustering with different k values, which will provide significantly different insights and the underlying patterns are to be explored. As there are other clustering algorithms, how the driving characteristics could differ by applying different methods should be studied.

In terms of different clustering algorithms, the author believes that DBSCAN clustering (density-based spatial clustering) should be attempted. Compared to K-means clustering which applies Euclidean distance to cluster the data, DBSCAN groups the closely packed points in the high-density regions, being able to mark the outlier points in the low-density regions. In addition, DBSCAN does not require the cluster values to be predefined. Therefore, DBSCAN analysis should be performed, and the results could be compared to that of K-means clustering, especially on the outlying characteristics as analyzed in this study. The author believes that DBSCAN can yield the insightful results which could be further used to improve and continue the research on HCV running behavior.

The analysis in this study is done by applying the available attributes in the dataset. The author believes that the clustering results could be improved if some attributes are available such as the weight and volume of freight carried, the type of freight carried, the operating vehicle type, and the CO2 emission values with respect to time and distance travelled. With the widespread adoption of HCVs, their impacts on road and transport infrastructure as well as the infrastructure's ability to accommodate HCVs should be studied. Since the parking constraint of HCVs in Japan has occurred, the HCV parking system and scheduling to handle them at SA/PAs should be developed. As the number of HCVs is expected to increase, their operational routes are also expected to be expanded onto the urban road networks in densely populated areas. As a result, studies should be continued in HCV effects on the local and regional society.

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