RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Development of a Logistics Decision Support Tool for Small and Medium Companies to Evaluate the Impacts of Environmental Regulations in California

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16. Abstract
Satisfying the demand for goods requires the movement of commercial and private vehicles, which are responsible for multiple negative impacts including noise, emissions, and traffic congestion. While efficiency is crucial for sustainable and profitable freight transportation, operations are typically inefficient with respect to emissions and social impacts. The reasons for such inefficiency are diverse, including the need for several attempts to complete a delivery and the under usage of vehicle capacity. The arrival of zero-emission and near-zero-emission medium- and heavy-duty vehicles may reduce (tailpipe) emissions. Multiple government agencies have supported the development and promotion of cleaner vehicles through strategies such as economic incentives to support purchases and disincentives to using internal combustion engine vehicles. However, small- and medium-sized companies face challenges in adopting cleaner vehicles, either because of high purchase costs or because the volume of their operations may not justify the expense. To address this issue, this work evaluates cooperative strategies between non-competing companies that would exploit economies of scale through the sharing of vehicle capacities in joint routing. The work develops a decision support tool named Cargo Aggregator Beta 1.0, which provides companies willing to cooperate with an efficient joint route to pick-up and deliver cargo from different origins and destinations. The tool, based on an extension of the vehicle routing problem, allows users to consider different vehicle capacities, decide on charging and/or refueling points, consider multiple depots, and guarantee the completion of all deliveries in a general time window. The tool can be used to better understand the impact of sustainability policies that would limit the amount of pollutant emissions generated, or policies that seek to restrict fleet composition. Numerical analyses using study cases in California show the potential benefits of implementing these collaborations in reducing both costs and emissions.

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Executive Summary

Development of a Logistics Decision Support Tool for Small and Medium Companies to Evaluate the Impacts of Environmental Regulations in California

Glossary

Acronym	Definition
ACT	Advanced Clean Truck
ACF	Advanced Clean Fleet
CARB	California Air Resources Board
CSFAP	California Sustainable Freight Action Plan
EVSE	electric vehicle supply equipment
SMEs	small and medium enterprises
TCO	total cost of ownership
VRP	vehicle routing problem
VRPSD	vehicle routing problem with split deliveries
VRPTW	vehicle routing problem with time windows
ZEV	zero-emission vehicles

Executive Summary

Transportation and logistics operations generate negative externalities such as worsening air quality, greenhouse emissions, the degradation of water resources, noise, and congestion (Santos et al., 2010). These negative externalities have driven decision makers to reconsider transportations systems. Subsequently, several new systems have been proposed that would be more efficient and less environmentally disruptive, such as the use of zero and near-zero-emission vehicles, advanced communications and information technologies, and efficient logistics strategies through new optimized operational algorithms.

To mitigate negative transportation impacts, California's agencies have developed (or are in the process of developing) several initiatives and regulations to foster cleaner technologies, including: the Advanced Clean Truck (ACT) rule, the California Sustainable Freight Action Plan (CSFAP), and the ongoing development of the Advanced Clean Fleet (ACF) rule. Overall, these initiatives aim to improve freight environmental efficiency, foster the use of zero and near-zero-emission vehicles (ZEVs), and improve economic competitiveness. Some of these initiatives take the form of purchase voucher incentives, vehicle manufacturer mandates, and regulatory emissions policies. Although these actions are potentially effective for sustainability, the immediate economic impacts that they would have on businesses, especially small- and medium-sized businesses, are not well understood. If the acquisition of typically expensive cleaner vehicles is mandated, it may negatively affect companies' cash flow. On the other hand, when the vehicle purchase is subsidized by the government, it could result in inefficient public spending if they those assets are not used to the fullest. To contribute to these efforts towards freight environmental efficiency, we developed a logistics decision-support tool (DST) named **Cargo Aggregator Beta 1.0**. This tool facilitates the joint routing of pick-ups and deliveries between cooperating companies to reduce their environmental impact and transportation costs. In addition, the tool can help us to better understand the impact of sustainability policies in terms of companies' operative costs. For example, sustainable policies forcing the partial substitution of diesel vehicles with cleaner vehicles may impact companies' economic profiles. However, when efficiently utilized, ZEVs could yield lower operative costs thanks to their low maintenance costs and fuel requirements. To achieve even lowers costs, the tool analyzes cooperative strategies that jointly exploit economies of scale. If two companies are able to cooperate and use a single truck for the delivery of a given amount of freight, this increases efficiency, as the single truck is used closer to its maximal capacity and travels fewer total miles than would two independently operated trucks, thereby reducing vehicle miles traveled (VMT).

Implementing the tool through a few case studies shows significant reductions (from 7.5% to 70%) in costs and tailpipe emissions (up to 100%) when companies cooperate compared with when they operate independently. Although in practice, unexpected situations such as changes in demand, vehicle failures, or delays could affect the overall benefits and expected output of cooperative strategies, cooperation may still be a viable alternative that deserves additional research and attention to improve the efficiency of freight.

Contents

1. Introduction and Background

Currently, there are various regulations and plans aiming to improve environmental efficiency and sustainability through the promotion of cleaner technologies in California. For example, the California Air Resources Board (CARB) initiated works on its Advanced Clean Truck (ACT) rule to support the California Sustainable Freight Action Plan (CSFAP; California Governor's Office, 2016) and is currently developing the Advanced Clean Fleet (ACF) rule among other regulations (California Air Resource Board, 2018). The ACT is considered a manufacturers' mandate with specific sales targets of zero-emission trucks, while the ACF is considering fleet requirements. These sustainability policies do not necessarily affect all companies in the same way, and may not generate the expected, or similar positive outputs among companies. This is because the supply chain structures and the complexity of operational decisions vary between different companies. In an empirical study, we found that a significant reduction of emissions may not necessarily be efficient at the business level (Jaller, Otero-Palencia, Yie-Pinedo, 2019). Taking the analogy of battery charging, the last 20% of the battery capacity can take much more time compared to the initial 80% of the charge. Similarly, for a single company, trying to achieve full reduction of emissions may not be cost effective. There are optimal levels, at least in the short term, for such reductions, and it would be more beneficial to get as many companies as possible to reach those levels, rather than spending limited resources to mandate complete reductions, for which the marginal return rates decrease. Therefore, tools to estimate reduction potentials and costs are important to help companies, policy makers, and planners more effectively align mandates and initiatives to the performance of business operations.

For years, the primary objective of logistics management has been to move inventory effectively and efficiently, while satisfying the customer's desired service level at the minimum cost. Even though companies have been able to achieve high levels of logistics sophistication and efficiency, there has been a high cost for the overall system in terms of negative externalities (Jaller et al., 2016). In general, inventory decisions (e.g., stock levels, replenishment, shipment sizes, frequencies) affect others related to transportation outcomes, facility location, and asset utilization. Operations in general, the routing and scheduling of shipments, have received significant attention in research and practice, and many companies have invested in tools, systems, and models to optimize such activities.

One of the strategies implemented to improve some of the common logistics performance metrics such as reliability, costs, promptness, and risk is cooperation and/or collaboration between companies. Cooperation allows the development of synergies aimed to benefit both partners. This project focuses on cooperative transportation operations, and builds on the well-known Vehicle Routing Problem (VRP), which aims to deliver cargo from origins to destinations at minimum cost. What differentiates this new model from the classic VRP and its most common extensions is the integration in a single model of pick-ups and deliveries, load capacity constraints, a unique time window, vehicles with range limitations and limited recharging points, multi depots, and a heterogeneous fleet. Through cooperation between companies, the proposed method exploits economies of scale by efficiently using vehicles and sharing their costs between companies. The goal is to maximize the use of the capacity of vehicles in shared trips, which reduces overall vehicle miles traveled (VMT) and indirectly reduces emissions. In addition to lowering operational costs, the strategy seeks to reduce the burden of investment in assets (ZEVs, in this case) and contributes to the objectives of the ACT and ACF by providing an alternative pathway for companies, especially small and medium enterprises (SMEs), to achieve such fleet upgrades. The model can also help elucidate the potential impacts of sustainability policies, such as those that cap emissions or that constrain fleet composition, and what companies will need to do to be compliant.

This report is organized as follows; Section 2 illustrates some of the most outstanding ZEV and automation innovations. Section 3 provides a review of the benefits of cooperative practices in the supply chain. Section 4 presents the research methodology, including a short review of the VRP model, the extension proposed, and the solution method. Next, Section 5 illustrates case studies that show the benefits of the proposed model. Finally, Section 6 provides conclusions, insights, and a discussion.

2. Zero and Near-Zero Vehicles: A Promising Alternative for a Sustainable Freight System

According to the Environmental Protection Agency (EPA, 2017), medium- and heavy-duty diesel trucks generate close to 25% of the transportation carbon footprint. On average, diesel trucks emit four times more nitrogen dioxide pollution and twenty-two times more particulates than cars that run on gasoline. Electrification, or replacing internal combustion engine vehicles with vehicles powered by electric motors, could significantly contribute to reducing both tailpipe emissions and global CO_2 emissions, when the electricity is generated by renewable and clean sources.

The heavy electric truck industry has shown significant progress in recent years, introducing more efficient trucks with higher load capacities. This progress is first due to the support received from governments such as the State of California, which encourages developers to manufacture zero-emission vehicles and encourages companies to use them. And second, the progress has been possible because many large companies have shown interest in acquiring these vehicles. This scenario has created a competitive environment for manufacturers that now feel compelled to quickly put their vehicles on the streets. Some have decided to join forces to take control of the market more quickly. The Startup Thor (now XOS Trucks), wanting to reduce its development time, has partnered with expert chassis company Navistar to manufacture trucks that use the Navistar Chassis and Thor electric motor. Another example is Daimler, which is working with Mitsubishi to mass produce the E-Fuso. Waymo is working with its sister company Google Logistics to boost the development of technologies to improve its trucks and design strategies to move cargo efficiently.

The arrival of all-electric and autonomous vehicles represents a challenge for countries, primarily because of the imperative to build recharge stations and to create economic incentives for companies to acquire these vehicles. Moreover, the transition to autonomous trucks is a challenge for lawmakers, who need to create new laws and policies warranting safety conditions for all road users while allowing manufacturers to keep developing their technologies. Undoubtedly there are many questions to be solved, and it seems the arrival of these technologies is imminent. Some of the main alternatives available, and their statuses, are displayed in Table 1.

Table 1. Examples of Medium- and Long-haul Vehicle Innovations

Developer	Development Status	Where	Features	Appearance
Tesla	Semi Class8, first units (300 mi range version) expected by of 2022 (three year after planned)	USA	Autopilot and other safety technologies Total weight capacity 40 ton Quick acceleration fully loaded (20 sec) Comparable capacity to class 8 diesel Range between 300 to 500	
Daimler and their electric truck divisions	E-Fuso Vision One truck expected by 2022 Freightliner Inspiration: self-driving all-electric truck in development New Lvl 2 Cascadia truck	Europe, Japan, and USA	E-Fuso Vision One, class 8: 350-mile range, GVW 23 tons, payload 11 ton eCascadia class 8: 250-mile range, GCW 41 ton. Recharge time 80% in 90 min. Freightliner eM2 ET: 230-mile range, recharge 80% in 60 min, GVWR 13 and 16.5 ton for class 6 and 7 configurations Cascadia improved navigation and safety devices; driver assistance, automatic lane centering, adaptive cruise control, and emergency braking, cameras, radar, ultrasonic sensors	
Waymo self-driving trucks	Truck delivering to Google's data centers, Atlanta Testing in California since 2020 and Arizona. Recently expanded to Texas and New Mexico.	Phoenix, USA	Same sensors powering the company's self-driving minivans Same self-driving software of passenger cars Expected to be completely driverless	
Kodiak Robotics	It has started making commercial deliveries with driver behind the wheel from Dallas to Houston.	Texas, USA	Self-drive and other safety technologies Focuses on "middle mile" highway routes Same capacity as class 8 diesel	
Embark Peterbilt	Delivering coast-to-coast for Electrolux and Ryder Sales being dependent on regulations	California, Florida, USA	Safety technologies Fully autonomous Same capacity as class 8 diesel	
Peterbilt	220EV available for class 6 and class 7 from 141 to 282 kWh	USA	220EV Class 6: 100–200-mile range, GVWR 13 ton 220EV Class 7: 100–200-mile range, GVWR 16.5 ton	

Thor (XOS) Trucks	Available for demos Production started in 2019 Pre-order available	California, USA	Prototype (300-mile range) Motor mounted between the frame rails Navistar International Corp.: chassis	
Hexagon	Purus eM2 all-electric available in class 6 and 7	USA	Purus eM2: 125-250+mile range, GVWR 13 to 16.5 ton for class 6 and 7 respectively Full charging time: 2 hours with Fast-DC	
Volvo Electric Trucks	Demonstrators in 2019 Volvo FE Electric truck presented in 2018 Sales started in 2019 in Europe for medium size, production and sales for heavy duty since 2020	Europe and USA	VNR electric 4x2 straight truck class 7: 150-mile range, GVWR 16.5 ton VNR 4x2 and 6x2 tractor class 8: 120-mile range, GVRWR 33 and 41 ton respectively Vehicles equipped with smart technologies: remote diagnostics, geofencing, and management platform	
Navistar	Straight truck available in class 6 and 7	USA	International eMV: 135-mile range, GVWR 13 to 16.5 ton for class 6 and 7 respectively. Full charging time: ~2 hours with DC charger	
Volvo Vera	Development phase Part of integrated solution Cargo to port terminal in terminal in Gothenburg	Sweden	Full autonomous, all-electric vehicle Less emissions and low noise levels Remotely controlled and monitored Safety technologies	
BYD Electric Trucks	In production in Ontario Various model available class 6 and 7	USA and Canada	-All-electric, 6F/6F Class 6 and 8TT range up to 200 mi. -GVWR 13 and 52.5 ton for 6F/6F and 8TT respectively -Full charging time 2-3 hour	
Cummins Kenworth T370	Introduced in 2018 as hybrid electric solutions Traveled over 6 million miles in a fleet setting in the U.S. and China	China, Europe and USA	Configured with exportable grid quality electric power to recharge other vehicles The PowerDrive hybrid system for light, medium, and heavy-duty Could pair with diesel or natural gas engines and battery pack outputs 50-mile pure electric range 300+ miles hybrid fuel economy	
Einride	Demonstrated T-log operations On testing since 2020	Sweden	Autonomous, all-electric logging truck 120-mile range. Lvl. 4 autonomous driving Detection sensors cameras, lidar and radars and intelligent routing software Remotely controlled	

2.1 The Power Supply Challenge

In general, electrification alternatives are seen positively by both governments and the public due to their contribution to reducing GHG emissions. One of the major challenges for all-electric trucks, either those with automation levels or not, is the need to ensure the efficient recharging of batteries for daily duties. It is important to note that the infrastructure for recharging batteries could be shared between light-duty and freight vehicles, and currently there is an insufficient number of stations in the US for light-duty vehicles, even considering that 80% of the charging is done at home (Dolsak & Prakash, 2021). The number of electric charging stations in the US is still small but growing, especially because the government has provided incentives to build more stations, and manufacturers have made investments in expanding their charging networks to increase costumers' confidence in buying EVs. Additionally, the private sector has started to build public charging infrastructure and identified viable business models. In September 2018 there were about 22,000 public charging stations in the US and Canada that are classified as level 2 (240 volts chargers) and DC fast charging (fast-charging stations supply a range of 60 to 80 miles per every 20 minutes of charging, on average). In contrast, there are seven times more gas stations, about 168,000. Volkswagen has been installing 2,800 electric vehicle charging stations in 17 of the largest cities in the US (Hawkins, 2018) since 2019, and has invested $2 billion in charging infrastructure across the country. However, most automakers rely heavily on the burgeoning networks installed by governments, utility companies, and third-party companies. It is a cheaper option, but it also implies more uncertainty and less control. Luxury automakers (Mercedes-Benz, BMW, Jaguar, and Audi) have launched and plan to continue launching electric cars since 2019 (Hawkins, 2018), and virtually all major automakers are betting their future on electrification. This revolution has been supported by the rapid decrease in the price of batteries, which dropped by more than 70 percent between 2008 and 2014. Auto manufacturers have a choice: build their own charging networks or rely on third-party networks.

In terms of aggregate global growth in the 100 most populated metropolitan areas in the US, there is a projected need for 82,000 workplace charging stations, 103,000 Level 2 public stations, and 10,000 DC fast stations by 2025 (Nicholas et al., 2019). Compared to what was in operation at the end of 2017, the estimates for 2025 charging needs are 7 times for workplace, 3 times for level 2, and 3 times for DC fast stations. Combining these three types of non-domestic charging, the need for 195,000 charging points by 2025 are 4.3 times more charging points than were available at the end of 2017. These estimates do not include domestic charging, rapid charging in the corridor between metropolitan areas, or other stations in rural areas, which were outside the scope of our analysis. The largest charging gaps are in markets where electric vehicle absorption will grow fastest, including in many cities in California, Boston, New York, Portland, Denver and Washington, D.C. In brief, much more charging infrastructure is needed to maintain the transition to electric vehicles. In the main US markets as of 2017, only approximately a quarter of the workplace and public chargers that will be needed by 2025 are in place. The deployment of charging infrastructure will have to grow by approximately 20% per year to meet the 2025 targets.

Specifically, in California, several programs have been announced that aim to deploy substantial charging infrastructure to reduce the charging infrastructure gap. For example, a recent study analyzed the charging needs for large California markets through 2025 for light vehicles (Nicholas et al., 2019). The study only includes the 10 largest metropolitan areas, which together represent 86% of the state's population: Los Angeles, San Francisco, Riverside, San Diego, San Jose, Sacramento, Fresno, Bakersfield, Oxnard, and Stockton (Nicholas et al., 2019). The analysis indicates that about 84,000 charge points are required by 2025, with nearly 16,000 (15%) already placed at the end of 2017. In executing the large announced statewide infrastructure construction projects, Electrify America and three major electric power utilities could cover approximately 27,000 workplace and public charge points across California. So, the final coverage is expected to be up to 40% of the charging gap. Beyond these installations, 41,000 charging points would need to be constructed, a substantial gap that is expected to be filled through public and private efforts.

As mentioned, the estimations presented above are mainly based on light-duty electric vehicles; charging demand for medium and heavy-duty electric trucks was not considered. Hence, the 4,100 extra charging points are a lower bound for the market. While trucks may only represent a small share of the traffic in urban areas, they generate more than half of overall emissions for specific contaminants (Jaller et al., 2016). Nevertheless, the global all-electric truck market is expected to grow at a compound annual rate of approximately 65.0% over the next five years, reaching $12.4 billion in 2024, from $610 million in 2019 (Nicholas et al., 2020).

In a study that aims to evaluate the use of zero-emission vehicles in last-mile deliveries (Jaller et al., 2021), four general charging strategies were distinguished: home/depot-charging; public charging, inductive charging, and battery replacement. Charging time is unique for the fleet characteristics in terms of their battery, use of battery over time (charge and discharge), and Electric Vehicle Supply Equipment (EVSE) infrastructure. The authors mention that considering some European pilots, depot-charging may be the most viable option, however, considering the depot and yard, and the operations performed with and to the vehicles, one charger per vehicle is often required. Usually, charging is performed overnight, while other logistics operations are conducted at the facilities. As a result, retrofits to the electric infrastructure at the facility and the grid may be needed to make functional chargers. The authors developed a sensitivity analysis and found that even if charging infrastructure costs were 10 times higher, the total cost of ownership (TCO) impact would represent less than a 20% cost increase. Empirical data from different last-mile delivery fleets show operational differences among vocations, in particular, beverage, linen, food, and parcel delivery routes within a 100-mile distance represent more than 80% of their daily trips. Moreover, more than 95% of parcel routes are below this level. These are important findings because they show opportunities for electrification in last-mile distribution since these range requirements are easily fulfilled by commercially available vehicles and charging technologies.

In summary, the need for recharging infrastructure is higher for California than estimated by available studies, even though most recharges are expected to be done at the depot at least for the last- mile, while medium size trucks may use public chargers. In the case of long-haul, vehicles are more likely to have to use charging stations arranged on the roads, however, estimating this required station gap is not an easy task. This is because such estimates depend on a multitude of factors, such as vehicle sales projections, driver profiles, required charging energy by activity, the hour of charging demanded by activity, number of charger points available by activity, and accessibility to charging points, among others.

2.2 Shared Mobility in Freight Transportation

Analogous to passenger transportation, shared mobility options exist in freight transportation. On the passenger side, this concept consists of shared trips when passengers have a similar destination. Shared mobility is part of the so-called sharing economy, “a socio-economic ecosystem built around the sharing of human, physical and intellectual resources, which allows the production, distribution, trade and consumption of goods and services by different people and organizations” (Matofska, 2016). The trend of renting, sharing, or sub-leasing vehicles or their excess capacities can be framed in the concept of transportation as a service (TaaS), also known as mobility as a service (MaaS). This is ideal for companies or individuals looking for easy, affordable, and flexible transportation without the hassle or cost of owning a vehicle (Kim, 2018; Ya’u et al., 2019). The widespread use of smartphones and emergence of mobility apps during recent years has facilitated this kind of mobility strategy. Some of the outstanding companies in these endeavors are Uber, Lyft, Doordash, and Echo. In general, these companies rely on high technology and algorithms to support their operation and match clients with available resources.

The work conducted in this project aligns with the concept of collaboration or cooperation in logistics, which also lies on the boundaries of TaaS. According to this concept, companies share vehicles and their trips to exploit economies of scale provided by a better use of the capacity of ZEVs. This cooperative strategy has potential to reduce both operative costs and pollutant emissions, since it favors the reduction of VMT and subsequently the reduction of tailpipe emissions. The strategy could also help mitigate other disproportionate externalities of transportation. A further description of the concept of cooperation is provided in the next section.

3. Cooperation in the Supply Chain

3.1 Potential of Cooperative Strategies

The concept of cooperation, also known as collaboration, in the supply chain has evolved over time (Montoya-Torres & Ortiz-Vargas, 2014). One of the first definitions of supply chain collaboration is given by Narus and Anderson (1996) who defined collaboration as "the cooperation between independent companies, somehow related, that share their own capacities and requirements with their clients." Similar terms, such as coordination, cooperation, strategic alliances, etc., have been employed in the literature (Bäckstrand, 2007; Montoya-Torres & Ortiz-Vargas, 2014). A wider definition can be obtained from the work of Simatupang and Sridharan (2005): "Collaborate means to obtain common goals and objectives in order to create competitive advantage and higher (individual and global) incomes for the members of the supply chain than the ones that could be obtained if each member works on its own."

Traditionally it has been considered that collaboration can be developed <u>*vertically*</u> or <u>*horizontally*</u> (Barratt, 2007). However, Chan & Prakash (2012) also include a <u>*lateral*</u> classification. Vertical collaboration consists of integration with suppliers (between logistics functions) and with clients, while horizontal collaboration refers to collaboration with competitors and with non-competing companies. It is important to note that in vertical collaboration companies share responsibilities, resources, and performance information to serve end customers. An example of vertical integration in the context of inventory management is provided by Alp, Ulk, & Nasuh C (2014) who present a joint replenishment model for multiple retailers, who make use of shared transportation units to reduce their costs. This strategy proves to have substantial cost benefits. Horizontal collaboration occurs between companies at the same level of the supply chain, while lateral collaboration is the combination of the benefits and capabilities of vertical and horizontal collaborations (Hsu & Hsu, 2008).

Collaboration is often reported in the literature to have good results in reducing logistic costs, enhancing service levels, improving communications, reducing the bullwhip effect, etc. (Ireland, R. & Bruce, 2000; Småros et al., 2003). In particular, strategies concerned with collaboration in inventory management and transportation have received special attention, considering the positive effect they can have in supply chain effectiveness and profitability (Barratt, 2007; Fiestras-Janeiro et al., 2011; Holweg et al., 2005). Some of the benefits of using these practices reported in the literature are presented below:

- Bullwhip effect reduction (Småros et al., 2003).
- Inventory level reduction, capacity use improvement, and supply chain flexibility (Disney & Towill, 2003; Jaller et al., 2020; Otero-Palencia et al., 2018, 2020; Zhang et al., 2007).
- Reduction of supply times, increase in quality, faster innovation speed, quick resolution of problems, efficiency in technology transfer, increase in customer satisfaction and higher profitability (Fawcett et al., 2008).
- Resources efficiency improvement (Le Blanc et al., 2004).

- Reduction in transaction costs, increase in exchange of learning resources, knowledge exchange, reduction and control of supply risk, reduction of administrative costs, improvement of communication (Chan & Prakash, 2012).

3.2 Collaboration in Inventory Systems and Transportation

The implementation of collaborative inventory strategies has been influenced by external drivers, such as the dynamics of competition, rapid changes in customer tastes, the speed of change in technologies, fluctuations in demand, the risk of technological obsolescence and financial pressures that demand a rapid return on investment, and, of course, profitability (Fawcett et al., 2008). Collaboration offers an opportunity to develop differentiating and hardly-inimitable capacities that may well become competitive advantages (Simatupang & Sridharan, 2005).

An observed common benefit of collaboration in inventories is the reduction of the level of inventories, which is a highly desirable effect for companies, since it enables opportunities for reducing both management and operative costs (Otero-Palencia et al., 2020). This makes sense considering that typically small and midsize companies must replenish their inventories in relatively big lots to avoid large ordering costs but doing so increases their holding costs and inventory risks (e.g., obsolescence, damage due to handling, or even robbery). The reader is referred to the Appendix A for additional discussions on inventory and transport. In addition, Singer & Donoso (2007) add that this type of collaboration favors cash flow, since it induces a greater turnover of inventories and therefore capital. Further, when collaboration includes vertical integration, it facilitates the predictability of demand, leading to more accurate supplies and fewer inefficiencies; inventory collaboration could lead to an improvement in service level and supply reliability. Danese (2006) points out that a decrease in the number and frequency of stockouts is a direct benefit of supply chain integration; it improves the availability of inventories to customers, thereby increasing the level of service.

Seeking to exploit these benefits, several collaborative inventory models have been analyzed by academics. Özen, Sošić, & Slikker (2012) exhibited an analysis of a decentralized inventory model made up of a manufacturer, a warehouse, and a retailer. The authors demonstrated that by exchanging information, the demand forecast could be better calculated, improving the efficiency of the entire chain. Another representative example is the work carried out by Bartholdi & Kemahlioğlu-Ziya (2005), who tested the effectiveness of a centralized inventory or *pooling strategy* for manufacturer-retailer supply chains. In this work, the model was validated for two retailers, demonstrating the possibility of reducing inventory costs. The results are scalable for larger numbers of manufacturers and retailers. One of the challenges noted for *coalition* formation under this type of strategy are the barriers to sharing information placed by the players. About this issue, some authors have proposed solution strategies: contracts, capital commitment and joint investment, and negotiation strategies (Fiestras-Janeiro et al., 2011). Another outstanding example is the work by Yu (2010), who demonstrated that through supplier-distributor alliances, the cost of perishable product inventories and the rate of the non-fulfillment of orders can be reduced. Similarly, T. Zhang et al. (2007) showed that inventory holding can be reduced by optimizing delivery transportation policies.

On other topics, Chan & Prakash (2012) argue that lateral inventory integration policies are potentially more advantageous than horizontal and vertical ones. In a model where two manufacturers with continuous review provisioning policies (s, S) and (s, Q) integrate their inventory, the lack of information and the supremacy exercised by one of the two manufacturers in horizontal integration disadvantaged the flexibility of the chain and its inventory levels, but when manufacturers knew each other's demand information, better forecasts were made that improved demand forecasts and reduced inventory levels. Other reference models are reported by Kelle, Miller, & Akbulut (2007), and Zavanella & Zanoni (2009). In general, collaborative practices demonstrate great potential that can be exploited by those companies that are willing to share information. However, the testing of many other collaborative models and further debate in the scientific community is necessary for their extension in the industry.

4. Methodology

The classical vehicle routing problem (VRP) proposed by Dantzig and Ramser in the late fifties seeks to find a set of routes at a minimal cost. This is done by determining the shortest path and minimizing the number of vehicles, as well as beginning and ending the route at one depot once the demands of all nodes are met. A single vehicle is allowed to visit each node once, with a limited capacity. After analyzing the complexity of the VRP, multiple authors (Archetti & Speranza, 2012; Dror & Trudeau, 1990; Lenstra & Kan, 1981) have concluded that since it cannot be solved in polynomial time, plus other considerations, the VRP and practically all its extensions are NP-hard problems. i.e., finding the optimum solution of relatively large instances of the problem (even just more than 100 nodes) is not possible in a moderate time. The VRP has been of interest to mathematicians and engineers since its inception, due to its applicability and importance in real-world settings. Several extensions have been proposed over time, the most outstanding are described next:

- Vehicle routing problem with split deliveries is a variation of the classical VRP, where each customer can be served by more than one vehicle. Besides the delivery routes, the amounts to be delivered to each customer in each vehicle must also be determined.
- Vehicle routing problem with time windows implies that each node must be served before a specified time.
- Multi-depot vehicle routing problem includes multiple depots from which vehicles can start and end.
- Inventory routing problem involves the coordination of inventory management and routing to customer.
- Capacitated vehicle routing problem considers the case where the vehicles have a limited carrying capacity of the goods that must be delivered.
- Vehicle routing problem with pickup and delivery addresses the case where several goods need to be moved from certain pickup locations to other delivery locations. The goal is to find optimal routes for a fleet of vehicles to visit the pickup and drop-off locations.
- Open vehicle routing problem considers vehicles that are not required to return to the depot.
- Heterogeneous fleet vehicle routing problem includes vehicles with different features, mainly differences in load capacity.
- Electric vehicle routing problem targets electric vehicles characteristics, e.g., limited range and the impacts of charging infrastructure availability.

It is common to see in the literature extensions that combine several different extensions of the problem, such as the Multi-depot VRP with heterogeneous fleet (Salhi et al., 2014) or the Multi-Depot VRP with pick-ups-and-deliveries (Sombuntham & Kachitvichyanukul, 2010). A comprehensive literature review of the VRP is outside the scope of this report; a broader review is provided by Caric & Gold, (2008) and Montoya-Torres et al. (2015).

This work lies within the boundaries of the VRP to minimize costs, but it also considers sustainable policies, as well as the incorporation of cleaner vehicles. It is also part of a research trend particularly oriented to the analysis of sustainable transportation systems known as eco-routing, which also embraces the VRP (Erdoĝan & Miller-Hooks, 2012; MirHassani & Hooshmand, 2019). Eco-routing is a broad term that includes point-to-point routing (Huang & Peng, 2018; Schröder & Cabral, 2019), and traffic assignment (Woo et al., 2017). Moreover, it includes models accounting for different factors that can influence vehicle efficiency (Zhou et al., 2016), such as weather, vehicle, roadway, traffic, and driver-related factors.

Overall, this work proposes an integer mixed linear formulation with multiple depots, electric and heterogeneous fleet, and pick-ups and deliveries VRP. The proposed model analyzes three logistics decisions: optimum route, depot (operative center) locations, and fleet composition and charging/refueling points, while constrained by the load capacity of vehicles and range. Additionally, the model considers environmental policies in the form of operational constraints. The first sustainability constraint limits the maximum quantity of emissions produced by the whole fleet, while the second sustainability constraint controls the number of ZEVs in the fleet. The reader is referred to Appendix B for a detailed description of the proposed VRP extension.

As mentioned, the VRP is a complex problem to model, and ultimately solve. In the literature there are several approaches to modelling the VRP. For example:

I. **Vehicle flow formulations:** This is the most basic formulation and consists of using integer variables associated with each arc, integers that represent the number of times that a vehicle traverses the arc. This approach is typically limited to cases where the solution cost can be expressed as the sum of costs associated with the arcs.
II. **Commodity flow formulations:** This approach uses integer variables associated with the arcs or vertices that represent the flow of commodities that go along the routes of the vehicles. Typically, these models are preferred by modelers aiming to use exact methods.
III. **Set partitioning problem:** These formulations feature an exponential number of binary variables associated with different feasible circuits. The VRP is formulated as a set partitioning problem, which decides the collection of circuits that would minimize the costs while all constraints are satisfied.

Letchford & Salazar-González (2006) offer a comprehensive review of these formulations and establish similarities and differences between then. They also propose and discuss strategies to improve the convergence of solution methods by tightening the formulation and controlling the sub-tour elimination constraints. In general, solving the VRP by exact methods is not viable; even problems with a few more than 100 nodes cannot be solved in a moderate computational time (Caric & Gold, 2008). Therefore, heuristics and mainly metaheuristics have been proposed to solve the problem. The VRP extension proposed in this work is no exception. Therefore, we developed a hybrid solution method that includes exact methods, mainly for small cases, and genetic algorithms (metaheuristic) for all others. See Appendix B for details.

5. Case Studies

The following case studies show the benefit of cooperative strategies for load consolidation, aggregation, matching, and shared routing through the application of Cargo Aggregator Beta 1.0. The parameters of costs, rebate policies, and vehicle characteristics are based on information from the California Air Resources Board's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program.[1] California offers incentives to public and private companies for the acquisition of clean vehicles and their operation. For example, there are purchase vouchers available for vehicles and discounts on electricity rates. Table 2 shows cost information and other features that will be used in the case studies.

Table 2. Electric and Diesel Class 8 Vehicle Parameters

Parameter[2]	Value
Current diesel rates (USD/gal)	4.57
Clean fuel rate (USD/kWh)	0.102
Miles traveled per year (mi)	63000[3]
Average vehicle's service life (yrs)	12
Sales tax rate clean vehicle	7.5%
Model year	2021
Maintenance Cost (Compound Annual Growth Rate)	3%
Discount rate	2%
Asset Depreciation Schedule (yrs)	7
Tax Shield Tax rate	35%
Clean vehicle purchase price over diesel (times)	3
Diesel vehicle fuel efficiency (mpg)	6.5
Electric vehicle energy efficiency (KWh/mi)	2.06
Diesel vehicle maintenance cost (USD/mi)	0.443
Diesel vehicle maintenance cost (USD/mi)	0.233

To estimate the variable cost per mile per vehicle, we considered a Freightliner Cascadia 2021 (USD $160,000) and the battery electric Freightliner e-Cascadia (USD $480,000), which is available in the HVIP project with a rebate of USD $120,000. Figure 1 illustrates the payback period of the electric vs. the diesel baseline vehicle. In brief, the discounted payback period procedure is useful to determine the profitability of a project/investment. A discounted payback period gives the number of years it takes to break even from the initial expenditure, by

[1] California HVIP: https://californiahvip.org/tco/

[2] Parameters are available in: California HVIP: https://californiahvip.org/tco/

[3] Class 8 truck average VMT in the US: https://afdc.energy.gov/data/10309

discounting future cash flows, i.e., showing when the investment will pay off, or when the cash flows generated from the project will cover the cost of the project. This procedure typically recognizes the time value of money. In the example in Figure 1 the intercept point (at 5.13 years) between the orange line (clean vehicle) and the blue line (diesel vehicle) represents the moment when, under regular conditions, all costs related to the vehicles are the same. From this point on, it is more profitable to use the electric vehicle.

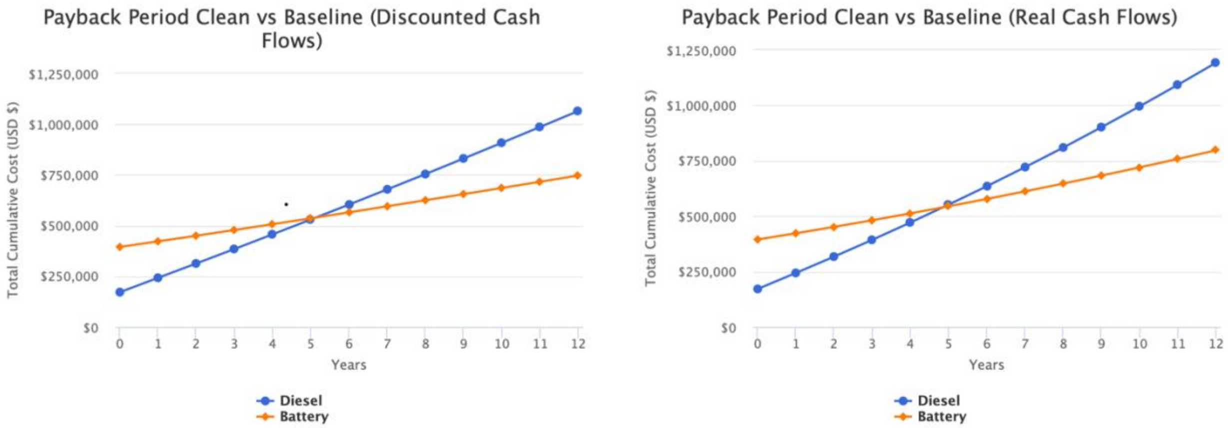
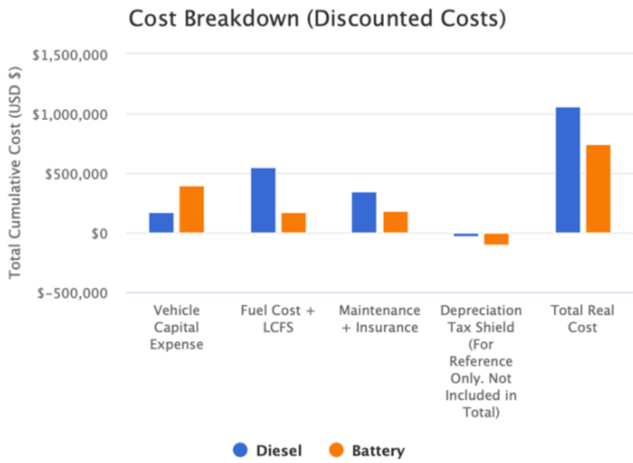


Figure 1. Estimated Payback Period (years) of Incremental Purchase Price of Clean Fuel Vehicle. Adapted from https://californiahvip.org/tco/

Figure 2 shows the itemized results of the payback analysis in Figure 1. Although the purchase cost of the diesel vehicle is 3 times lower than the clean vehicle, the savings in maintenance and fuel can make the investment in clean vehicles viable and profitable.

At present value, for a depreciation period of 7 years, the estimated savings in fuel for the clean vehicle are approximately USD 35,894 and maintenance savings are USD 15,695. Tax shield depreciation per year is up to USD 9,628 for the clean vehicle, and lifetime savings without the purchase price are USD 686,463. Total real savings including the purchase price with taxes (USD 171,600 for diesel and USD 394,800 for battery electric) are USD 395,864. In general, in the mid-long term (5-15 years), full-electric vehicles seem to be more efficient than diesel vehicles. The final purchase decision will depend on investors' expected return and risk analyses. It is important to recall that while the operational range of electric vehicles may limit their application on long-haul travel, this study incorporates charging and fueling at facilities to optimize routes and operations.



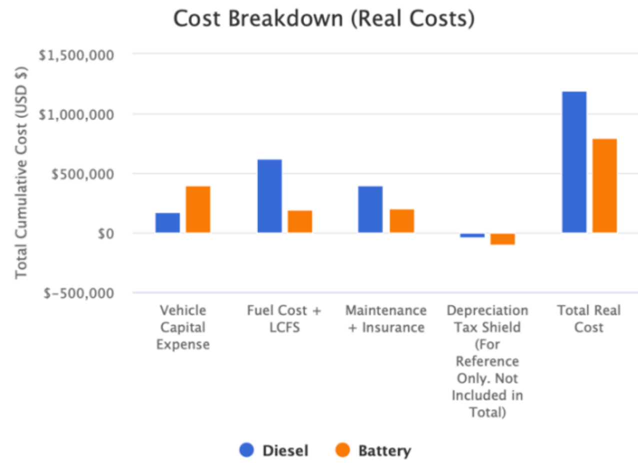


Figure 2. Cost Breakdown from Payback Analysis (Adapted from https://californiahvip.org/tco/)

5.1 Example 1: 2 Companies and Diesel Vehicles

This example shows the benefits of cooperation for reducing vehicle miles traveled (VMT) and subsequently pollutant emissions. Cooperation in terms of joint routing coordination may yield a significant VMT reduction thanks to a better use of vehicle capacity and the reduction of non-compensated trips, i.e., empty truck or near-empty truck trips. This example shows the large reductions in VMT and emissions that are possible with cooperation even without ZEVs. The example considers one week of operation; larger reductions may be achieved over time.

Two companies, Company A and Company B, located in Fresno and the San Francisco Bay Area, respectively, trade with three suppliers and several clients. Company A and B do not trade between each other but have similar cargo origins and destinations and are willing to evaluate a potential cooperation to reduce both VMT and emissions. Currently, the companies cannot afford ZEVs, so their expectation is to efficiently use Company A's vehicles. Due to commercial agreements, Company A delivers supplies to its main client (in the Bay Area) and picks up supplies from its three suppliers (located in Fresno and the Bay Area). Company A also performs reverse logistics by returning disposal material and containers from its suppliers, and empty containers from its main client. This transportation operation must be carried out in a time frame of seven days since the inventory cycle of the company is one week. The company owns a diesel 2012 heavy-duty truck, which uses as an operative center the same facility of the company (Table 6).

On the other hand, Company B is a retailer company and has several suppliers. Five of its main suppliers in Fresno and the Bay Area do not offer delivery service, so the company must pick up goods at the suppliers' location. All logistic operations must be completed in eight days. Currently, Company B does not own a truck. It has an agreement with a third-party logistics company. Suppliers' locations, demand between nodes, and cost information are provided in Table 3, Table 4 and Table 5. Table 6 shows the information about the vehicles currently used by the 2 companies. Information related to the average idle and waiting time at each node, service time, and the location of charging or refueling stations is available in Table 7 and Table 8 for Company A and B, respectively.

Table 3. Example 1: Company A and B Origin-Destination Distance Matrix

Distance (mi)	Comp. A	Sup. A1	Sup. A2	Sup. A3	Main C.	Comp. B	Sup. B1	Sup. B2	Sup. B3	Sup. B4	Sup. B5
Company A	0	15	20	210	220	230	220	240	250	20	25
Supplier A1	15	0	10	225	235	245	235	255	265	5	15
Supplier A2	20	10	0	230	240	255	250	260	270	15	5
Supplier A3	210	225	230	0	10	20	10	30	40	240	250
A Main Client	220	235	240	10	0	10	20	20	302	40	250
Company B	230	245	255	20	10	0	12	10	20	232	242
Supplier B1	220	235	250	10	20	12	0	22	32	220	230
Supplier B2	240	255	260	30	20	10	22	0	10	242	252
Supplier B3	250	265	270	40	30	20	32	10	0	252	262
Supplier B4	20	5	15	240	240	232	220	242	252	0	10
Supplier B5	25	15	5	250	250	242	230	252	262	10	0

Table 4. Example 1: Company A Demand Matrix

Demand (ton)	Company A	Supplier A1	Supplier A2	Supplier A3	Main Client
Company A	0	1	1	3	11
Supplier A1	2	0	0	0	0
Supplier A2	4	0	0	0	0
Supplier A3	5	0	0	0	0
Main Client	1	0	0	0	0

Table 5. Example 1: Company B Demand Matrix

Demand (ton)	Company B	Supplier B1	Supplier B2	Supplier B3	Supplier B4	Supplier B5
Company B	0	0	0	0	1	0
Supplier B1	3	0	0	0	0	0
Supplier B2	2	0	0	0	0	0
Supplier B3	3	0	0	0	0	0
Supplier B4	3	0	0	0	0	0
Supplier B5	4	0	0	0	0	0

Table 6. Example 1: Vehicle Characteristics

Vehicle Feature	Company A	Company B
Max payload Capacity (ton)	11	16
Annual depreciation ($)	9625	N/A
Use fixed cost ($)	300	130–1000 *
Variable cost per mile ($)	1.35	N/A
Max Range (mi)	1950	N/A
Tailpipe emissions (COe/mile)	1876 (1.57)	1820
Range consumption due to idle (mi/min)	0.087	N/A
Refueling time per mile (min/mi)	0.064	N/A
Average Speed (mi/hr)	50	

*Company's B 3PL agreement rates: 150 up to 30 mi; 220 up to 50 mi; 1000 up to 250 miles

Company A and B have nearby origins and destinations, enabling the possibility of logistic cooperative agreements. The companies could take advantage of economies of scale with more efficient inventory replenishment and vehicle routing. This work provides a cost-efficient solution for these endeavors.

Table 7. Example 1: Company A Node Characteristics

Nodes features	Company A	Supplier A1	Supplier A2	Supplier A3	Main Client
Preferred location of O. Center	1	0	0	0	0
Refueling loc. (1 Avl, 0 Not Avl.)	1	1	1	1	1
Service time at node (min/ton)	10	20	10	30	10
Idle time at node (min)	60	40	30	60	40

Table 8. Example 1: Company B Node Characteristics

Nodes features	Company B	Supplier B1	Supplier B2	Supplier B3	Supplier B4	Supplier B5
Preferred location of O. Center	0	0	0	0	0	0
Refueling loc. (1 Avl, 0 Not Avl.)	1	1	1	1	1	1
Service time at node (min/ton)	10	20	10	30	10	10
Idle time at node (min)	60	40	30	60	40	60

Results in Table 9 show the route that Company A (acting independently) must perform to deliver and pick up its cargo efficiently. As mentioned, Company B outsources its routing to a third-party logistical company with rates that were previously negotiated. Table 10 shows an operative summary when companies cooperate. Notice that Company A inevitably incurs non-compensated trips, i.e., near-empty trucks or empty truck trips.

For instance, observe the non-compensated trip from Supplier 3 to Company A in Table 9. This is a return trip of 210 mi length impacting Company A's economy. By including more origins and destinations, the truck can be partially loaded with cargo from other companies or destinations, thus reducing the operational costs.

Table 9. Example 1: Operative Results for Company A

Origin	Destination	At Destination: Arriving Cargo	At Destination: Delivery Cargo	Cargo Origin	Range Fueled/Charged
Company A	Client	11	11	Company A	0
Client	Supplier 3	2	0	-	0
Supplier 3	Company A	5	5	Supplier 3,4	0
Company A	Supplier 3	2	2	Company A	0
Supplier 3	Company A	0	0	-	0
Company A	Supplier 1	2	1	Company A	0
Supplier 1	Supplier 2	3	1	Company A	0
Supplier 2	Company A	6	6	Supplier 1,2	0

Table 10. Example 1: Operative Results for Cooperative Operation

Origin	Destination	At Destination: Arriving Cargo	At Destination: Delivered Cargo	Cargo Origin	Range Fueled/Charged
Company A	Supplier A1	2	1	Company A	676
Supplier A1	Supplier A2	3	1	Company A	0
Supplier A2	Company A	6	6	Supplier A1, A2	0
Company A	Supplier B5	2	0	-	0
Supplier B5	Supplier B4	6	0	-	0
Supplier B4	Supplier A3	9	2	Company A	0
Supplier A3	Company B	10	7	Supplier B4, B5	0
Company B	Supplier B1	3	0	-	0
Supplier B1	Supplier B3	6	0	-	0
Supplier B3	Supplier B2	8	0	-	0
Supplier B2	Company B	11	8	Supplier B1,B2,B3	0
Company B	Supplier B4	4	1	Company B	0
Supplier B4	Company A	3	3	Supplier A3	420
Company A	Supplier A4	11	11	Company A	0
Supplier A4	Company A	2	2	Supplier A4	0

Table 11 compares the operational cost when companies perform their logistic operations independently and cooperatively. By cooperating, companies could reduce their transportation costs and emissions significantly.

The aggregated VMT when companies act independently is 1,937 mi (Company A 905 mi; Company B 1,032 mi), while the collaborative method renders 1,096 mi, which represents a global reduction of approximately 43%. This reduction is due to a better use of the vehicle's capacity and because fewer VMT are required to connect all origins and destinations than when the companies act independently. Figure 3, based on Table 11, shows that the total cost under the cooperative scenario is USD 1,964.19; a global reduction of approximately 53% (1-(1,964.19/(1,706.34+2,450))). The individual costs are calculated according to the volume of cargo transported; therefore, Company A's cost is 1,964.19*(27/43) = USD 1,233.20, which represents a 23% reduction. On the other hand, Company B's individual cost is 1,964.19*(16/43) = USD 730.86, which represents a 70% reduction. Notice that Company B's relative reduction is larger than Company A's, due to Company B's independent, typical, but cost-inefficient operation. Company A, on the other hand, already had an optimum individual operation. Such cost reductions represent a time window of just 1 week compared to the potential savings spread over 52 weeks in a year. Annual savings would be larger.

Table 11. Example 1: Comparative Summary

	Company A	Company B	Cooperative Operation
Total distance traveled (mi)	905	1,032	1,096
Total weight transported (ton)	27	16	43
Fixed Costs (USD)			
Vehicle's fractional depreciation (1 week)	184.59	-	184.59
Equipment (Chargers)	-	-	-
Vehicle's use fixed cost	300	2,450.00	300
Operative center opening cost	0	-	0
Variable Costs (USD)			
Vehicle miles traveled cost	1,221.75	-	1,479.60
Total Costs (USD)	1,706.34	2,450.00	1,964.19
Individual costs under cooperation	1,233.33	730.86	-
% Cost reduction	-28%	-70%	-53%
Tailpipe emissions (kg-COe/ton-cargo)	62.88	117.39	47.82
Individual emissions under cooperation	30.02	17.79	-
% Emissions reduction	-52%	-85%	-73%

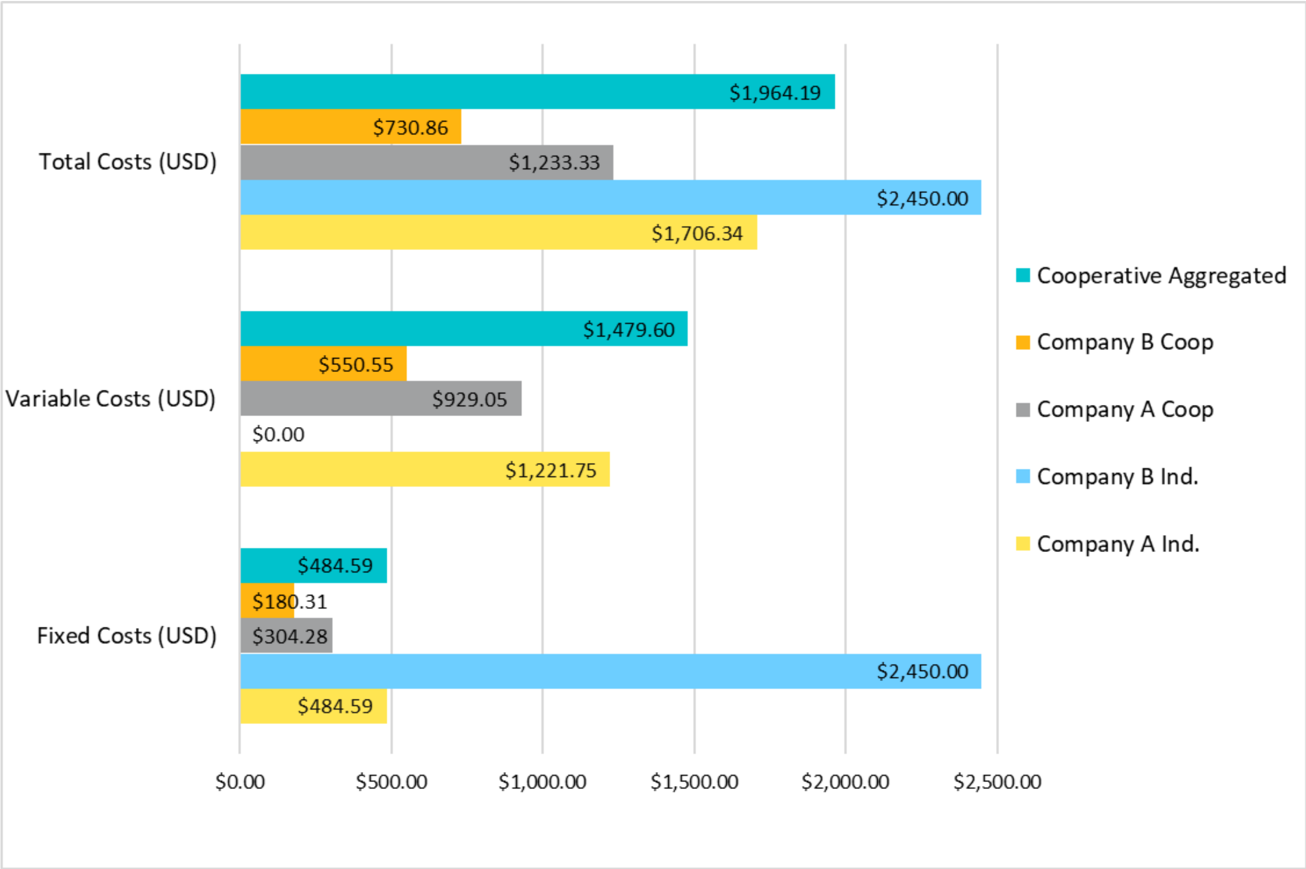


Figure 3. Example 1: Transportation Cost Breakdown

Different vehicles generate different emission rates, even when equipped with the same powertrain. For instance, Company A's truck produces 1870 gr of CO_2e per mile, while Company B's truck generates 1820 gr of CO_2e per mile. However, in the cooperative scenario Company A's truck is used since they already own the truck, however, due to a more efficient operation, total emissions are significantly reduced. Figure 4 based, on Table 11**,** shows Company A's independent emissions for its more efficient route: 62.88 kg-CO_2e/ton, which is reduced to 30.02 kg-CO_2e-mi/ton or a 52% reduction in the cooperative scenario. Company B's current emissions are about 117.39 kg-CO_2e-mi/ton, which are reduced up to 17.79 kg-CO_2e-mi/ton or 85% in the cooperative scenario. In general, the global reduction offered by the cooperative scenario is about 73% (30.02 + 17.79 kg-CO_2e-mi/ton to 47.82 kg-CO_2e-mi/ton).

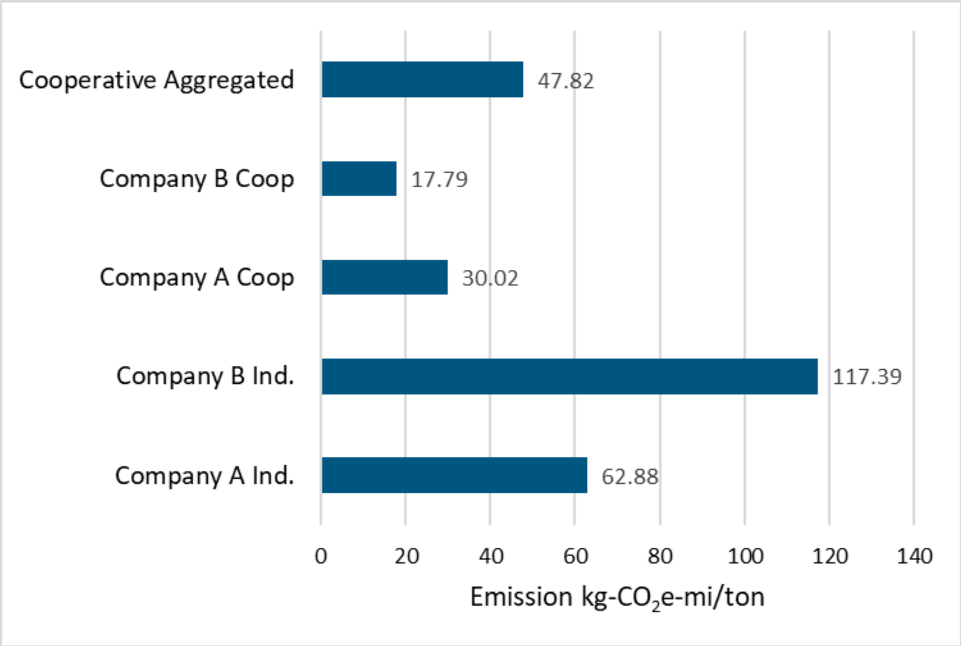


Figure 4. Example 1: Emissions per Scenario

In brief, the features of the logistic operations of Company A and B—the location of origins and destinations, cargo volumes, budget, and fleet—affect their efficiency and the emissions generated. As illustrated, sometimes companies inevitably incur non-compensated trips or low-use truck trips that directly impact the companies' economy. The more inefficient the logistic operation is, the more VMT are generated and subsequently the more emissions are generated. In the example, the cooperative scenario is convenient for both companies in terms of cost and emissions. This is thanks to an improvement in the use of the vehicles' capacities and the reduction of non-compensated trips, with yields not only in savings but also in fewer emissions. These benefits are achieved within the time windows determined by the companies, which is important to avoid inventory stock-outs. If completing all routes takes longer than the time window, the probability of stock-outs and lost-sales may increase. In this case, the relative proximity of the companies' cargo origins and destinations make such reductions possible. In some cases, it may not be convenient for companies to establish cooperation agreements. Each case must be evaluated independently, and this is where the ***Cargo Aggregator Beta 1.0*** would be useful.

5.2 Example 2: 3 Companies and ZEVs

This example shows the potential of cooperation in joint routing to leverage the purchase costs of ZEVs. Even with rebate credits and other economic benefits, small- and medium-sized companies may not be able to afford the substitution of their diesel vehicles. Purchasing ZEVs in a cooperative way may provide a viable way to do so.

Company A has warehouses in Stockton, Oakland, and Sacramento, California. Company B operates in the same cities. A third company, Company C, operates one warehouse in Oakland and one in Sacramento where it also has a retail store. Each company sends cargo between their locations, and Company A and B have a weekly inventory cycle. Due to the dynamics of their demand and inventory policies, they typically do not fully occupy the capacities of their vehicles. The geographic proximity of these companies and their logistic inefficiencies suggest that they could undertake cooperative practices to reduce costs and emissions. In addition, due to sustainability policies, the companies are required to cut, by at least 40%, their current emissions by substituting their diesel vehicles with ZEVs. Table 12 shows the features of the available vehicles. Three scenarios were developed. The first scenario evaluates the VMT and emissions generated when each company performs their own operations using a Peterbilt 579 from Table 12; this is considered the baseline scenario and the objective is to cut at least 40% of these emissions.

Figure 5 illustrates cost-efficient routes for each company when they perform operations independently (without cooperation). For instance, Company A starts its route at the main warehouse (A-W1), where the vehicle is uploaded with 10 tons (62.5% of the capacity), then it visits the second warehouse (A-W2), where those 10 tons are downloaded, and 2 tons are uploaded, reaching just about 12.5% of the vehicle's capacity. Then the vehicle visits A-W1 again, where 2 tons are downloaded, and 14 tons are uploaded (87.5% of the capacity). Later, the vehicle heads to A-W3, where 14 tons are downloaded, and 6 tons are uploaded, which are required by A-W2. Finally, the route ends when the vehicle travels 86 mi empty from A-W2 to A-W1. In general, the capacity use of the vehicle is low, and one trip is non-compensated.

On the other hand, Company B and C perform their operations using their vehicles' capacities in the range of 12.5% to 93%. Therefore, these companies may take advantage of the potential of cooperation in joint routing.

Table 12. Example 2: Vehicles Characteristics

Vehicles Features Matrix[4]	Peterbilt 579 (new)	e-Cascadia (new)
Max payload Capacity (Ton)	16	14
Annual depreciation ($)	9,625.20	31,157.1
Use fixed cost ($)	250	250
Variable cost per mile ($)	2.02	0.79
Max Range (mi)[5]	1,950	250
Tailpipe emissions (gr COe/mile)	1,569	0
Range consumption due to idle (mi/min)	0.09	0
Average Speed (mi/hr)	50	

[4] Parameters are available in: California HVIP: https://californiahvip.org/tco/

[5] Assuming 10.2 kg of CO_2e per gallon of diesel and 6.5 mpg.

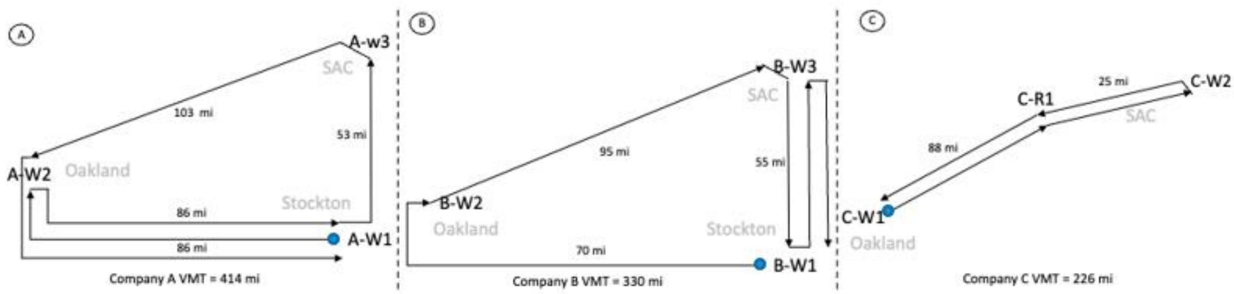


Figure 5. Example 3: Company A, B, and C Routes Without Cooperation Note: The blue dot is the starting point

Table 13 summarizes the operative results of six scenarios in terms of costs and emissions. Scenarios A, B, and C refer to cost-efficient alternatives where, respectively, companies A, B, and C perform their operation using a single diesel vehicle (see Figure 5). Scenarios Coop. 1, 2, and 3 refer to cooperative alternatives, with 0%, 50%, and 100% ZEVs, respectively, in the fleets. Observe that thanks to better use of the fleet capacity and the consolidation of cargo in Coop. 1, the aggregated VMT produced by the three companies (414 + 330 +226 mi) is reduced from 970 mi to 851 mi weekly (by 12.2%) by performing the route illustrated in Figure 6. Also notice that the alternative Coop. 1 uses two vehicles instead of three. On average, this alternative reduces the global cost (sum of the cost of the three companies) by about 20.96%, and reduces CO_2e emissions by up to 12,27% without using ZEVs.

Table 13. Example 2: Costs and Emissions for Individual and Cooperative Operations

	A	B	C	Coop. 1	Coop. 2	Coop. 3
	Comp. A Diesel	Comp. B Diesel	Comp. C Diesel	Cooperative Diesel X2	Cooperative >50%	Cooperative Full Electric
Total distance traveled (mi)	414	330	226	851	851	851
Total weight transported (ton)	28	24	38	90	90	90
Fixed costs (USD)						
Vehicles' fractional depreciation (1 week)	308.50	308.50	308.50	617.00	1,069.78	1,522.55
Equipment's fractional depreciation (chargers)	-	-	-	-	9.62	19.23
Vehicle's use fixed cost	150	150	150	300	300	300
Variable costs (USD)						
Vehicle miles traveled cost	836.28	666.60	456.52	1,719.02	1,110.17	672.29
Total Costs (USD)	1,294.78	1,125.10	915.02	2,636.02	2,489.56	2,514.07
% Cost variation A+B+C Vs Coop 1,2,3	-	-	-	-20.96%	-25.35%	-24.61%
% Costs variation Ind. vs. Coop1	-16.0%	-34.0%	-12.0%	0%	-	-
% Costs variation Ind. vs. Coop2	-20.7%	-37.6%	-16.8%	-	0%	-
% Costs variation Ind. vs. Coop3	-19.9%	-37.0%	-16.0%	-	-	0%
Tailpipe net emissions (ton-CO_2e)	649.57	517.77	354.59	1,335.22	558.56	0
% Emissions variation A+B+C vs. Coop 1,2,3	-	-	-	-12.27%	-63.30%	-100%
Weighted emissions (ton-CO_2e-mi/ton)	23.20	21.57	9.33	14.84	7.74	0
% Emissions variation Ind. vs. Coop1	-73.62%	-80.62%	-51.41%	0%	-	-
% Emissions variation Ind. vs. Coop2	-86.24%	-89.89%	-74.66%	-	0%	-
% Emissions variation Ind. vs. Coop3	-100%	-100%	-100%	-	-	0%

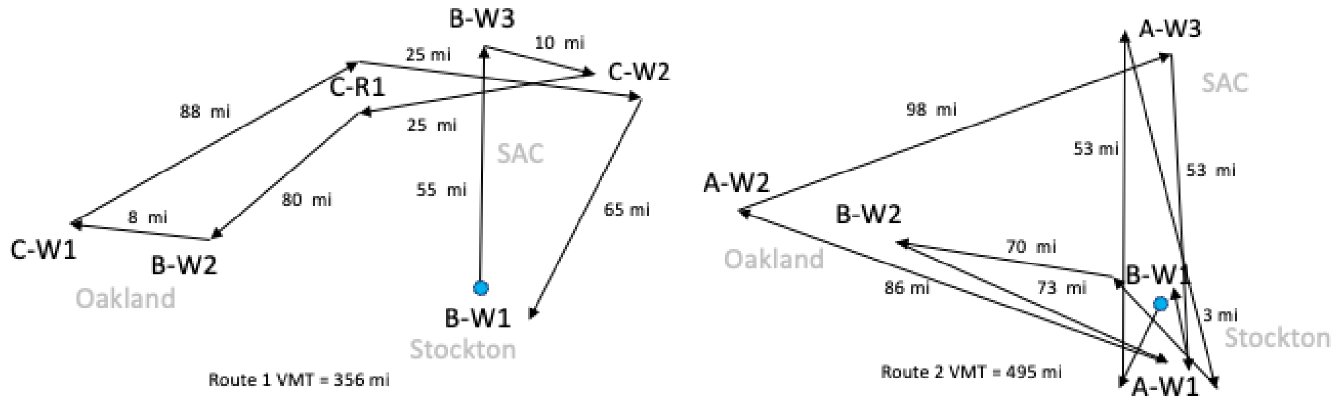


Figure 6. Example 2: Resulting Routes Note: The blue dot is the starting point

In individual terms, Companies A, B, and C reduce their costs by 16%, 34%, and 12%, respectively. This cost allocation is made proportional to the miles per ton traveled per company. Company C carries the highest amount of cargo and its VMT contribution is the lowest. So, Company C has lower chances of aggregating cargo with the other two companies. The higher the number of shared trips, the higher the cost reduction. A similar situation arises when one analyzes the reduction of emissions. Companies A, B, and C reduce their emissions (ton-CO_2e/ton) by 73.6%, 80.62%, and 51,41%. Since companies A and B have a higher level of aggregation, they can achieve a higher reduction—i.e., they travel more miles sharing a higher number of tons of cargo loaded per vehicle. A similar analysis can be made with the other cooperative alternatives. Observe that the Coop. 2 alternative yields a cost reduction and emissions reduction of approximately 25.35% and 63.30%, respectively, outperforming the required emission reduction of 40%. This conclusion assumes that weekly expenses are 6% smaller than those associated with the full diesel alternative from Coop.1, which may favor the company's' cash-flow. However, more stringent sustainability policies may require reductions greater than those rendered by Coop. 1. Observe that although this policy limits the substitution of ZEVs for diesel vehicles to 50% of the fleet, it produces a reduction larger than 50%. This is due to the higher use of the ZEVs in comparison with diesel trucks. Coop. 3 reduces 100% of the tailpipe emissions but assumes higher investments and slightly higher weekly operative expenses. Cooperation largely improves the efficiency of the emissions production. This can be observed in Table 13 in the weighted emissions row, which shows that Companies A, B, and C produce 23.2, 21.57, and 9.33 ton-CO_2e-mi/ton working independently, while the average efficiency of production of emissions is reduced to 14.8 ton-CO_2e-mi/ton on average for the Coop. 1 alternative, which uses only diesel vehicles.

Figure 7 captures the benefits of using ZEVs in the fleets in terms of efficiency. Net CO_2e emissions produced by the 100% diesel alternative are reduced by 58% when the 50% ZEVs alternative is implemented. Similarly, the weighted emissions (kg-CO_2e-mi/ton) are largely reduced due to the substitution of diesel vehicles with ZEVs. Figure 7(b) shows that substituting 50% of the fleet with ZEVs improves the efficiency of emissions by 48%. Notice that not necessarily 50% of the VMT is performed by ZEVs, since their limited range and capacity may limit the length of the routes performed with them.

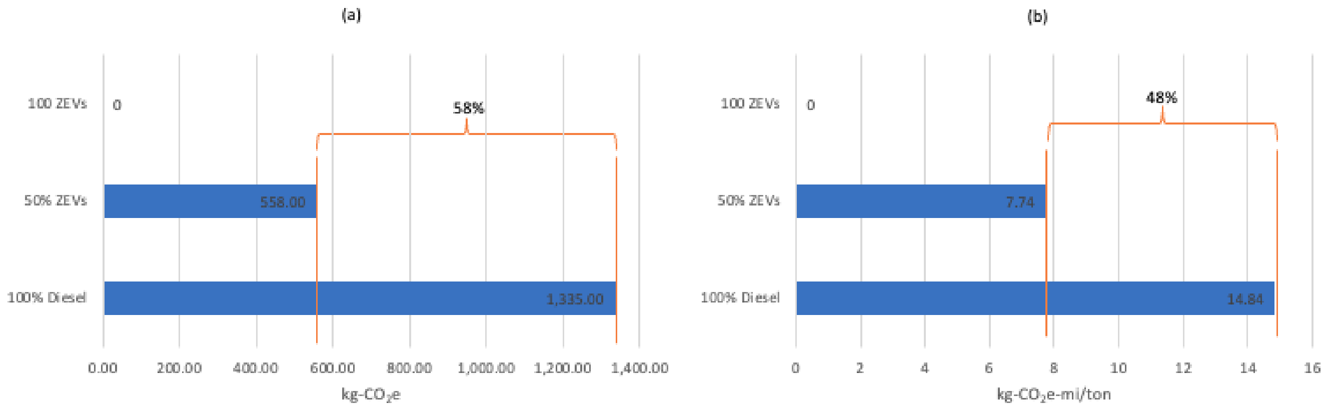


Figure 7. Example 2: Net Emissions (a) and Weighted Emissions (b)

5.3 Example 3: Integrated Companies and ZEVs

This case study aims to show how cooperation in routing and cargo aggregation could enable the substitution of less sustainable vehicles by cleaner vehicles in a cost-efficient way. Economies of scale realized through better use of vehicle capacities yield significant cost reductions. When the use rate of the fleet increases, and costs are shared between companies, the unit transportation costs decrease and therefore the individual cost per company also decreases. When cargo is aggregated between companies, fixed and variable costs can be split between more units, yielding lower unit costs than when the companies operate independently. In addition, the substitution of diesel vehicles by ZEVs typically implies large investments, which could be difficult for SMEs with traditionally low cash flows. Splitting the cost and risk of vehicle substitution with another or other companies could be a convenient alternative for SMEs.

In this case study, Company X and Company Y are both suppliers and clients for each other, i.e., some facilities belonging to Company X also supply facilities for Company Y and vice versa. The companies have several facilities in San Jose, Bakersfield, and Los Angeles. They move 86 tons weekly in total: Company X moves 45, and Company Y moves 41. Both companies own trucks and perform their logistic operations independently. Upcoming sustainable policies will constrain the amount of emissions that companies can generate. These policies are either designed to reduce the amount of emissions (by a certain percentage) that companies produce when using only diesel vehicles, or to mandate that a percentage of vehicles in a fleet must be ZEVs. The companies want to take advantage of the rebate credits and energy discounts offered by the State of California to encourage the use of ZEVs. The time window of both companies is one week. The features of the available vehicles are the same as in Table 12**.**

This example considers several scenarios that are the product of the sustainability policies. The first kind of policy mandates reductions ranging from 5% to 100% in CO_2e emissions over the base, which only considered diesel vehicles. The second kind of policy mandates substitutions of 20% to 100% of diesel vehicles with ZEVs. For instance, for a 20% policy, a company with 10 trucks would have to keep 2 ZEVs in the fleet. Notice that the effective capacity of diesel vehicles is 18 tons of cargo, while fully electric trucks have a capacity of 16 tons of cargo (Table 11). These differences could affect the number of trips required of electric vehicles, however, the results in Table 14 reveal that the increase in VMT when using a full ZEV fleet is only 85 miles when compared with the VMT of a fully diesel fleet. The results in Table 14 are the output of the tool proposed here when companies cooperate, which is based on the model from Section 4.2**.** Observe that the large savings realized from using electric vehicles depend on variable costs, due to the low cost of energy in California (0.098 $/kW with available discounts), even when estimating the costs to install charging infrastructure at the facilities. Performing the whole operation only with diesel vehicles renders a cost of $7,317.45, while the full ZEVs option renders a cost of $ 2,928.93, which is a 60% reduction in cost. An intermediate option is using 40% ZEVs and 60% diesel. This option is just 2.8% less expensive than 0% ZEV and 100% diesel and implies a large investment. Still, this mixed option of 40% ZEV and 60% diesel is 13.6% less expensive than the full diesel alternative. As can be seen, the major portion of the cost corresponds to the purchase of the vehicles, so in an analysis with a longer period (for instance, 1 year) the benefits of operating with ZEVs may be larger. Finally, observe in Table 14 that the full diesel alternative still renders 11% emission reductions when compared with the scenario that the companies operate individually, at their optimal level of operations. This is thanks to a reduction of VMT due to a more efficient use of the fleet. Also, notice that the emissions reduction in the 40%/60% mix scenario is approximately 59%, this with just two of the fleet's five vehicles being ZEVs. This is because most of the cargo is loaded/transported on those vehicles.

Table 14. Example 3: Comparison of Results

	Full Diesel (5 Peterbilt 579)	Mix 40% ZEVs (3 Peterbilt 579 - 2 e-cascadia)	Full Electric (5 e-cascadia)
Total distance traveled (mi)	3,623	3,708	3,708
Total weight transported (ton)	86	86	86
Fixed Costs (USD)			
Vehicles' fractional depreciation (1 weeks)	1,542.50	2,117.16	3,806.38
Equipment's fractional depreciation (chargers)	-	412	412
Vehicle's use fixed cost	1250	1,250	1,250
Operative center opening cost	0	0.00	96.15
Variable Costs (USD)			
Vehicle miles traveled cost	7,317.45	4,955.69	2,928.93
Total Costs (USD)	10,109.95	8,734.94	8,493.55
% Costs difference vs. full electric	19.0%	2.8%	-
Net Tailpipe emissions (kg-CO_2e)	5,683.70	2,585.36	0.00
% Emissions reduction vs. full diesel	-11%	-59%	-100%

Figure 8 shows a comparison between the sustainability policies mentioned earlier, when Companies X and Y cooperate. Figure 8(a) compares the operative costs of performing the operation under cooperation and the sum of the costs of the companies when working independently. For instance, it shows that a fleet configuration of 80% ZEVs and 20% diesel vehicles is the most convenient in terms of costs and produces a large reduction in CO_2e emissions, a reduction of between 80 to 85%. It may yield a cost reduction of approximately 27% when compared with the individual operation of the companies (i.e., operative cost of Company X + Company Y). Figure 8(b) indicates that this alternative entails weekly expenses of approximately $8,392; 17% less than the full diesel alternative, which may be convenient for SMEs with limited cash-flow. However, Figure 8(c) shows that such a reduction requires a large investment in vehicles, charger stations, and the opening of additional operative centers: approximately $ 160,000 per year (for four ZEVs), which may be over the budget of SMEs, even under cooperation. On the other hand, Figure 8(d) shows that the alternative represents approximately $480,300 of public expenses through rebate credits to the companies and the subsidization of energy.

Figure 9(b) demonstrates that the 80% ZEVs alternative is more convenient for the public sector than supporting the companies independently, which may represent a total investment of $720,400 against $480,300 (+33%) for reaching a reduction of 100%, which is only between 15 to 20% higher than the 80% ZEVs alternative. Observe that in Figure 9**,** when companies work independently, they cannot meet some of the policy mandates. For instance, since each company needs only three trucks per week to perform their operation, they must substitute 100% of their trucks to meet the 80% ZEVs policy. In general, cooperation allows companies to perform their operation at a lower cost while leveraging the substitution of their fleets with less investment. This is convenient for both the companies and the public sector. Decision makers in each company must analyze which alternative meets the currently mandated sustainability policies and is financially convenient. For instance, the 40% ZEVs alternative may yield a cost and emissions reduction of about 24% and 60% respectively, but would entail less investment than the 60, 80%, and 100% ZEVs alternatives, and with moderate weekly expenses, would favor the companies' cash-flow.

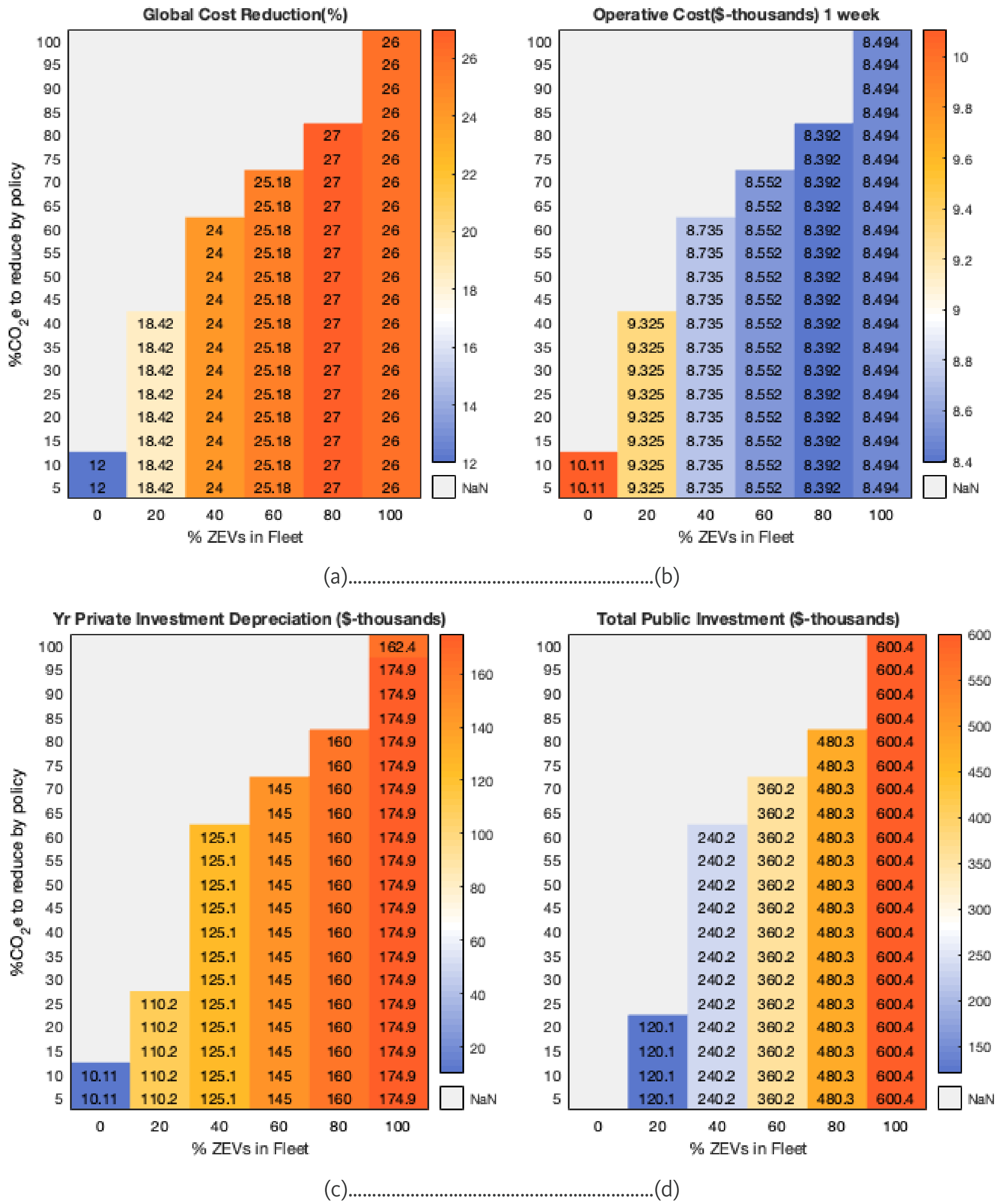


Figure 8. Example 3: Global Reductions and Required Investments per Policy under Cooperation

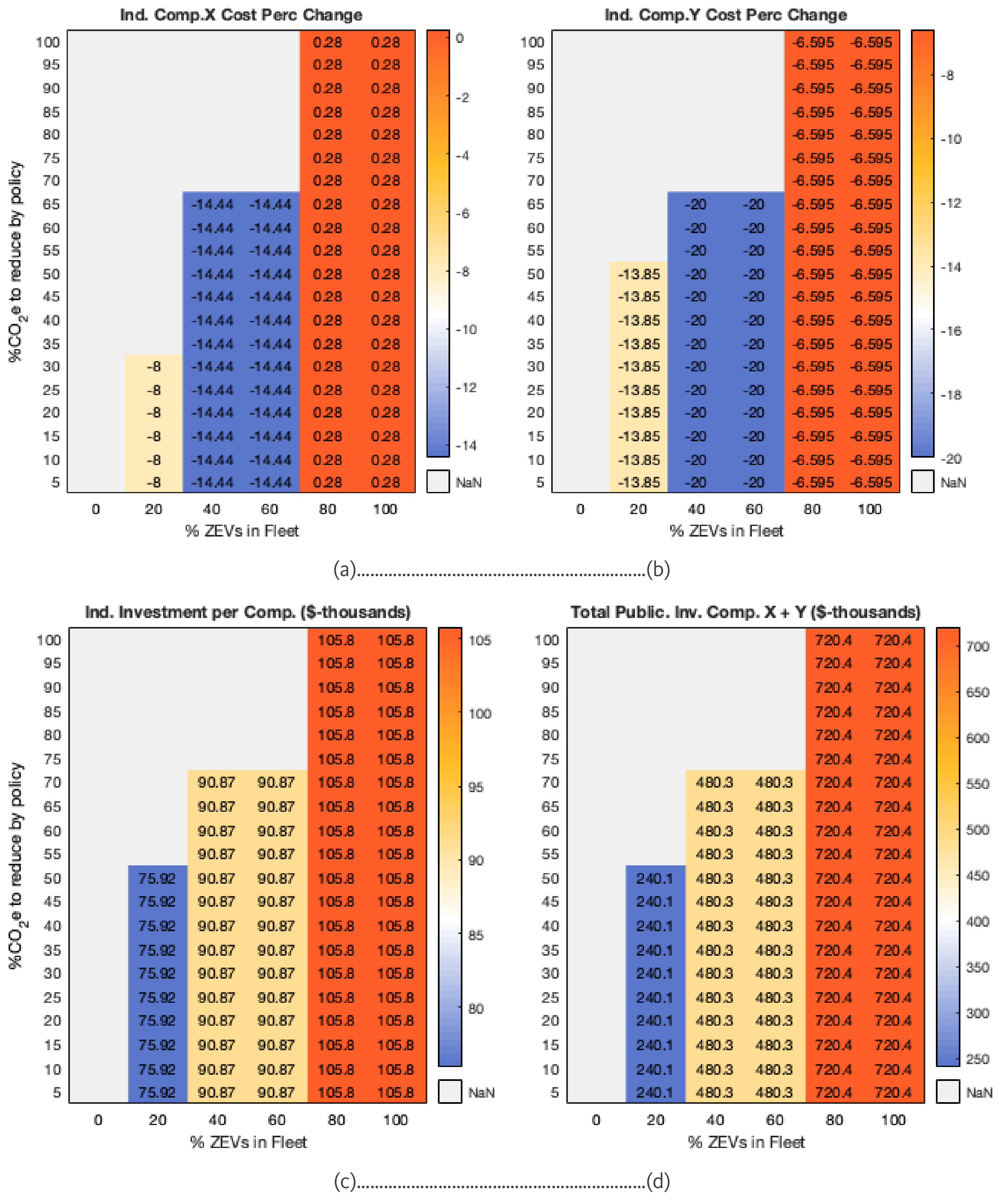


Figure 9. Example 3: Individual % Change in Operational Cost and Investments per Policy

6. Conclusions, Insights, and Discussion

The U.S. federal government and the State of California have announced imminent environmental regulations that will limit the production of polluting emissions. Transportation is one of the primary sources of greenhouse gases and is one of the sectors that is expected to be greatly impacted by new regulations. To mitigate disruptions in public and private companies, the State of California has arranged projects that favor the massification of ZEVs. However, it is still uncertain how these regulations could affect the operations and economies of SMEs, many of which would be hard-pressed to comply with such regulations. In this project, we developed a tool to evaluate the impact of regulations aimed at limiting the volume of emissions and policies that restrict the composition of a company's fleet. The main purpose of this research is to analyze the potential of establishing cooperative practices between non-competing transportation companies. In this study, we found that cooperation in joint vehicle routing has the potential to reduce both transportation operating costs and emissions. Such reductions are possible for three fundamental reasons. First, cooperative routing allows better use of vehicle capabilities and capacities when compared with individual routing, by reducing the amount of un-compensated or almost empty trips. This, consequently, renders a global reduction of VMT and therefore emissions. Second, sharing the fixed costs related to the purchase and management of cleaner technology vehicles reduces the companies' investment costs, potentially allowing a higher cash-flow. Through cooperative strategies companies can acquire essential assets at a lower cost and use them more efficiently. Third, savings and/or surplus from cooperation enables SMEs to access ZEVs, which, due to their high purchase price, may not otherwise be affordable. This provides ideas and insights for policymakers to create policies oriented to SMEs and foster higher market penetration of ZEVs.

The tool named *Cargo Aggregator Beta 1.0* is based on an extension of the vehicle routing problem (VRP) which allows multiple depots, heterogeneous fleets, limited ranges and cargo capacities, optional refueling and charging, and general time windows to comply with the established inventory replenishment cycle of companies. The model is solved by a hybrid method composed of a metaheuristic based on genetic algorithms and exact methods. With this tool, companies can determine efficient routes to pick-up and deliver cargo between locations while considering the previously mentioned operational features. Also, it provides the fleet composition and the location of operative centers. Furthermore, the tool allows an analysis of the sustainable regulatory policies mentioned earlier, and their impacts in economic and operative terms. The model's most favorable benefit is determining joint-efficient routes, which could not be determined using regular routing software.

The potential benefits of collaborative strategies that this research confirms raise two important questions: 1) What considerations would be necessary to put collaborative strategies into practice? and 2) Could cooperation become a key strategy for the massification of ZEVs? To address the first question, it is important to realize that these strategies would not be viable for all companies for several reasons. The first basic prerequisite for cooperation is the geographical proximity of cargo origins or destinations between companies. Without such proximity the collaborative VMT could be similar or more than the VMT of the companies operating independently. This is because the vehicles would have to detour or take longer routes. Second, the companies' cargo must be compatible, or else cargo deterioration could occur. Third, companies must agree on their routing cycle time (or time window) to comply with their inventory individual replenishment cycle. In general, a good synchronization is required to reduce the risk of stock-out or excess inventory. The proposed tool does not provide the time window; the users must determine it. Time windows that are too large may produce imprecise demand estimation, and therefore reprocessing. Fourth, these strategies are ideal when companies often perform less-than-truckload trips, since, with cooperation, vehicles can pick up and deliver other loads in the route. However, even companies performing full-truck-load trips may find cooperation profitable if their vehicles often have downtime. Fifth, the companies involved must agree to share information on their costs and product demand. This may be an important barrier, but a surmountable one with such legal procedures as contracts, non-disclosure, and trade agreements. Misleading information could cause operative inefficiencies, delays, reprocessing and higher costs. In addition, companies must consider these strategies as an opportunity to reduce not only their costs but also their environmental impact. Sixth, companies must agree on the location and costs of new operative centers for vehicles, or the closure of existing ones. Finally, the complexity of several factors such as the time windows, individual budgets, geographical locations, service time at each location, type of vehicles available, cargo volume and the complexity of the operation may not yield convenient results for companies. The higher the number of companies cooperating, the higher the complexity of coordination. Accordingly, we do not recommend establishing these strategies between large groups of companies. Each possible collaborative strategy, however, must be thoroughly evaluated. This research has confirmed the potential benefits, in cost and emission reductions, of doing so, and has developed a useful model, the *Cargo Aggregator Beta 1.0*, for that purpose.

In addressing the second question—whether cooperation could become a key strategy for the massification of ZEVs—it should be noted that by September 9th of 2020, California[6] reported that 4.1 million (99.8%) of businesses statewide are SMEs, which are the main target of this project. Moreover, California moves a significant portion of US cargo given its privileged geographic location, the presence of first-level ports, and a strong industry. The estimated truck flows on highway segments to, from and within California between 2012 and 2045 will rise to 50,000 trucks per day in each of the biggest five corridors, moving more than 10,000 tons per year between places typically more than fifty miles apart (FHWA, 2017). Each of those corridors could generate more than 3,925 metric ton of CO_2e per day (US EPA, 2021). Furthermore, the California Air Resources Board (2019) reported that transportation is the biggest source of GHG emissions (39.7% of 418 million of CO_2e), with passenger vehicles being the largest source of the whole inventory (28.5%) followed by heavy-duty trucks (7.8%). In conclusion, cooperative practices have a large potential market in California and could generate significant GHG emission reductions and save costs. The case studies developed in this report show that cost savings generated through collaborative practices could range from 7.5% to 78%, and (tailpipe) emission reductions could reach 100%. However, a larger sample and further research is needed to accurately

[6] https://www.gov.ca.gov/wp-content/uploads/2020/09/Small-Business-Fact-Sheet-9.9.20.pdf

estimate the impact of these practices and, if they are of proven benefit, to identify the mechanism to foster them.

The findings from this research support planning activities within the state and contribute to the goals of having an efficient, sustainable, and competitive transportation system. Results are useful and provide perspective for policymakers to evaluate the impact of sustainable policies and strategies to foster ZEVs. Through these kinds of practices, the State of California may reduce its global share of emissions in a cost-efficient manner, considering that cooperative routing would allow the purchase of ZEVs at lower investment levels. This proposal aligns with the Advanced Clean Truck (ACT) rule and the ongoing design of the Advanced Clean Fleet (ACF) rule, and the California Sustainable Freight Action Plan (CSFAP), as well as the Senate Bill 535 released by the Office of Environmental Health Hazard Assessment (OEHHA), the Climate Protection Act of 2008 (SB 375), and the California Global Warming Solutions Act of 2006 (AB 32), among others. Also, the research findings could provide insights to agencies aiming to implement strategies and efforts as part of the Community Air Protection Program, developed in response to California Assembly Bill 617.

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Appendix

Appendix A. Insights and Directions to Efficiently Manage the Replenishment of Inventory and its Transport

Transportation operations are strongly linked to inventory replenishment and its planning. Determining the frequency and the amount of inventory to be replenished in each cycle or time window is complex. This is due to the high holding cost of excess inventory. On the other hand, a lack of inventory, or stock outs, leads to a loss of sales. In this study, we did not focus on determining either the replenishment time windows nor the size of the inventory lot. For such purposes, we recommend the Joint Replenishment Problem model, which can be found in Khouja & Goyal, (2008); Otero-Palencia et al. (2018). As mentioned, such mathematical models can be considered as tools for determining the most efficient size and frequency of inventory replenishment, however, adequate management is vital. We provide insights for companies to manage their inventory in an efficient manner by following the guidelines of the Supply Chain Council (APICS), which gather the best practices of the industry in terms of supply chain management. We present here a short review of the industry SCOR standard (version 12.0 and refer readers to this document for further detail Supply Chain Council (2012).

There are two types of typical inventory replenishment processes: those that involve cross-border processes or imports, and those that do not because the suppliers and products are in the national territory or “inland.” Henceforth, the former will be referred to as imports and the latter as national replenishment.

The results presented in this section are results from informal meetings with cargo generating companies (manufacturers and retailers), customs agencies, and third-party logistic operators, and reviews of the literature of best practices. After fully understanding these processes, it was possible to characterize the inventory replenishment processes. Later, following the guidelines of the standard logistics model for the typification of the supply chain by SCOR 12, three of the five basic supply chain management processes were identified during the interviews and literature review (Figure 10): Plan, Make, Source, Deliver, and Return. This work focusses mainly on the Plan and Source processes, and slightly on the sub-element of the Deliver process known as the Compliance process, since they are involved in the inventory replenishment problem. A short definition of these processes according to the SCOR 12 standard is provided next:

- **Plan:** The processes associated with determining requirements and corrective actions to achieve supply chain objectives.
- **Make:** The process of adding value to products through mixing, separating, forming, machining, and chemical processes.
- **Source:** The processes associated with ordering, delivery, receipt and transfer of raw material items, subassemblies, product and/or services.

- **Deliver:** The processes associated with performing customer-facing order management and order fulfillment activities.
- **Return:** The processes associated with moving material from a customer back through the supply chain to address defects in product, ordering, or manufacturing, or to perform upkeep activities.

Figure 10. SCOR 12 General Processes Framework. Adapted from Supply Chain Council (2012)

As previously mentioned, this analysis focuses on the inventory replenishment activities: i.e., source. However, for estimating the cost of the entire process, planning and delivery activities must also be considered. Figure 11 describes the observed standard inventory replenishment process, either national or international (those that involve imports). These activities are framed on the source process. National replenishment and import activities follow in principle a similar procedure. However, in the case of imports, an additional agent may incorporate into the process; often, a third-party logistics licensed as a customs agency. The process begins with a replenishment signal from either a department related to manufacturing goods, or the sales department after checking over the inventory level. Note that although there could be differences between the companies, there exist common processes to both. Depending on the size of the company, they may or may not have a purchasing department; however, for practical purposes this department may be understood as the person in charge of purchasing for the company. Then, the company supplier(s) intervenes, regardless of size. The process is similar for the finance or accounting department, which oversees carrying out the accounting transaction to pay suppliers. As mentioned, depending on whether the inventory replenishment involves an import, a customs agency would enter the process. Finally, there must be a logistics department in the company or at least one person in charge of receiving and verifying the merchandise when it arrives at the doors of the company. Sometimes this department oversees the purchasing department as well.

Notice again, it is possible that small differences exist between companies. However, the proposed diagram has all the minimum actors in the process of legalization of cargo in an import. There are some previous negotiations between a supplier and an importer that are developed voluntarily; in these instances, the terms of negotiation to be used must be agreed upon. Once this agreement is reached, an exchange of important documents must be given that guarantee the legality of the transaction. These documents must be provided to the customs agency. Another important actor/agent is the shipping company used and the destination port, who must coordinate the logistics of receiving the cargo that is transported in containers; and the port itself is responsible for giving right of way to the customs authorities to proceed with the necessary verifications if any apply.

The associated planning process for sourcing consists of the development and establishment of courses of action over a specified time of period that represents a projected appropriation of material resources to meet supply chain requirements. This process regularly involves mid-level and upper management in the companies. For large and medium-sized companies it involves the meeting and joint work of directors from departments such as sales, logistics, purchasing, accounting, and even the CEO. For small businesses it could even be carried out by the business owner or person in charge of purchases. The level of planning is divided into long-, medium-, and short-term. The short- and medium-term planning closely support the operations and supply activities described in Figure 11, while in the long-term planning is oriented more towards negotiations with suppliers of materials and services. The general process is simple in essence and is presented in Figure 12. Planning consists of balancing the requirements of products on sale and the resources available to meet the demand. It is not always feasible to meet all the demands since not all resources are always available in sufficient quantity. For example, companies often have liquidity problems to source raw materials in the required amounts. Also, certain raw materials are sometimes scarce.

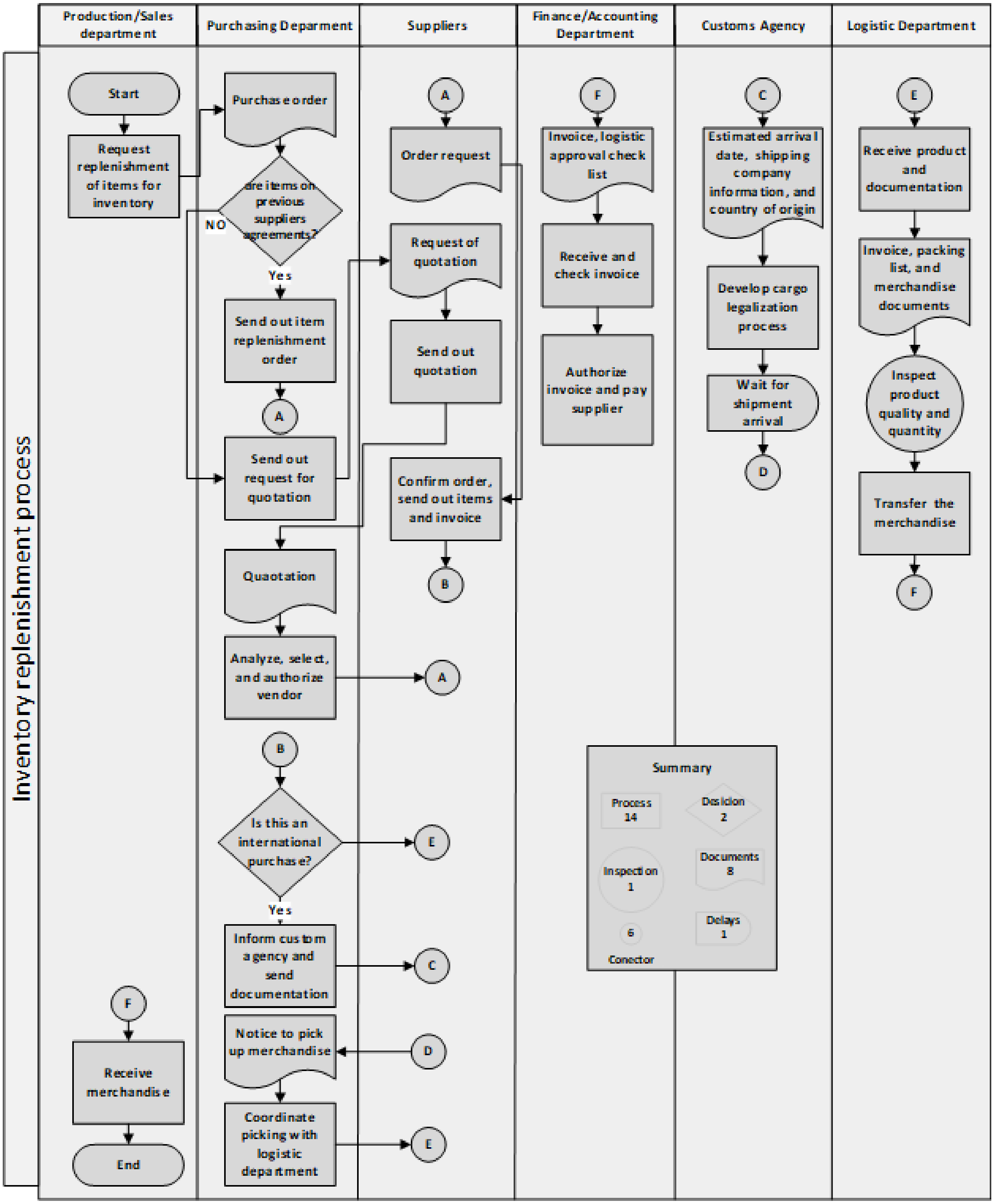

Figure 11. Description of Typical Inventory Replenishment Process

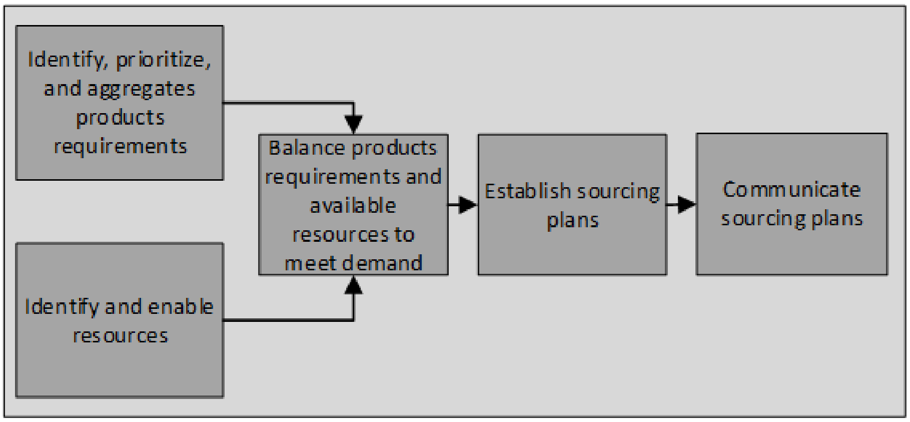

Figure 12. Description of Typical Source Planning Process

Once the planning and source process is determined, the next step is to measure its performance. Under the SCORE 12 standard performance is measured according three dimensions: cost, time, and documentation. In this project we focus on cost. Cost elements are described below.

- **Labor costs:** occur by virtue of the time the work team dedicates to activities at different levels, since management to operations for different logistic processes.
- **Automated activities:** those that originate to support logistic processes based on the use of technology, such as software, licenses, computers, etc.
- **Cost of the use of property, facilities, and equipment:** those that originate in the use of the physical infrastructure of the company and equipment during the logistic work.
- **Inventory cost and risks:** correspond to fees related to post-shipment handling or port handling, and any fees paid to a third party that provides services to the cargo.
- **Transportation costs:** those related to the fees charged by the freight forwarders and third-party logistics for transportation and any related freight service.
- **Fees, taxes, and others:** those related to fees due to cargo handling, services from third-party logistic operator, fares for sea transportation, and the fees of the customs brokerage companies. Moreover, these also include taxes imposed by the government, legal paperwork, and rights fares.

Appendix B. An Integer Mixed Linear Formulation with Multiple-Depots, Electric-and-Heterogeneous-Fleet, and Pick-ups-and-Deliveries, VRP

The proposed model analyzes three logistics decisions: optimum route, depot (operative center) locations, and fleet composition and charging/refueling points, while constrained by the load capacity of vehicles and range. The main assumptions of the model are listed below.

1. All nodes have the same time window
2. Origins and destinations are linked with a commodity
3. Pickups and deliveries are viable from multiple nodes
4. Multiple depots (operative centers where vehicles depart) are possible
5. Vehicles always return to the same operative center
6. Nodes can be visited a single time, duplicate nodes (i.e., same coordinates) are required for modeling multiple commodities.
7. Demand at each node cannot exceed the vehicle's capacity.
8. Fleet can be heterogeneous
9. Vehicles range is limited
10. Vehicles can be charged just in open charging locations
11. Commodities must be compatible and non-perishable
12. Demand shortages are not allowed

Sets

I	$Set\ of\ all\ nodes$ I $= \{1, \dots, n+m\}, where\ n\ is\ the\ number\ of\ pickup\ and\ delivery\ nodes, m\ is\ the\ number\ of\ potential\ operative\ centers$
I_p	$Set\ of\ pick-up\ nodes\ \mathrm{I}_p = \{\bar{1}, \dots, pn\}.\ \mathrm{I}_p \subseteq I$
I_d	Set of delivery nodes $\mathrm{I}_d = \{\bar{\bar{1}}, \dots, dn\}.\ \mathrm{I}_d \subseteq I$
K	$Set\ of\ vehicles\ \ K = \{1, \dots, kn\}.$
K'	$Subset\ of\ ZEV\ vehicles\ \ K'' = \{1, \dots, kn'\}. K' \subseteq$ K
A	$Set\ of\ all\ arcs\ A = \{(i,j), \dots, (2,2), \dots, (n+m, n+m)\}$
Y	$Set\ of\ all\ pairs\ "client"\ /\ "provider"\ Y = \{(\bar{\imath}, \bar{\bar{\imath}}), \dots, (2,2), \dots, (pn, dn)\}.\ (\bar{\imath}, \bar{\bar{\imath}}) \subseteq I$

Decisions Variables

$\boldsymbol{x_{ijkd}}$: 1 if the vehicle **k** from the OC **d** is selected to travel from **i** to **j**, 0 otherwise. (i,j)$\in A; k \in K; d \in I \backslash \{1, \dots, n\}$.

$L_{jl}^{(\bar{\imath}, \bar{\bar{\imath}})}$: $Continous\ variable\ denoting\ the\ load\ on\ vehicle\ destined\ for\ node\ \bar{\bar{\boldsymbol{\imath}}}\ from\ its\ \bar{\boldsymbol{\imath}}\ provider\ when\ the\ vehicle\ travels\ from\ \ \boldsymbol{j}\ to\ \boldsymbol{l}.$ (j, l) $\in A; \bar{\bar{\imath}} \in \mathrm{I}_d$.

$\boldsymbol{S_{ijkd}}$: $Continous\ variable\ denoting\ the\ remaning\ time\ (before\ the\ due\ date) when\ the\ vehicle\ \boldsymbol{k}\ from\ OC\ \boldsymbol{d}\ starts\ service\ \ in\ \boldsymbol{j}\ before\ leaving\ \boldsymbol{i}.$ (i,j)$\in A; k \in K; d \in I \backslash \{1, \dots, n\}$.

$\boldsymbol{C_{ij}}$: $\textit{Continous variable denoting the range remaning in vehicle when reaching } \boldsymbol{j} \textit{ before visiting } \boldsymbol{i}.$ $(\mathrm{i},\mathrm{j}) \in A$

$\dot{\boldsymbol{C}}_{\boldsymbol{ji}}$: $\textit{Continous variable denoting the range charged in vehicle after service } \boldsymbol{j} \textit{ to start heading to } \boldsymbol{j}$ $(\mathrm{j},\mathrm{i}) \in A$

$\boldsymbol{W_{kd}}$: $1 \textit{ when vehicle } \boldsymbol{k} \textit{ is pruchased for the OC } \boldsymbol{d}, 0 \textit{ otherwise}.\ k \in K; d \in I \backslash \{1, \dots, n\}.$

$\boldsymbol{Z_d}$: $1 \textit{ if the OC } \boldsymbol{d} \textit{ is opened}, 0 \textit{ otherwise}.\ d \in I \backslash \{1, \dots, n\}.$

Parameters

f_k: *Fixed cost of using vehicle type k*

α_k: *Unit running cost of the vehicle type k*

F_k: *Purchase cost of vehicle type k*

e_k: *Emission rate of vehicle k*

Q_k: *Capacity of vehicle type k*

$MaxR_k$: *Max range of the vehicle type k*

idC_k: *Avg. idling comsuption of the vehicle o type k*

St_i: *Avg. service time at i per ton*

$idle_i$: *Avg. idle time at i*

D_{ij}: *Distance between i and j*

$q_{(\bar{\imath},\bar{\bar{\imath}})}$: *Amount of ton of cargo for the pair* $(\bar{\imath},\bar{\bar{\imath}})$

B_d: *Cost of opening the operative center d*

Pw: *Max time available (time window) in labor hours*

ε: *Percentage reduction in emissions*

E: *Reference Emission Level*

AS: *Average speed*

λ: *Minimun allowed percentage of ZEVs in the fleet*

$I_{\gamma(i)}$: *Function that gives 1 if i has a charging station, o otherwise*

The general model formulation is:

$$\textit{Minimize}:\ TC\left(x_{ijkd}, W_{kd}, Z_d\right)$$

$$= \sum_{d \in I \backslash \{1,\dots,n\}} \sum_{k \in K} f_k \sum_{i \in I \backslash \{1,..,n\}} \sum_{j \in I \backslash \{n+1,..,n+m\}} x_{ijkd} + \sum_{d \in I \backslash \{1,\dots,n\}} \sum_{k \in K} \sum_{i \in I} \sum_{j \in I} \alpha_k D_{ij} x_{ijkd} + \sum_{k \in K} \sum_{d \in I \backslash \{1,\dots,n\}} F_k W_{kd} + \sum_{d \in I \backslash \{1,\dots,n\}} B_d Z_d \tag{A-1}$$

Subject to:

Flow constraints:

$$\sum_{d \in I \backslash \{1,\dots,n\}} \sum_{k \in K} \sum_{j \in I} x_{ijkd} = 1, \qquad \forall\ \mathrm{i} \in I \backslash \{n+1, \dots, n+m\} \tag{A-2}$$

$$\sum_{d \in I \backslash \{1,\dots,n\}} \sum_{k \in K} \sum_{i \in I} x_{ijkd} = 1, \qquad \forall\ j \in I \backslash \{n+1, \dots, n+m\} \tag{A-3}$$

$$\sum_{i \in I} x_{ijkd} = \sum_{i \in I} x_{jikd}, \qquad \forall\ j \in I; \mathrm{k} \in \mathrm{K}; d \in I \backslash \{1, \dots, n\} \tag{A-4}$$

Cargo constraints:

$$\sum_{j \in I \setminus \{n+1,..,n+m\}} L_{j\,\bar{\bar{\imath}}}^{(\bar{\imath},\bar{\bar{\imath}})} - \sum_{j \in I \setminus \{n+1,..,n+m\}} L_{\bar{\bar{\imath}}j}^{(\bar{\imath},\bar{\bar{\imath}})} = q_{(\bar{\imath},\bar{\bar{\imath}})}\,, \quad \forall\, \bar{\bar{\imath}} \in \mathrm{I}_d; (\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \tag{A-5}$$

$$\sum_{j \in I \setminus \{n+1,..,n+m\}} L_{\bar{\imath}j}^{(\bar{\imath},\bar{\bar{\imath}})} - \sum_{j \in I \setminus \{n+1,..,n+m\}} L_{j\,\bar{\imath}}^{(\bar{\imath},\bar{\bar{\imath}})} = q_{(\bar{\imath},\bar{\bar{\imath}})}, \quad \forall\, \bar{\imath} \in \mathrm{I}_p; (\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \tag{A-6}$$

$$\sum_{l \in I \setminus \{n+1,..,n+m\}} L_{l\,j}^{(\bar{\imath},\bar{\bar{\imath}})} - \sum_{l \in I \setminus \{n+1,..,n+m\}} L_{j\,l}^{(\bar{\imath},\bar{\bar{\imath}})} = 0, \qquad \forall\, j \in \mathrm{I}_d \setminus \{\bar{\bar{\imath}}\}; (\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \tag{A-7}$$

$$L_{j\,\bar{\bar{\imath}}}^{(\bar{\imath},\bar{\bar{\imath}})} = \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} q_{(\bar{\imath},\bar{\bar{\imath}})} x_{j\bar{\bar{\imath}}kd} \quad \forall\, \bar{\bar{\imath}} \in \mathrm{I}_d; \bar{\bar{\imath}} \neq j \;\in \mathrm{I}; (\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \tag{A-8}$$

$$0 \leq L_{l\,j}^{(\bar{\imath},\bar{\bar{\imath}})} \leq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} q_{(\bar{\imath},\bar{\bar{\imath}})} x_{ljkd}, \quad \forall\, (l,j) \in \mathrm{A}; (\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \tag{A-9}$$

$$\sum_{(\bar{\imath},\bar{\bar{\imath}}) \in \mathrm{Y} \setminus \{(\bar{\jmath},\bar{\bar{\jmath}})\}} L_{l\,j}^{(\bar{\imath},\bar{\bar{\imath}})} \leq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} \left(Q_k - q_{(\bar{\imath},\bar{\bar{\imath}})}\right) x_{ijkd}, \; \forall\, j \in \mathrm{I}_d;\; l \in I \tag{A-10}$$

Vehicle range constraints:

$$\sum_{i \in I \setminus \{n+1,..,n+m\}} C_{ij} - \sum_{i \in I \setminus \{n+1,..,n+m\}} C_{ji} + \sum_{i \in I \setminus \{n+1,..,n+m\}} \dot{C}_{ji} = \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} D_{ij}\, x_{ijkd}\,, \forall\, j \in I \setminus \{n+1,\dots,n+m\} \tag{A-11}$$

$$C_{ij} \leq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} MaxR_k x_{ijkd}\,, \forall\, (i,j) \in \mathrm{A} \tag{A-12}$$

$$C_{ij} \geq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} \left(D_{ij} + idle_j idC_k\right) x_{ijkd}\,, \forall\, (l,j) \in \mathrm{A} \tag{A-13}$$

$$\dot{C}_{ij} \leq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} I_{\gamma(i)} MaxR_k\, x_{ijkd}\,, \forall\, (i,j) \in \mathrm{A} \tag{A-14}$$

$$C_{dj} \leq \sum_{d \in I \setminus \{1,\dots,n\}} \sum_{k \in \mathrm{K}} MaxR_k\, x_{ijkd}\,, \;\; \forall\, j \in I \setminus \{d, n+1, \dots, n+m\} \tag{A-15}$$

Time constraints:

$$\sum_{\mathrm{d}\in I\setminus\{1,\ldots,n\}}\sum_{\mathrm{k}\in\mathrm{K}}\sum_{\mathrm{i}\in I} S_{ijkd}-\sum_{\mathrm{d}\in I\setminus\{1,\ldots,n\}}\sum_{\mathrm{k}\in\mathrm{K}}\sum_{\mathrm{i}\in I} S_{jikd}=\sum_{\mathrm{d}\in I\setminus\{1,\ldots,n\}}\sum_{\mathrm{k}\in\mathrm{K}}\left(\frac{D_{ij}}{AS}+idle_j+q_jSt_j\right)x_{ijkd}\,,\quad \forall\, j \in I\setminus\{n+1,\ldots,n+m\} \tag{A-16}$$

$$S_{ijkd}\leq (Pw-idle_i-q_iSt_i)x_{ijkd}\quad \forall\, i,j\in I;\mathrm{k}\in\mathrm{K}; d\in I\setminus\{n1,\ldots,n\} \tag{A-17}$$

$$S_{ijkd}\geq\left(\frac{D_{ij}}{AS}+idle_j+q_jSt_j\right)x_{ijkd}\ \forall\, i,j\in I;\mathrm{k}\in\mathrm{K}; d\in I\setminus\{1,\ldots,n\} \tag{A-18}$$

$$S_{djkd}=PwW_{kd},\qquad \forall j\in I\setminus\{n+1,\ldots,n+m\};\ \mathrm{k}\in\mathrm{K}; d\in I\setminus\{1,\ldots,n\}; \tag{A-19}$$

$$\sum_{\mathrm{i}\in I\setminus\{n+1,\ldots,n+m\}} S_{idkd}\leq Pw-\min_{\bar{\imath},\bar{\bar{\imath}}\in\mathrm{I};(\bar{\imath},\bar{\bar{\imath}})\in\mathrm{Y}}\left(D_{d\bar{\imath}}+D_{\overline{(\imath,\bar{\imath})}}+D_{\bar{\bar{\imath}}\,d}\right))W_{kd},\qquad \forall\,\mathrm{k}\in\mathrm{K}; d\in I\setminus\{1,\ldots,n\} \tag{A-20}$$

$$\sum_{\mathrm{i}\in I\setminus\{n+1,\ldots,n+m\}} S_{idkd}\geq (Pw-\sum_{\bar{\imath},\bar{\bar{\imath}}\in\mathrm{I};(\bar{\imath},\bar{\bar{\imath}})\in\mathrm{Y}}\left(D_{d\bar{\imath}}+D_{(\bar{\imath},\bar{\bar{\imath}})}+D_{\bar{\bar{\imath}}d}\right))W_{kd},\qquad \forall\,\mathrm{k}\in\mathrm{K};\ \mathrm{k}\in\mathrm{K}; d\in I\setminus\{1,\ldots,n\} \tag{A-21}$$

Vehicles' purchase constraints:

$$\sum_{\mathrm{j}\in\mathrm{I}} x_{djkd}\leq nW_{kd},\qquad \forall\,\mathrm{k}\in\mathrm{K}; d\in I\setminus\{1,\ldots,n\} \tag{A-22}$$

Operative centers opening constraints:

$$\sum_{\mathrm{k}\in\mathrm{K}} W_{kd}\leq knZ_d,\qquad \forall\, d\in I\setminus\{1,\ldots,n\} \tag{A-23}$$

$$x_{d_1ikd_2}=0,\qquad \forall\, i\in I\setminus\{n+1,\ldots,n+m\};\ \mathrm{k}\in\mathrm{K}; d_1\neq d_2\in I\setminus\{1,\ldots,n\} \tag{A-24}$$

$$x_{id_1kd_2}=0,\qquad \forall\, i\in I\setminus\{n+1,\ldots,n+m\};\ \mathrm{k}\in\mathrm{K}; d_1\neq d_2\in I\setminus\{1,\ldots,n\} \tag{A-25}$$

Nonegativity constraints:

$$\boldsymbol{L_{ijkd}},\boldsymbol{C_{ij}},\boldsymbol{\dot{C}_{ij}},\boldsymbol{S_{ij}}\ \geq \boldsymbol{0} \tag{A-26}$$

$$\boldsymbol{x_{ijkdr}}\in\{0,1\};\ \boldsymbol{Z_d},\boldsymbol{W_{kd}}{:}\,integer$$

The objective function (A-1) represents the total transportation cost, which includes the vehicles' fixed operating costs, traveling costs, purchase costs, and the operative centers' (OC) opening cost. Constraints (A-

2) and (A-3) warrant that each pick-up or delivery node is visited and left one time. (A-4) guarantees that at most one vehicle type originating from a given depot will cover an arc (i, j). The group of constraints (A-5) to (A-10) guarantee that demand at each delivery node is met. (A-5) guarantees that the quantity remaining after visiting pick-up node j is exactly the load before visiting this node minus its demand. (A-6) shows that the load quantity picked up in each pick-up node is exactly the load destined for their delivery node. (A-7) avoids nodes receiving wrong cargo. (A-8) guarantees that each delivery node (client) receives its demanded amount of cargo from its pick-up node (supplier). (A-9) guarantees that the amount of each cargo type flowing between any arc ranges between zero and the demand for each cargo type. (A-10) is the upper bound of load for each arc; it guarantees that the capacity of the vehicle is not exceeded, and that the remaining load is at most the capacity minus the load delivered to each node. Constraints (A-11) to (A-15) warrant that the vehicles do not run out of charge/fuel in terms of range to satisfy subtour elimination. We model range as a commodity. (A-11) shows that the available range of a vehicle when heading to any node i is equal to the range consumed by reaching any node j plus the range charged at j. (A-12) is the upper bound of the range of each vehicle; it warrants that each vehicle range when heading to any node is at most its maximum range capacity. (A-13) is the lower bound of the range of each vehicle for each arc: it warrants that the remaining range is at least enough to traverse the arc plus the consumption expended due to idling. (A-14) avoids the vehicles being overcharged. (A-15) shows that vehicles leave their operative center fully charged. Constraints (A-16) to (A-21) guarantee that all routes are complete into the planning horizon window of the inventory, and that they satisfy subtour elimination. We model time as a commodity. (A-16) sets the remaining time after each node is visited and the vehicles are loaded, downloaded, or both. (A-17) is the upper bound of the time when a node is visited; it shows that the remaining time is the total time window minus the idle and the service time at each node. Conversely, (A-18) is the upper bound of the remaining time; it guarantees that the remaining time is enough for the vehicle to reach each node and complete the service. (A-19) shows that when a vehicle leaves its operative center it has at most the time window to operate. i.e., the time (as a commodity) assigned to each vehicle. (A-20) is the upper bound of the remaining time when a vehicle completes its assigned route. This is at most the time window minus the single trip to serve a client-supplier pair. Conversely (5-21) is the lower bound of this time. It is at least the time window minus the time consumed in a series of trips where each client-supplier pair is visited by a single vehicle, which previously leaves its operative center plus a return trip. Constraint (A-22) control that if a vehicle is used, it is previously bought. Similarly, (A-23) controls that if a vehicle leaves an operative center, it is because the center is open. Constraints (A-24) and (A-25) control that any vehicle leaving an operative center cannot be linked to a different depot respectively. (A-26) provide non-negativity and binary constraints.

Additionally, the model considers environmental policies. These policies are represented by linear constraints that are added to the main model from (A-1) to (A-26). The first sustainability constraint (A-27) limits the maximum quantity of emissions produced by the whole fleet. The second sustainability constraint (A-28) controls the number of ZEVs in the fleet.

First Policy: Reducing Fleet Emissions

This policy seeks to improve environmental efficiency and sustainability by reducing the quantity of emissions that companies generate from their transportation operations. The model assumes a base emission level E , and an expected percent reduction ε.

$$\sum_{d \in I \setminus \{1,\ldots,n\}} \sum_{k \in K} \sum_{i \in I} \sum_{j \in I} \boldsymbol{e_k x_{ijkd}} \leq \varepsilon E \tag{A-27}$$

Second policy: Requiring zero and near-zero-emission vehicles in the fleet composition

The second policy will require companies to keep a minimum percentage of zero and near-zero-emission vehicles in their fleets.

$$\frac{\sum_{k \in K'} \sum_{d \in I \setminus \{1,\ldots,n\}} \boldsymbol{W_{kd}}}{\sum_{k \in K} \sum_{d \in I \setminus \{1,\ldots,n\}} \boldsymbol{W_{kd}}} \geq \lambda \tag{A-28}$$

Model Solution Method

We developed a hybrid solution method comprised of exact methods, mainly for small cases, and genetic algorithms (metaheuristic) for all others. The steps of the method are presented next:

Step 1: Initialize parameters.

Step 2: Write objective function, equality and inequality constraints

Step 3: Start Genetic Algorithm Alpha: Randomly determines a feasible route including all nodes and randomly assigns segments of the route to the available vehicles. When designing a route, just integer variables are considered, while continuous variables are estimated solving the relaxation of the LP problem. The algorithm halts if the best-found solution has not been improved in n generations

Step 4: Start Genetic Algorithm Beta: Randomly chooses a vehicle and assigns a pick-up order, then randomly decides if the vehicle must deliver the picked-up order or must pick up another one. Again, when designing a route, just integer variables are considered, while continuous variables are estimated solving the relaxation of the LP problem. The algorithm halts if the best-found solution has not been improved in $2n/3$ generations

Step 5: With the best solution found in *Step 4*, this step runs RINS[7] and DIVING[1] heuristics twice, then runs branch and bound and/or branch and cut methods until a solution is found, or up to 60 minutes elapses. If no feasible solution is found in the first 10,000 nodes, the algorithm halts and the solution is the best solution found either in Step 3 or Step 4.

[7] Search heuristics RINS and DVING from IBM available in https://www.ibm.com/docs/en/icos/12.9.0?topic=heuristics-relaxation-induced-neighborhood-search-rins-heuristic