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Article

Evaluating the Effects of the A-Double Vehicle Combinations If Introduced to a Line-Haul Freight Transport Network

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Abstract: One of the solutions to improve the eco-efficiency of road freight transport is to combine existing transport modules into Longer and/or Heavier Vehicles (LHVs). The scientific and industrial communities have paid increasing attention to an LHV, known as the A-double combination, consisting of a tractor, two 13.5-m semitrailers, and a dolly converter. The present research contributes to the existing literature by developing a methodology based on a cost-benefit approach to quantify the effects of the A-double combinations if introduced to a line-haul transport system. Four implementation scenarios and sensitivity analyses of main variables were evaluated within a case study of 48,472 line-haul trips in Denmark. The results indicate that in the least beneficial scenario, the A-double combinations reduce transport cost by 9.65% while reducing trips, CO_2 emissions, and road wear by 17.91%, 5.34%, and 9.55%, respectively. Besides, the use of A-double combinations can significantly reduce empty tractor-semitrailer trips. However, the benefits are relatively less in the case of just-in-time deliveries and cargo constrained by vehicle weight. Also, cost saving is highly sensitive to driver salaries, fuel prices, and driving speeds. This research provides valuable insights into the potentials of A-double combinations under different regulations and freight characteristics from a micro perspective.

Keywords: longer and heavier vehicles; duo trailers; line-haul; freight transportation; carbon emissions; A-double; Denmark; high capacity vehicle; road wear; empty trips

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1. Introduction

In many countries, the majority of domestic freight transport is increasingly made by road vehicles, leading to more negative effects on the environment and society. In Denmark, the transport sector was responsible for 28% of total CO_2 emissions in 2017, and a fourth of these transport emissions is caused by freight transport [1]. Many studies showed that allowing larger vehicles on roads can reduce the negative effects of freight transport while providing cheap and efficient transport services [2–4]. Although larger vehicles have higher values of emission factors and cost per km, their higher capacities allow for transporting the same cargo amount at a reduced cost and lower environmental impacts per tonne-km [5–7]. Permitting larger road vehicles is not new to Europe because in 2007, most European countries, including Denmark, allowed the trial of the European module System (EMS) vehicles with a maximum length of 25.25 m and a gross vehicle weight (GVW) of 60 tonnes [8]. In this study, LHVs are used to refer to vehicle combinations that are longer and/or heavier than the EMS combinations. In recent years, some countries, e.g., Sweden and Finland, have been allowing LHVs with 76-tone GVW and a length of 34.5 m [9]. The introduction of LHVs has provoked an intense debate, with conflicting opinions on the positive and negative effects of allowing LHVs [6]. According to McKinnon [10], the main positive effects of LHVs are lower transport costs, lower fuel consumption, and GHG emissions. Besides, a reduction in the number of accidents is likely to occur due to reducing the number of vehicles and the distance travelled on the road. On the negative side, the lower costs of the road freight transport might result in a modal shift of freight transport from sea and rail to road. Moreover, additional investment in road infrastructure might be required to strengthen bridges and expand road crossings and intersections. In addition, the LHV might have a high impact on road wear. For this reason, the literature has paid increasing attention to evaluating the different effects of using LHVs if allowed on the road transport system [11–13].

One of the LHVs that is highly attractive for many transport practitioners is the A-Double combination, as shown in Figure 1. The A-double combination involves a tractor, two 13.5-m semitrailers, and a converter dolly. The overall length of this combination ranges from 32 m to 34.5 m [13–17], depending on the regulations. The A-double combination can enable hauliers to combine two trips of the tractor-semitrailer combination into a single A-double trip when possible or operate the two tractor-semitrailer combinations when necessary. This would offer greater flexibility to further improve transport efficiencies of the tractor-semitrailer combinations. Some EU countries, e.g., Sweden [14], Finland [17], and Spain [18], are testing the A-double combinations within single night trips and the results from these trials reported savings in the transport costs, CO_2 emissions, and drivers by 25%, 27–30%, and 50%, respectively.

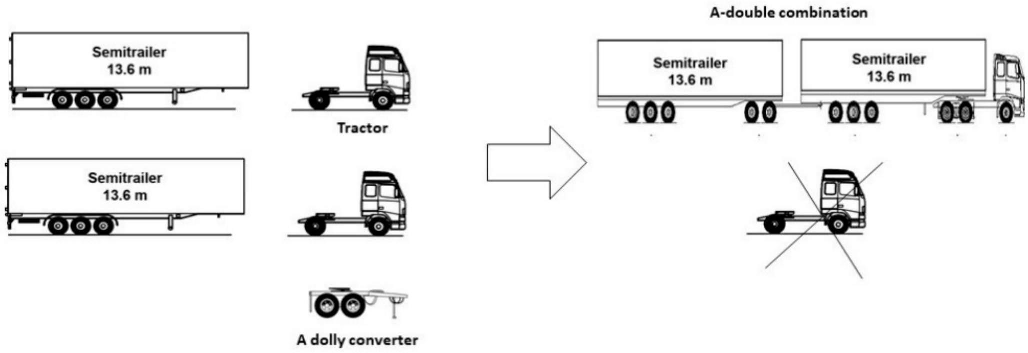

Figure 1. Transport equipment used in the A-double combination.

The literature has very few studies on the effects of A-double combinations [11–13,16]. These studies have investigated the effect of A-double combinations either from the micro or macro perspective. Macro-based studies [12,16] examine the aggregated effects of LHVs on the country level and quantify the long-term effects such as modal shift, see e.g., [19]. Compared to macro-based studies, micro-based studies provide a better understanding of the effects of LHVs since they take into account detailed freight and delivery characteristics, e.g., delivery requirements, cargo weights, and capacity constraints [19]. We only found two studies investigating the A-double vehicles from a micro perspective [11,13]. The present study differs from these two studies in that it investigates the effects of A-double combinations in new scenarios and under constraints that were not considered before in the literature. For example, operating an A-double combination, in practice, might necessitate delaying the departure of a semitrailer trip until another semitrailer trip is made available at the terminal. However, existing studies did not consider such trip delays. Regulatory constraints, e.g., the limits of the driving speed, and driving times of the A-double combination, are also rarely considered. Therefore, the present study aims to contribute to the literature by developing a cost-benefit method to evaluate the effects of using the A-double combinations on operational transport costs, empty trips, CO_2 emissions, and road wear in a line-haul transport system from a micro-perspective standpoint. Besides, the current study examines four possible implementation scenarios of the A-double combination compared to the business-as-usual scenario. Moreover, the method is used in a sensitivity analysis to investigate the effect of the key variables on the likely effects of the A-double vehicles. The developed method was applied to a case study including 48,472 trips of the tractor-semitrailer combinations made among seven terminals in Denmark. The findings of the case study might provide policy-makers with useful knowledge on the environmental and economic effects of the A-double combination from a micro perspective. In particular, this might help policymakers to consider the A-double combinations among the solutions for moving Denmark faster towards a low carbon society while making the freight transport system more efficient. The method and findings of this study might help practitioners to decide, based on their freight and fleet characteristics, whether using the A-double combinations (if allowed) is beneficial for their transport practices or not.

2. Literature Review

The literature has focused on quantifying different effects of the LHVs on road traffic safety, road infrastructure, bridges, environment, and transport costs. Relevant literature is mostly published as technical reports, while peer-reviewed publications are relatively low. This section presents a detailed overview of the main findings found in the LHV literature. The findings will be discussed in relation to the impacts on transport cost, road infrastructure, CO_2 emissions, road traffic safety, and modal shift. Finally, we conclude the findings and gaps found in the literature.

2.1. Impacts on Transport Cost

Some studies investigated the ability of EMS vehicles to reduce transport costs. In Germany, Sanchez Rodrigues et al. [6] reported the experiences of six German companies with the trails of EMS vehicles. The results show that some companies could reduce their driver and fuel costs by an average of 33%. Overall, all companies could reduce their fuel consumption per tonne-km by 30%. Some studies investigated vehicles that are heavier than EMS vehicles. In Finland, Liimatainen et al. [7] noted that increasing the GVW up to 76 tonnes resulted in reducing the total vehicle-km by 4% between 2013 and 2017 and a transport cost saving of 126 million € in 2017. Although there was some modal shift of freight transport from rail to road, CO_2 emissions reduction was around 0.1 million tonnes. Vierth and Haraldsson [20] evaluated the potentials of using vehicle combinations with a GVW up to 90 tonnes in the Swedish round wood transport. The results demonstrated that the vehicle combinations could achieve a 21% reduction in the vehicle kilometers compared to the 60-tonne articulated vehicles. Some studies investigated vehicles that are longer than EMS vehicles. In Sweden, David Lindqvist et al. [11] investigated the effects of using longer vehicles (64 tonnes/34.5 m) on DHL's line-haul network. The results showed that it is not a cost-effective scenario if all current vehicles (64 tones/25.5 m) are replaced by the longer vehicles, while the scenario in which both vehicles are used leads to a 6% operating cost reduction compared to the current situation. In addition, the total external cost, including CO_2 emissions, road wear, and accident costs, is reduced by 8%. However, the savings are relatively higher when the longer vehicles are used only among terminals having high cargo volume. Bergqvist and Behrends [13] evaluated the pre and post-haulage costs of the intermodal transport chain in a scenario where it is allowed to transport two 40-foot containers by a longer vehicle (34 m). The results showed that this scenario made it possible for shippers to achieve an overall cost reduction, ranging between 5 and 10% in their intermodal transport chain. Thus, the authors raised the need for changing the current freight vehicle regulations to allow such longer vehicles in transport chains. Through a case study of a major Finnish pulp and paper company, Palander [21] studied the effects of allowing a 9-axle vehicle combination, having a 76-tonne GVW and a payload up to 51 tonnes, on the transport operations. Compared to the current fleet (60 tonnes and payload up to 40 tonnes), the LHVs could reduce fuel consumption by 6.2% within 1 year of their introduction while on the long run, 15.5% reduction in the fuel consumption could be achieved when HCVs are fully implemented. Some studies investigated vehicles that are longer and heavier than EMS vehicles. Pålsson et al. [12] performed a cost-benefit analysis to evaluate the effects of heavier vehicles (74 tonnes/25.25 m) and longer and heavier vehicles (74 tonnes/34 m) on the Swedish freight transport system compared to the EMS vehicles. The results showed that both vehicles increase the tonne-kilometers by

0.9–8.8%, but the longer and heavier vehicles (74 tonnes/34 m) achieve a relatively higher increase. Knight et al. [16] conducted a significant modelling study to assess the effects of allowing eight different vehicles on the freight transport system in the UK. For example, allowing the LHVs (82 tones/34 m) on only motorways would lead to a 13% reduction in distance traveled compared to the tractor-semitrailer combinations.

2.2. Impacts on Road Infrastructure

Several studies have addressed the impacts of LHVs on road infrastructure in terms of road wear [16,22,23]. Leduc [23] noted "road wear generally decreases with the increasing number of axles per vehicle while road wear increases with increasing the GVW. But what is important is the load distribution, not only the vehicle weight". Most studies have estimated the road wear due to vehicles by the so-called "fourth power law", which is the equivalent 10-tonnes axle load per vehicle raised to the fourth power [8]. Different versions of the fourth power law exist in the literature. For example, the Swedish road administration considers the fourth power-law with a reduction factor for single axle, tandem, or tridem axles, while the Danish Road Directorate further considers tire configuration and suspension design-related factors and differentiated between road surface types [24]. Knight et al. [16] found that the wear cost per km of the A-double combination (82 tonnes/34 m) is 1.8 of the wear cost per km of the tractor-semitrailer combination. However, the A-double combination would achieve a 10% reduction in the road wear per 100 tonnes of goods as the A-double combination reduces the number of trips compared to the standard articulated truck. Some studies have estimated the additional investments in road infrastructure to allow the LHVs. Stephens et al. [25] showed that there would be an additional cost of pavements (0.01 USD per km) in both the interstate and highways to replace the current vehicle (53 tones/29 m) with heavier ones (60 tones/25 m) with the same number of axles. The EU Commission [26] reported that though permitting the EMS vehicles would require high infrastructure investment costs, these additional infrastructure costs do not exceed the overall savings of EMS vehicles.

2.3. Impacts on CO_2 Emissions

The literature has paid increasing attention to the impacts on the environmental performance of road freight transport. Tunnel and Brewster [27] showed that increasing the GVWs would lead to savings in fuel and emissions between 4–27% per tonne-mile compared to ordinary vehicles. An interesting observation is that the additional weight should be enough to offset the additional fuel consumption demands of the heavier vehicle. This implies that increasing the GVW does not always guarantee better environmental benefits. The Dutch and Danish trials of EMS vehicles reported some savings in fuel consumption and emissions [22,28]. Some studies noted that the higher the loading factor of LHVs is, the better is their environmental performance [27]. According to Leduc [23], "it can be estimated that the payload of LHVs should be roughly above 65–70% of its maximum carrying capacity to be more energy-efficient than a fully-loaded conventional HGV (tractor-semitrailer combination)". David Lindqvist et al. [11] showed that the use of A-double combinations (64 tones/34.5 m) in DHL's line-haul network would reduce the GHG emissions by 7% compared to current fleets (64 tones/25.5 m). However, some studies showed that the savings in the CO_2 emissions might be partially eroded by any modal shift in the long run [5]. Knight et al. [16] showed that the A-double combinations (82-tonne/34 m) would reduce the CO_2 emissions per tonne-km by 22% compared to the tractor-semitrailer combinations, but due to possible modal shift, the CO_2 emissions would decrease in the long run. Pålsson and Sternberg [12] showed that CO_2 emissions seem to decrease with using LHVs, and the A-double combinations (74 tonnes/34 m) would achieve the greatest reduction in CO_2 emissions. In addition, imposing kilometre-based charges on the LHVs for using road networks would negatively impact the CO_2 emission savings.

2.4. Impact on Road Traffic Safety

The impact of the LHVs on road safety has been an important concern of scientists, the public, and politicians. Those who generally oppose the introduction of LHVs argue that the LHVs would be a safety risk. However, some scholars pointed out that there is a lack of empirical evidence showing that LHVs would significantly result in more traffic accidents [29,30]. It was reported that in Alberta, the introduction of LHVs reduced the risk of accidents by 58% compared to standard articulated trucks [29]. Wåhlberg [31] conducted a meta-analysis of the difference in accident risk between long and short truck configurations. The results showed that since allowing LHVs significantly reduces the number of smaller vehicles on the roads, LHVs would result in fewer accidents. Klingender et al. [32] estimated a reduction of 1491 million € in the accident costs if LHVs were allowed on EU roads. Through econometric modeling, Castillo-Manzano [33] found that overall, EMS combinations have fewer traffic accidents, but they increase the severity and lethal consequences of accidents. Sanchez-Rodrigues et al. [6] suggested that the EMS combinations have fewer traffic accidents since they are restricted to specific roads or are prepared with safer technological advances, or are operated by more experienced drivers.

2.5. Impact on Modal Shift

Modal shift is another concern raised by those who oppose allowing the LHVs. Some studies argue that such a modal shift might increase GHG emissions from the freight transport sector in the long run [5,16]. Liimatainen et al. [7] noted that the introduction of LHVs might be against the EU goal of promoting rail transport because LHVs induce a modal shift from rail to road. Pålsson and Sternberg [12] studied the modal shift if LHVs are allowed in Sweden. The results showed that in the long-term, the modal shift from rail to the road would be 6.4% and 8.7% due to heavier vehicles (74 tonnes/25.25 m) and LHVs (74 tonnes/34 m vehicles), respectively. To avoid such a modal shift, the authors suggested implementing a kilometre-based charge for the LHVs. This would, in turn, counteract the decrease in the road freight price. The authors noted that for both 74 t/25.25 m and 74 t/34 m vehicles, higher kilometre-based charges (e.g., SEK 1.60 per km) would diminish the LHV benefits and lead to a modal shift from road to rail and sea. In the UK, Knight et al. [16] estimated that the introduction of LHVs would lead to a shift between 8–18% of total tonnes-kilometres carried by rail to road. Meers et al. [34] investigated the reverse modal shift in the container transport chain if EMS combinations are allowed in Belgium. The results showed that a 5% price decrease of road transport would shrink the market share of intermodal transport by 15% and 63% if the price decreased by 15%. In Finland, Liimatainen et al. [7] reported that the amount of freight carried by train decreased by about 4% during the period (2014–2017) at which LHVs have been permitted. However, Bergqvist and Behrends [13] showed that LHVs might be useful to intermodal transport chains since the A-double combinations allow transporting two 40-foot containers together for further transport via seaports or railways. This might improve the overall performance of intermodal transport.

To sum up, the recent literature has paid increasing attention to LHVs. The A-double combination is one of the most attractive LHVs and is currently tested on a small scale in Sweden [14], Finland [17], and Spain [18]. However, there is a lack of studies that evaluate the economic and socio-economics effects of A-double combinations in line-haul transport networks. We only found two studies investigating the A-double vehicles from a micro perspective [11,13]. However, these two studies did not consider important constraints such as the allowable delayed departure of semitrailer trips, the limits of the driving speed, and driving times of the A-double combination. Therefore, the current study contributes to the literature by developing a cost-benefit approach taking into account important operational and regulatory constraints. The developed approach can be used to quantify the effects of the A-double combinations if introduced to a line-haul transport system. Moreover, the present work investigates new scenarios that have not been considered before in the literature. The new scenarios will be illustrated in Section 3. Unlike existing studies, the current study also reports the effects on empty trips.

3. Method

The A-double combinations, if allowed, will face some financial, operational, and regulatory constraints similar to other LHVs. As a financial constraint, the use of A-double combinations might incur additional costs to hauliers for accommodating the A-double combinations in their terminals, adapting exiting equipment, and purchasing a dolly converter and a more powerful tractor [16]. However, our field investigation showed that the majority of tractors registered in Denmark can haul the A-double combination, especially if its GVW is set to 60 tonnes, maintaining the Danish vehicle weight limit. In addition, a 60-tonne GVW would also reduce the amount of investments needed for reinforcing the road pavements. Moreover, the A-double combination is expected to operate on a restricted route network, e.g., motorways connecting line-haul terminals, to reduce the road infrastructure investments further. Sixty-tonne A-double combinations imply that two semitrailer trips cannot be coupled if they result in an A-double trip with a GVW exceeding 60 tonnes. To avoid traffic peaks and impacts on road safety, the A-double trips might be allowed during predefined times of the day, e.g., night times from 10 PM to 5 AM. From the perspective of hauliers, there might be operational constraints due to the need for delaying semitrailer trips. For example, hauliers might need to delay the departure of a trip until another trip is made available at the same terminal, so the two semitrailer trips are available for operating a single A-double trip. However, the increasing need for just-in-time deliveries might impose a limit on the allowable delay time of trips. Based on discussions with some hauliers, the A-double combinations would help them, in the first place, to avoid running empty tractor-semitrailer combinations. For example, if there are three tractor-semitrailer trips in the same route and one of them is empty. In this case, hauliers would prioritize coupling the empty trip to another loaded trip instead of coupling two loaded trips and run an empty trip. This is mainly because running empty trips results in an economic loss of time, fuel, amortization, etc.

3.1. Scenarios

The following four scenarios were evaluated and compared to the business-as-usual scenario, i.e., the tractor-semitrailer combination (44 ton/16.5 m):

Scenario 1: GVW of the A-double combination is restricted to 60 tonnes;
Scenario 2: as scenario 1 and the allowable trip delay is limited to 3 h. Note that a 3-h limit is suggested based on inputs from field practitioners;
Scenario 3: as scenario 1 and the A-double trips are allowed only during the night from 10 p.m. to 5 a.m.;
Scenario 4: as scenario 3 and the allowable trip delay is limited to 3 h.

Based on literature review and inputs from practitioners, the following five indicators were considered when comparing the four scenarios with the business-as-usual scenario:

- Operational cost saving:

It indicates the possible savings in the transport cost if the A-double combination is allowed and integrated into the conventional tractor-semitrailer fleet. This cost saving is internal to the hauliers.

- Empty trip saving:

It indicates the possible reduction in the total number of empty tractor-semitrailer trips if the A-double combination is allowed. As stated before, hauliers might save empty trips by coupling them using dolly converters to conventional tractor-semitrailer trips.

- Total trip saving:

It indicates the possible reduction in the total number of trips made by tractor-semitrailer combinations. This indicator includes empty trips as well.

- CO_2-emission (Kg) saving:

It indicates the possible saving in the amount of CO_2 emissions in case that A-double combinations are allowed. CO_2 emissions harm public health and incur costs to society.

- Road wear saving:

It indicates the possible saving in the damage of road pavements due to road wear caused by A-double combinations. Road wear has always been a concern raised by road keepers since increasing road wear might require more money for road maintenances.

3.2. Data

For purposes of analysis, a data set is collected from a major Danish logistics company. The collected data describes the line-haul trips performed in 2019 among seven terminals located in Denmark. Only seven terminals are considered to account for the possible route restrictions. The company uses three vehicle combinations for line-haul transport: the conventional tractor-semitrailer combination, the truck and centre-axle trailer (44 tonnes/18.75 m), and the EMS combinations. The data showed that the percentages of line-haul trips made by the three vehicles are 69% (conventional tractor-semitrailer), 1% (the truck and centre-axle trailer), and 30% (EMS combinations). In total, 48,472 trips of the tractor-semitrailer combinations were made among the seven terminals. Of these trips, 13.6% were empty trips. For each trip, the provided data describes its departing time, origin, and destination terminals. In addition, the cargo volume carried by each trip is measured by the number of Euro pallets. The average pallet weight most frequently handled by the company is 400 kg. Therefore, the cargo weight carried by each trip is calculated by multiplying the number of pallets by the average pallet weight.

3.3. Cost-Benefit Model

To evaluate the potentials of the A-double combination in different scenarios, a cost-benefit model is developed based on two calculation steps. Given the historical trip data between each terminal pair, the first step is to estimate the number of the tractor-semitrailer trips that can be replaced by A-double trips under three constraints: the 60-tonne GVW, predefined time (10 PM:5 AM), and the allowed trip delay (3 h). The relevant studies use mostly two approaches to calculate the number of LHV trips between two terminals: cargo combining and trip combining. In cargo combining, the number of LHV trips is calculated by dividing the total cargo volume by the volumetric capacity of the LHV as in [11]. On the other hand, the trip combining fits more the LHVs consisting of modular units and calculates the number of LHV trips by reorganizing the modular units into LHV trips as in [15,35]. For example, if there are three tractor-semitrailer trips from one terminal to another, trip combining reorganizes them into one A-double trip and one tractor-semitrailer trip. We follow the trip-combining approach because it allows for considering the trip-delay constraint and calculating the effect of the A-double combination on the number of empty trips. Moreover, it allows for evaluating a more practical situation where both A-double and tractor-semitrailer combinations are used simultaneously.

The results from the first step are the number of A-double trips and the number of tractor-semitrailer trips (not replaced) for each terminal pair on each day of 2019. Second, a parametric cost model is developed to estimate, based on the travelled distance, three cost types for both combinations: operational cost, CO_2-emission cost, and road wear cost. The benefits of the A-double combination are the possible savings, calculated by the difference between both combinations costs divided by the business-as-usual cost. In the following, different cost estimations and input data are explained.

3.3.1. Operational Costs

To calculate operational cost per km for each combination, both fixed and variable costs per km of each combination are estimated. Fixed costs are the predetermined expenses required to purchase the vehicles and make them always ready for work. Fixed costs do not change with how much the vehicles are used. Variable costs are those expenses that change with the amount by which the vehicles are utilized. The different costs for each combination are obtained by calculations shown in Table 1, following studies in [11,16]. The operational costs of both combinations were calculated using input data from the company and market prices in Denmark. The different cost values of the A-double combination are shown in the last column of Table 1, relative to that of the tractor-semitrailer combination.

Table 1. Calculations of different fixed and variable costs.

		Fixed Costs	Formula	Relative Cost Value [a]	
CD	:	Capital depreciation cost (DKK/h)	$\frac{Annual\ depreciation^{b} + cost\ of\ capital}{Hours\ utilized\ per\ day\ x\ working\ days\ per\ year}$	1.32	(1)
IC	:	Insurance cost (DKK/h)	$\frac{Annual\ insurance\ cost}{Hours\ utilized\ per\ day\ x\ working\ days\ per\ year}$	1.15	(2)
TRC	:	Tax and registration cost (DKK/h)	$\frac{Annual\ \text{Tax and registration}\ cost}{Hours\ utilized\ per\ day\ x\ working\ days\ per\ year}$	1.07	(3)
Variable cost					
TC	:	Tire cost (DKK/km)	$\frac{Price\ per\ tire * number\ of\ tires}{Tire\ life\ \ (Km)}$	1.83	(4)
RMC	:	Repair and maintenance cost (DKK/km)	$\frac{Annual\ cost\ of\ repair\ and\ maintenance}{Annual\ distance\ (Km)}$	1.30	(5)
FC	:	Fuel cost (DKK/km)	*Fuel consumption* [c] *(L/Km) x fuel cost (DKK/L)*	1.67	(6)
DC	:	Depreciation cost (DKK/km)	$\frac{Purchasing\ price\ of\ the\ unit}{life\ time\ distance\ (Km)}$	1.18	(7)
DR	:	Driver cost rate (DKK/h)	$\frac{Annual\ driver\ salary}{Hours\ utilized\ per\ day\ x\ working\ days\ per\ year}$	1.00	(8)
Operational cost					
OC	:	Operational cost (DKK/KM)	$\frac{(CD+IC+TRC+DR)}{Average\ combination\ speed\ (Km/hour)} + TC + RMC + DC + FC$	1.40	(9)
TOC	:	Total operational cost (DKK)	*OC (DKK/Km) x travelled distance per combination*	-	(10)

[a] The cost values of the A-double combination relative to that of the tractor-semitrailer combination. [b] The annual depreciation is calculated using the double-declining-balance depreciation method [36]. [c] The fuel consumption (L/Km) is calculated based on Table 2 and a fuel density of 850 g/L.

Table 2. CO_2-emission and fuel consumptions for both vehicle types at different payloads, adapted from [16].

	CO_2 Emission (g/km)	Fuel Consumption (g/km)	Payload (tones)
The tractor-semitrailer combination	575.954	181.661	0
	768.313	242.308	11
	878.314	276.994	18
The A-double combination	997.225	314.150	0
	1315.49	414.705	25
	1449.871	457.218	37
	1758.198	554.614	60.4

3.3.2. CO_2-Emission Cost

The CO_2-emission cost for each combination is estimated by:

$$CO_2\text{-}emission\ cost\ (DKK) = DKK\ per\ kg\ CO_2\ x\ Emission\ factor\ of\ the\ combination\ (kg\ CO_2\ per\ km)\ x\ Combination\text{-}km \quad (11)$$

The CO_2-emission cost is estimated using the emission data provided by the study [16] that used the Passenger car and Heavy-duty Emission Model to estimate the CO_2-emission factors for both combinations at different payload values and a speed of 87 Km/h (see Table 2). Linear interpolation and extrapolation were used to get the emission values at other payload values.

3.3.3. Road Wear Cost

Following the work in [16], the road wear cost for each combination is estimated by:

$$\textit{Road wear cost (DKK)} = \textit{DKK per ESAL-km x ESAL of the combination x Combination-km} \quad (12)$$

where *ESAL* is the equivalent number of standard axles and indicates the wear factor of the combination. The *ESAL* is calculated by the method developed by the Swedish road administration [24]. The *ESAL* is calculated as follows:

$$ESAL = \sum_{i=1}^{n} \left(\frac{W_i}{10}\right)^4 x\, k_i \quad (13)$$

where i is the number of axles or axle groups; W_i is the weight of axle (group) i in tonnes; and k_i is a factor that equals 1 (single axle), 0.0952 (tandem axle), and 0.0302 (tri-axle).

The axle weights used in the calculations are shown in Figure 2, as provided in [8] when both combinations are at their full lading patterns. The ESAL of the A-double combination is found to be 10% higher than that of the tractor-semitrailer combination. However, if the road wear cost is analyzed in terms of the total distance required to transport the same amount of cargo, the A-double combination would reduce the road wear by around 45% compared to the tractor-semitrailer combination. The Danish trial of EMS vehicles [22] reported that hauliers often operate larger vehicles at weights exceeding the allowed limit. To consider that this might also occur if the A-double combination is allowed, the EASL of the A-double combination is increased by a factor of 30%. Although different values can be investigated, this value is reasonable to analyze the effects.

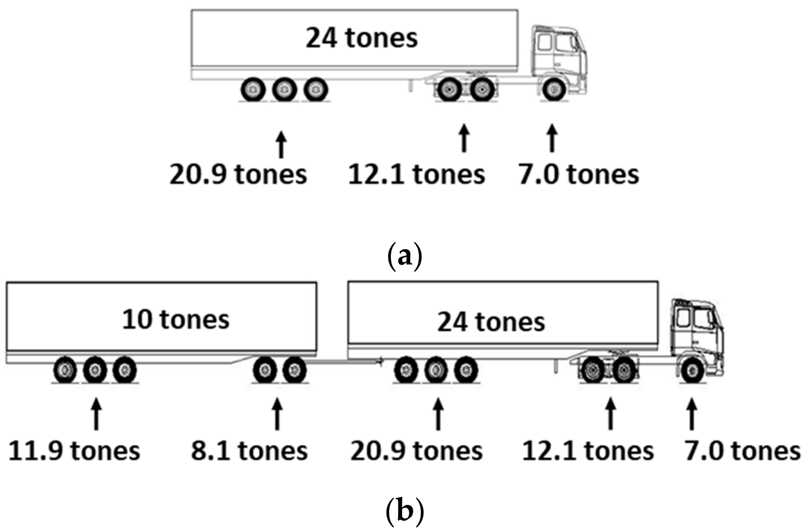

Figure 2. The load axles for (**a**) the tractor-semitrailer combination at a payload of 24 tonnes and (**b**) the load axles for the A-double combination with a GVW of 60 tonnes, adapted from [8].

4. Results and Discussions

This section illustrates the results of the four scenarios compared to the business-as-usual scenario. The five indicators were estimated as the daily average of all days in 2019. Also, the sensitivity analysis of the results to the main variables was conducted and discussed.

4.1. Main Scenarios

Figure 3 shows the different savings obtained in the four scenarios. It can be noted from Figure 3 that in all scenarios, the use of the A-double combination achieves different levels of positive savings. In scenario 1, the total trip saving is around 45.5%, very near to the “optimal case”, meaning a single A-double trip can replace two tractor-semitrailer trips. It is clear from the results that the trip-delay constraint (Scenario 2) significantly reduces the empty trip saving while it has a relatively slight impact on the operational and total trip savings. The night-trip constraint (Scenario 3) significantly reduces the trip and operational cost savings. This indicates that the night-trip constraint has a relatively larger impact on the savings than the impact of the trip-delay constraint. Scenario 4 (trip-delay constraint and night-trip constraint) has the lowest savings. As stated before, the historical data showed that the number of empty semitrailer trips is around 13.6% of all trips made among the seven terminals. If the A-double combinations are allowed in the line-haul network, hauliers can couple a dolly and an empty semitrailer to another empty or loaded semitrailer. This strategy would significantly reduce the empty trips by 42.09% in the least beneficial scenario, as shown in Figure 3. This confirms that the A-double combination provides the hauliers with an opportunity to reduce the empty trips.

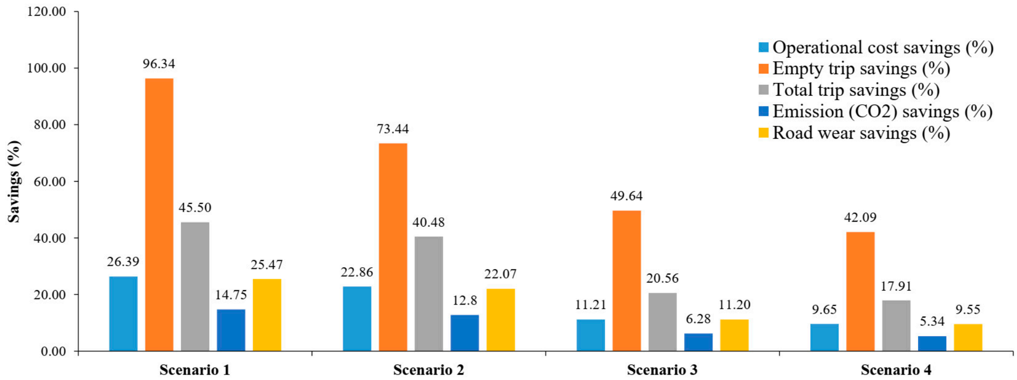

Figure 3. Different savings due to the use of the A-double in the four scenarios compared to the baseline scenario.

Figure 3 also shows that CO_2 emissions and amounts of road wear are reduced in the four scenarios compared to the business-as-usual scenario. This is because the A-double combination requires fewer trips and lower travelled distances to transport the same cargo amount in relation to the number of trips required by the tractor-semitrailer combination. The amount of CO_2 emissions is reduced by 5.43% in the least beneficial scenario, while the reduction in road wear ranges from 9.55% to 25.47% in the four scenarios. Thus, the A-double combinations would reduce the external costs that affect society.

The authors stress that the operational cost savings reported in these scenarios do not consider any initial capital investments on the infrastructure that may be required to allow the A-double combination on roads or freight terminals. Even if the A-double combination is allowed on a limited road network, such as the expressway system, the road infrastructure may need to be expanded. The road authority might compensate for the road investment by imposing higher road charges on the A-double combinations. In this case, this would certainly reduce the operational cost savings. For the A-double combination to achieve its most benefits, hauliers should, in principle, optimize routings and allocations of the A-double vehicles among the terminals, for example, the possibility to change the route for reaching the destination using the A-double combinations. In addition, an IT system is imperative to enable reliable information flow and efficient coordination among actors of the transport network. It is worth noting that Swedish and Finnish experiences reported that exchanging loading units of modular combinations among logistics companies has been a successful method to utilize the extra loading capacity efficiently. Besides, logistic companies might use a triangle-route strategy in which the A-double combination drives from one company to another to move semitrailers of different companies.

4.2. Sensitivity Analysis

Four types of sensitivity tests were performed to determine how the variations in the input data affect the results. The first sensitivity analysis is made by changing the pallet weight, while the second sensitivity analysis is made by changing the allowable delay time.

In the third sensitivity analysis, different cost parameters were decreased or increased by 10% and 30%. Finally, the fourth sensitivity analysis investigates the effect of varying the travelling speed of the A-double combination. In all sensitivity tests, scenario 2 is used. Table 3 illustrates the changing trend of the five indicators with changing the trip-delay time between 1 h and 5 h with a step of 1 h. The results show that the different indicators tend to be less affected when the trip-delay time exceeds 3 h. It can be also noted that the empty trip saving is affected the most by the trip-delay time. In general, the results indicate that there is still a potential for the A-double combinations in just-in-time deliveries where the allowable trip-delay time is too tight.

Table 3. Sensitivity analysis of different trip-delay values in scenario 2.

	Allowable Trip-Delay Time (h)				
	1	**2**	**3**	**4**	**5**
Operational cost saving (%)	17.07	21.12	22.86	23.34	23.70
Empty trip saving (%)	56.13	68.13	73.44	74.98	76.35
Total trip saving (%)	30.80	37.76	40.48	41.20	41.65
Emission (CO_2 kg) saving (%)	9.54	11.81	12.80	13.09	13.28
Road wear saving (%)	16.47	20.39	22.07	22.56	22.88

Table 4 illustrates the change in the five indicators with increasing the pallet weight between 200 kg and 727 kg. Note that 727 kg is the maximum pallet weight that a full semi-trailer can carry, i.e., 24,000 is the maximum payload of 33 EU pallets trip. At a pallet weight of 600 kg or more, the restricted GVW of the A-double combination becomes a binding constraint, and this in turn largely reduces the savings in the total trip, the operational costs, and other external costs. However, the empty trip saving is almost constant as the proposed method prioritizes empty trips when selecting which trips to be combined in A-double trips. It is obvious from the results that the 60-GVW A-double combination is a more cost-effective solution for volume-sensitive cargo (low-density cargo such as refrigerators and washing machines) that needs increased vehicle dimensions rather than increased GVW. However, using the A-double combination with weight-sensitive cargo is still beneficial due to saving empty trips. An interesting observation is that the CO_2-emission saving is the only indicator that increases with increasing the pallet weight between 200 and 500 kg. This is because, in general, LHVs have better environmental performances at higher weights, as indicated in [27]. One might think that the A-double combination always results in overall cost savings compared to the business-as-usual scenario. However, based on results in Tables 3 and 4, if the allowable time delay is too tight, using the A-double combination with weight-sensitive cargo might result in negligible savings.

Table 4. Sensitivity analysis to pallet weight in scenario 2.

	Pallet Weight (kg)						
	200	**300**	**400**	**500**	**600**	**700**	**727**
Operational cost saving (%)	22.86	22.86	22.86	22.86	9.87	7.57	7.12
Empty trip saving (%)	73.44	73.44	73.44	73.44	73.43	73.45	73.45
Total trip saving (%)	40.48	40.48	40.48	40.48	19.56	15.54	14.73
Emission (CO_2 kg) saving (%)	11.78	12.36	12.80	13.30	4.99	3.57	3.29
Road wear saving (%)	22.07	22.07	22.07	22.07	9.53	7.31	6.87

Figure 4 illustrates the sensitivity of the operational cost saving to the variations in cost parameters used in the parametric cost model. The other indicators are not considered in Figure 4 since they are not affected by the cost parameters. The cost parameters are shown on the left side of Figure 4. Each parameter was varied by −30%, −10%, 10%, and 30% with keeping the other parameters constant. The bars of Figure 4 refer to the deviation of the operational cost saving from the one in Scenario 2 when the cost parameters are changed.

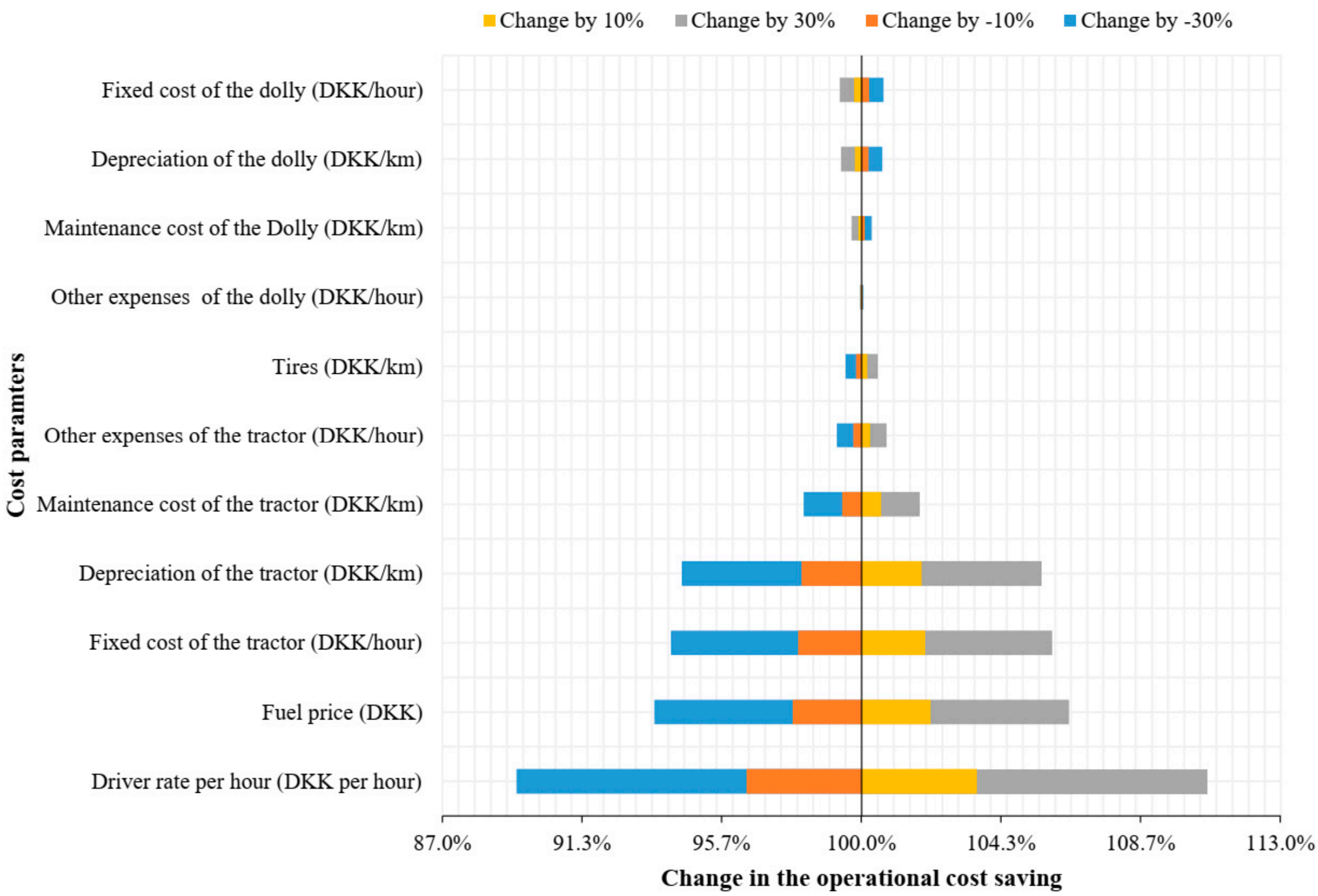

Figure 4. Sensitivity analysis of operational cost savings when 10% or 30% change in cost parameters.

Thus, Figure 4 shows which cost parameters significantly affect the operational cost saving. For example, if the fuel price increases by 30%, the operational cost saving increases by nearly 7% compared to its value in Scenario 2. From Figure 4, it is obvious that the two cost parameters affecting the saving the most are fuel price and driver rate per hour. The impacts of fuel prices and driver salaries are worth considering since fuel prices usually rise with some fluctuations. Increasing driver salaries is suggested as the number one strategy to face the driver shortage problem. An important implication of these results is that if fuel price and driver salaries are to continue rising in the future, the A-double combination will provide companies with a competitive advantage over the business-as-usual scenario. The tractor-related costs also have a relatively notable influence on operational cost saving. This is reasonable since the tractor's price and operating costs are relatively higher, and it is the only unit that is saved by using A-double combinations. Cost parameters related to dolly converters and tires have a negligible impact on the operational cost savings.

An important aspect that would also affect operational cost saving is the travelling speed of the A-double combination (see Table 1). The travelling speed directly affects how much time the vehicle requires to transport between two terminals, and thus time-based costs, e.g., driver salaries and fixed costs, would be affected by the allowable travelling speed of the A-double combination. Figure 5 shows how variations in the travelling speed in scenario 2 influence the operational cost saving. The findings illustrate that the cost saving is significantly reduced if policymakers set the A-double speed lower than the tractor-semitrailer combination speed (80 km/h).

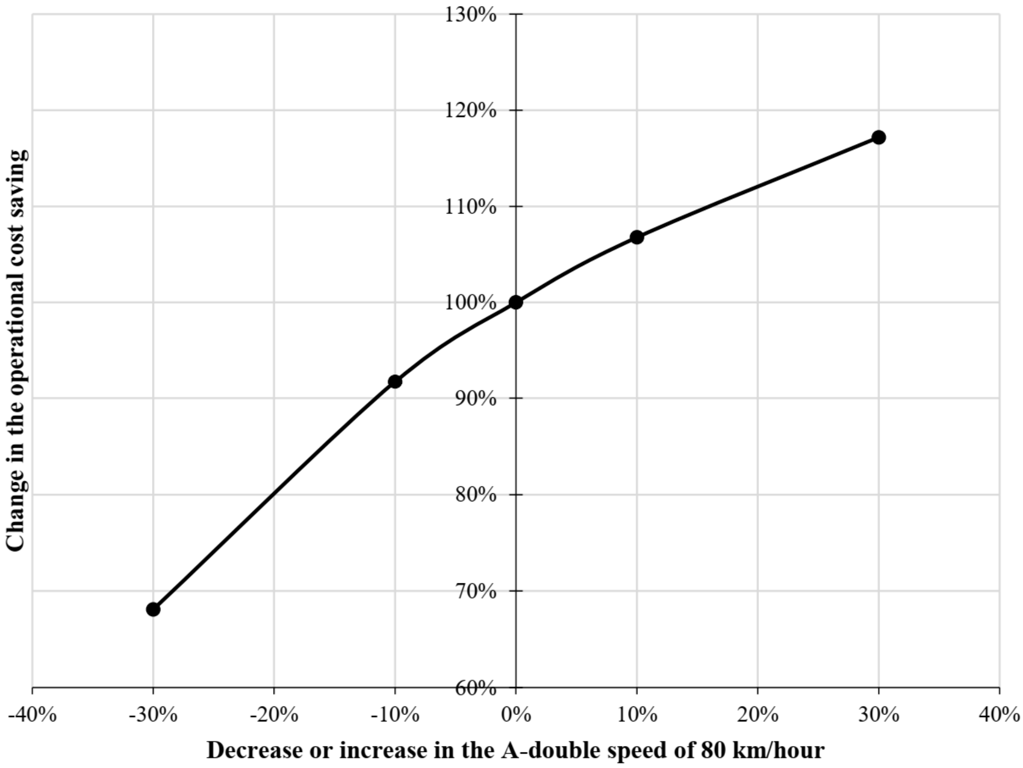

Figure 5. Sensitivity analysis of operational cost savings when 10% or 30% change in the average speed of the A double vehicle combinations in Scenario 2.

5. Conclusions, Implications, Limitations, and Future Work

This paper presents the findings of an in-depth analysis of the possible effects of A-double combinations if allowed in a line-haul freight transport network under operational and regulatory constraints in four possible implementation scenarios. In particular, the need for delaying trips is considered as an operational constraint on the haulier side, while the regulatory constraints are those imposed by authorities to reduce the likely effects of the A-double vehicles on traffic peaks, road infrastructure, and road traffic safety. More specifically, the current study considered three regulatory constraints related to the GVW, travelling speed, and driving times of the A-double trips. The four scenarios were evaluated and compared with the business-as-usual scenario (tractor-semitrailer combination) using five indicators: operational cost saving, empty trip saving, total trip saving, CO_2 emission saving, and road wear saving. The developed method and the sensitivity analysis were applied to a case study, including 48,472 trips of the tractor-semitrailer combinations made among seven terminals in Denmark.

Compared to the business-as-usual scenario, the results showed that for the scenario involving no constraint, the use of 60-tone A-double vehicles could reduce the operational cost by 26.39% while reducing empty trips, CO_2 emissions, and road wear by 96.34%, 14.75%, and 25.47%, respectively. The scenario limiting the trip delay to 3 h would significantly reduce the empty trip saving to 73.44% while other savings are slightly affected. For the scenario limiting the A-double trips to night times (10 p.m. to 5 a.m.), this would largely affect all savings. The scenario considering both constraints of the trip delay and night trips results in the lowest savings: operational cost (9.65%), total trip (17.91%), empty trips (42.09%), road wear (9.55%), and emissions (5.34%). It can be noted that in all scenarios investigated, the operational and external costs of the A-double vehicles are less than the business-as-usual scenario. In addition, the use of the A-double combination would lead to a significant reduction in the empty tractor-semitrailer trips by 42.09% in the least beneficial scenario.

Four sensitivity analyses were performed by investigating different values of trip-delay times, average pallet weights, cost variables, and travelling speed in the case study when calculating the six indicators. We noted that the results are sensitive to reducing the allowable trip-delay time lower than 3 h, and the empty trip saving is affected the most. This implies that the A-double combinations still have potential even if the company adopts a just-in-time delivery system where the allowable trip-delay time is too tight. Regarding the average pallet weight effect, the savings are significantly reduced when the pallet weight is 600 kg or more. This is mainly because of the 60-tonne GVW limit. This implies that the 60-tonne A-double combination is a more cost-effective solution for transporting cargo that needs increased vehicle dimensions rather than increased GVW. However, for different pallet weights, using the A-double combination would lead to substantial savings in the empty tractor-semitrailer trips. Regarding the cost parameters, we noted that the two cost parameters affecting the cost saving the most are fuel price and driver rate per hour. For example, increasing driver salaries and fuel prices by 30% would increase operational cost savings by 10.7% and 6.43%, respectively. This implies that if fuel price and/or driver salaries are to continue rising in the future, the A-double combination will provide companies with a competitive advantage over the business as usual scenario, especially with issues of the truck driver shortage. As a matter of road traffic safety, if policymakers set the travelling speed of the A-double vehicles to be lower than that of the tractor-semitrailer vehicles, we noted that this would highly reduce the operational cost saving by 31.9% for a 30% reduction in the travel speed. Thus, it would be better if the policymakers allow the A-double vehicles to drive at normal highway speeds while imposing special safety requirements, e.g., a performance-based standard system and reinforcing roadside and lane separation barriers to minimize accident risk.

From a research perspective, this study contributes to the literature by presenting a cost-benefit method to evaluate the effects of using the A-double combinations in line-haul transport systems from a micro-perspective standpoint. In addition, future research on this topic might be inspired by the developed methods, findings, and implementation scenarios of this study.

Although this study is based on a single company case, its findings are still useful to reduce the polarization in the LHV debate and show for the policymakers how different implementation strategies can control the negative impacts of LHVs and affect the benefits of the LHVs from micro perspectives.

From a company perspective, the results from this research indicate that transport planners might need to analyze, based on their freight and fleet characteristics, whether using the A-double combinations (if allowed) is beneficial for their transport practices or not. To achieve the most benefits of A-double combinations, logistics companies need to optimize routings and allocations of the A-double vehicles among the terminals. In addition, an IT system is imperative to enable reliable information flow and efficient coordination among actors of the transport network. Moreover, companies should adopt a collaborative approach in which they exchange loading units of modular combinations and use a triangle-route strategy in which the A-double combination drives from one company to another to move semitrailers of different companies.

This research has some limitations: First, it investigates the effects of a single company case. Although the findings might be useful to other companies, the results might not be generalized to other companies handling different commodities other than EU pallets. Therefore, there is a need to examine a wider set of different companies handling different commodities before deciding if the A-double vehicles are good or bad ideas on the country level. Second, this research did not quantify some effects, i.e., risk of accidents, traffic congestion, noises, and modal shift due to lack of reliable data.

Future research might focus, in the first place, on expanding this research by considering its limitations. In addition, it would also be beneficial to examine the likely effects of the A-double vehicles from a macro perspective using a commodity-based approach as in [37]. Finally, future work might consider empirical research to examine whether or not using A-double vehicles could be useful, taking into account views from all stakeholders involved with the LHV debate.

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