McMASTER INSTITUTE FOR TRANSPORTATION & LOGISTICS

Scoping Review on Aspects Surrounding the Adoption of Medium and Heavy Duty Trucks

March 2024

Scoping Review on Aspects Surrounding the Adoption of Medium- and Heavy-Duty Trucks

A report by

Abigail Amos
Mark Ferguson
Moataz Mohamed
Bruce Newbold

McMaster Institute for Transportation & Logistics (MITL)
McMaster University

March 2024

List of Figures

List of Tables

McMASTER INSTITUTE FOR TRANSPORTATION & LOGISTICS

Introduction

1. Chapter 1: Introduction

1.1. Background

This report is centred around a database/archive on ZEV trucking that has been developed at the McMaster Institute for Transportation and Logistics (MITL). The focus is on the decarbonization of medium- and heavy-duty trucking, paying particular attention to insights that will be relevant for the Canadian context. Primarily, this report is about the analysis of the archive. Before moving on to that important task, this section offers brief context on the trucking sector in Canada.

Canada's trucking industry is enabled by approximately 400,000 people (about ¾ of them drivers) whose collective efforts span the continentwhen cross-border activity is consdiered. Organizationally, these efforts are channelled through trucking firms that range from tiny owner-operators/independent operators, who may own their trucks, to huge firms that employ thousands. Most fleets are small ones, and the overall market is very fragmented, with no one party dictating terms. Thousands of other drivers are employed by private fleets, that tend to operate more locally and are often associated with firms of varying types that move their own freight [1].

The latest For-Hire Trucking Survey from Statistics Canada (discontinued in 2019) shows that approximately 134,000 for-hire trucking companies were active nationally and that they moved approximately 66 million shipments in a year. About 44% of operating revenue is linked to intra-provincial shipments that originate and terminate within a province. The remainder is split fairly evenly between inter-provincial shipments, shipments into Canada and shipments out of Canada [1]. This description give some sense of the scale of the efforts that will be required to decarbonize such a large and fragmented sector of the economy.

It is worth noting that the research group at MITL has deep experience in the related domain of electric buses [2] and has done a similar scoping review exercise in that context. This past experience offers some guidance for the current initiative. Electric transit buses certainly meet the criterion of being considered as medium and heavy vehicles but the decarbonization of transit buses is a significant, well-defined field in its own right and is considered beyond the parameters of this scoping review. Also, the decarbonization of bus transit is rather more advanced than is the case with medium- and heavy-duty trucking.

1.2. Objectives

Bearing the brief background in mind, the primary objective of this report is to perform a scoping review on the collected body of knowledge surrounding the adoption of zero emission medium- and heavy-duty vehicles that would greatly assist the decarbonization of the trucking sector.

This body of knowledge cannot literally be manifested, but the McMaster Institute for Transportation and Logistics has put considerable effort into the development of a representative archive/database that we believe goes a long way in this direction. Essentially then, the basis of this report will be the analysis of this multivariate database.

The archive is populated with collected works that span the period from 2015 to the present day. Note that analytical outputs shown below that are time dependent do not include records from the current year (2024).

Daudt et al [3] have provided the following definition of a scoping review, which was endorsed by the heavily cited work of Pham et al. [4]. They note that: “scoping studies aim to map the literature on a particular topic of research area and provide an opportunity to identify key concepts; gaps in the research; and types and sources of evidence to inform practice, policymaking and research. Pham et al. (2014) note that a scoping review should be seen as a type of literature review and suggest that such is implied by this definition.

1.3. Data Collection Process for the Archive

The primary database search tool used to identify items for potential inclusion in the final archive was the Web of Science. The Web of Science is particularly effective in assessing the breadth and applicability of the academic literature. Google Scholar and ordinary Google searches were important tools in rounding out the database with non-academic reports, which are important components of the overall archive.

There were two main queries used for Web of Science, a primary one and a secondary one. Both of these focused on works that had been completed since 2015. Note that rather than relying on every available field in Web of Science, the focus was on keywords appearing in the title and abstract.

The primary query was as follows:

("electric" or "hydrogen" or "fuel cell" or "natural gas" or "battery") and ("truck" or "trucks" or “van” or "vans") (**Abstract**) AND "truck" or "trucks" or "van" or "vans" (**Title**)

Expressed in words, this search was looking for at least one of the required technologies, including zero-emission technologies, to intersect with the description of a relevant vehicle-type in the abstract. At the same time, the relevant vehicle keyword needed to appear in the title of the work. Although the keywords for this search are not restrictive, the overall effect of the query is quite demanding.

The application of this query led to 515 results. While the query was somewhat demanding, the incidence of relevant works appearing in the list was reasonably high. Both the primary and secondary searches did uncover quite a few works that focus heavily on the intricacies of designing better powertrain architectures for medium and heavy trucks. These were excluded based on having a very indirect linkage to ZEV adoption processes.

At the end of the manual review process for the list of the 515 potential sources, 89 sources were retained. This was based on being identified as an in-scope study that had averaged a minimum of a citation per year since release. The citation constraint was not enforced for new articles that had arrived in 2022 and 2023.

The secondary query was similar to the primary one but was based on meeting the criteria required for the abstract only while excluding works that met the title criteria of the primary query.

("electric" or "hydrogen" or "fuel cell" or "natural gas" or "battery") and ("truck" or "trucks" or “van” or "vans") (**Abstract**) NOT "truck" or "trucks" or "van" or "vans" (**Title**)

This query gave rise to another 1,018 items but these were associated with a much lower incidence rate of inclusion. At the end of the manual review process for the list of the 1,018 potential sources, 44 sources were retained . As with the primary search, this was based on being identified as an in-scope study that had averaged at least a citation per year (in the case of more mature articles).

One relevant issue with scoping reviews is whether the quality of the works is a criterion for inclusion in the supporting database. With regard to the current review, the answer is in the affirmative but quality was assessed indirectly for peer-reviewed articles based on citation patterns. Of the 1,533 studies that were identified through Web of Science, we found that many were cited only very infrequently on a per year basis. We in fact sorted our initial lists by number of annual citations and found that as we worked our way down the list, the works often became excessively niche-oriented or esoteric. This appears to reduce appeal to other scholars and this lack of interest is reflected in the very few citations that certain works attract. Ultimately, we chose a cut-off of a citation per year, with many excluded works receiving fewer citations then this; some in fact receive no citations. No doubt there was a qualitative, judgement-oriented aspect to the exercise but the main driving rationale was to maintain a reasonable balance between academic and non-academic sources in the archive

Conversely, citations is a poor indicator for many key reports. For example, when the North American Council for Freight Efficiency (NACFE) releases a single report, it effectively may cover several demonstration projects that could involve a large number of participant companies and multiple freight contexts. Some individual company participants in such demonstrations are very significant. For example, the Tesla Semi is a rather noteworthy participant in the NACFE "Run on Less" demonstration.

With regard to the inclusion of reports, 75 were identified through appropriate Google searches and 51 were retained for membership in the final archive.

1.4. Description of the Archive/Database

At the end of the process described previously, the archive/database contains 184 items/works that span several disciplines, as detailed in Table 1-1. Some included works are predominately qualitative and others are mathematically quite intensive and modelling-oriented. Neither extreme in this respect determined whether a work was included or excluded.

Table 1-1. Summary of the query process

Stage	Initial records	Retained records
Title-based query	515	89
Abstract-based query	1,018	44
Non-academic sources	75	51
Totals	1,608	184

The archive consists of 19 different fields as seen in

Table 1-2, which shows the dictionary that is included in the spreadsheet deliverable. The dictionary offers a field-by-field description of the data and a good indication of what values each field can

assume. Many of the fields can take on only a small number of values which means that the database is well-suited for being queried.

Table 1-2: Dictionary Associated with the Archive

Chart Component	Definition	Available Options (where applicable)
Journal / Publisher	The Journal associated with academic items or the Organization/Publisher associated with reports that are not peer-reviewed	
Title	Full title of the article or report	
First Author Surname	The surname of the first author (if available)	
Authors	All authors of the item	
Year	Year of publication	2015-2024
Abstract	The abstract provided for the item. In cases where an abstract is not provided, suitable content from introductory section is provided.	
DOI / Primary link	A link to access the actual article/report (if possible)	
Citations	The number of times the paper was cited on Google Scholar (if available)	
Primary Theme	The primary theme of the item based on the following categorization: 1) Procurement barriers & total cost of ownership - Barriers & TCO 2) Operation feasibility, constraints and transferability to existing logistical needs - Logistics 3) Energy pathway - Energy 4) Infrastructure needs - Infrastructure Note that these categories may overlap to some extent on certain items but an effort is made to choose the most suitable option of the four.	Barriers & TCO, Logistics, Energy, Infrastructure
Highlights (By Author)	Highlights provided by author(s) (if available)	
Keywords	Keyword content words tagged to the paper by the author(s) (if available)	
Vehicle Use Context	Use context in which medium and/or heavy duty vehicles are examined. Note that "General" implies a general truck freight context, where a particular context is not readily identifiable	Drayage, General, Intercity, Long-haul, Mining, Municipal, Urban Freight, Cold Chain, Retail Fleet
Vehicle Size	Heavy duty vehicles (HDV) - includes trucks classes 7-8 Medium duty vehicles (MDV) - includes trucks classes 4-6	HDV, MDV, Both, or NA
Vehicle Technology	The type(s) of powertrain technologies	Distinct combinations of Battery, Hydrogen, Natural Gas
Continent	The continent(s) the paper focuses on. The item is marked "NA" If not identifiable or relevant or if truly global.	Distinct combinations of Asia, Europe, North America, Oceania, South America
Country of Focus	Subject country of the item (if identifiable). Marked as "NA" if not.	
Scale of Geography	Best description of the geographic resolution associated with the item. Marked as "NA"when this cannot be identifed.	International, National, Province/State, Municipal
Article/Report	Peer reviewed works are captured as articles and other items as reports.	Article or Report

Chart Component	Definition	Available Options (where applicable)
Nature of Initiative	A classification which highlights whether the item reflects earlier-stage efforts or real-world testing/application. Note that some individual items in the database may describe multiple pilots or demonstrations. "Modelling-oriented" reflect simulations and application of models with real data. "Qualitative/Conceptual" tends to reflect qualitative or light quantitative work or works that are review-oriented	Qualitative/Conceptual, Modelling-oriented, Demonstration, Pilot

To close this introductory chapter, a brief description of the upcoming two chapters is in order. Chapter 2 presents results associated with basic analytics that were completed on the archive. These analytics are associated with segmentations and keyword analysis of the archive. The concluding Chapter 3 synthesizes the Chapter 2 results to complete the review of the archive and offers conclusions that are structured around primary themes. The discussion emphasizes apparent gaps and potential opportunities related to research in this field.

McMASTER INSTITUTE FOR
TRANSPORTATION
& LOGISTICS

Results

2. Chapter 2: Results

The purpose of this chapter is to use basic analytics to explore the characteristics of the archive. Initially, several key segmenting fields of the database are explored one at a time to highlight basic trends evident in the data. In a subsequent section, some noteworthy bivariate segmentations are explored and discussed. This is a subset of a much larger set of potential field pairings in the database. A final significant analytical output covers the results of a manual keyword analysis of the main archive. This gives a good overall sense as well about the presence of key themes in the archive and associated implications.

2.1. Univariate Analysis

The basic analysis and associated discussion in this section deals with segmenting the key fields of the archive on a field-by-field basis. A better understanding of the individual fields is at the heart of understanding the archive's possibilities.

2.1.1. Article/Report Classification

One of the fundamental segmentations in the archive is whether an item is classified as a peer-reviewed article or as a report. A simple convention used was that if the item was not a peer-reviewed article, it would be considered as a report. So, the latter category includes various items such as non-academic white papers, academic reports that are not peer reviewed, major reports by associations or significant government or non-governmental (NGO) offerings.

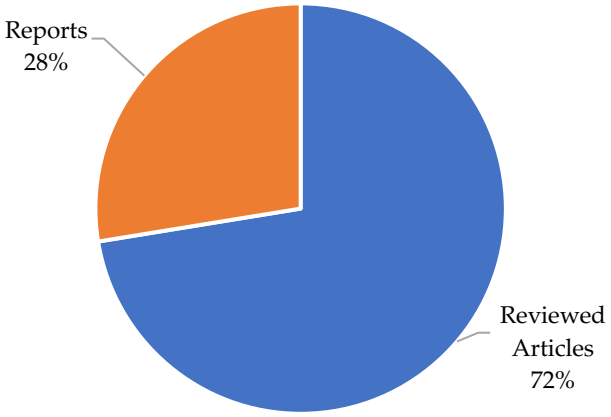

Figure 2-1: Peer-Reviewed Article versus Report Breakdown

Approximately 3 out of evey 4 items in the archive are peer-reviewed academic articles. Considering that the archive is emphasizing the more prominent of the peer-reviewed studies, this outcome gives a sense that there are many academics and research groups around the world that are working on aspects associated with the decarbonization of trucking. Also, as was noted in Chapter 1, consider that the substantial research efforts that go into powertrain architecture are essentially not represented in the figure.

One interesting note about reports, based on a separate tabulation, is that reports in the archive tend to be more oriented to North America. Reports are relatively less important in relation to other continents.

2.1.2. The Nature of the Associated Item/Initiative

A second fundamental aspect is the basic nature of an item itself. The intent is to represent a type of continuum where the most advanced items are evaluating ZEV trucks, or associated aspects, in real-life whereas other items are at earlier or conceptual stages. This categorization is by no means a commentary on the quality or sophistication of any given item/work but simply an attempt to capture it along the described continuum.

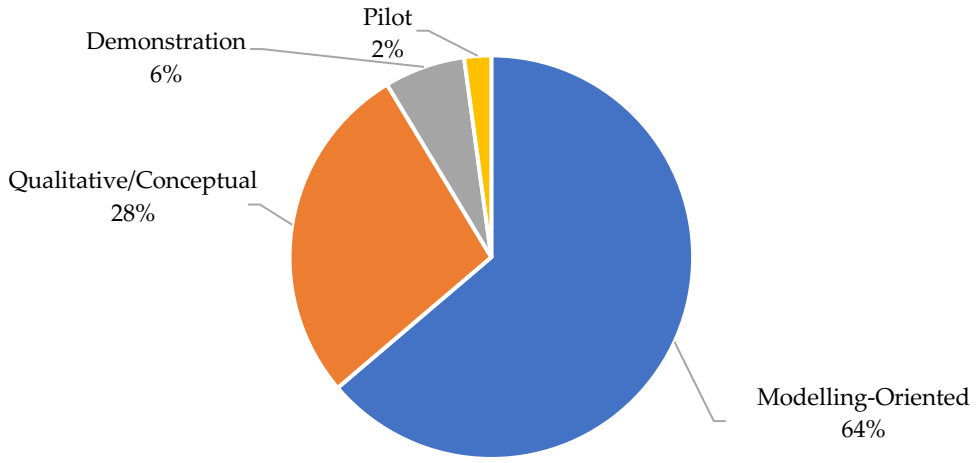

Figure 2-2: Breakdown of Archive Items by the Nature of Associated Initiative

Broadly speaking, the items are categorized to separate those associated to demonstration and pilot projects from everything else (Figure 2-2). Demonstrations and pilots account for less than 10% of the database but are disproportionately important to the overall archive. Bear in mind that some individual items included in the archive offer results or overviews of multiple demonstrations or pilots and these may appear as both peer-reviewed articles or reports.

Of the remaining two categories, which represent the vast majority, works that are modelling-oriented tend to dominate. This category makes use of quantitative analysis, simulation modelling and other types of modelling efforts. Any in-depth work that is carried out, including a total cost of ownership analysis, or a detailed analysis of energy flows or emission patterns, is considered to fall under this category as well.

On the other hand, the Qualitative/Conceptual category contains works that are definitely more qualitatively-oriented. These may make use of light quantitative analysis but are just as likely to offer thoughts about policy in the ZEV trucking domain. The works tend to be somewhat review-oriented and are often likely to cover a range of relevant themes as opposed to being highly-focused on a single aspect. As part of the effort, these works are likely to suggest concepts in need of further investigation.

2.1.3. Year of Publication

The year associated with the individual items in the archive is an important aspect to track as it offers useful insight on trends that are unfolding over time.

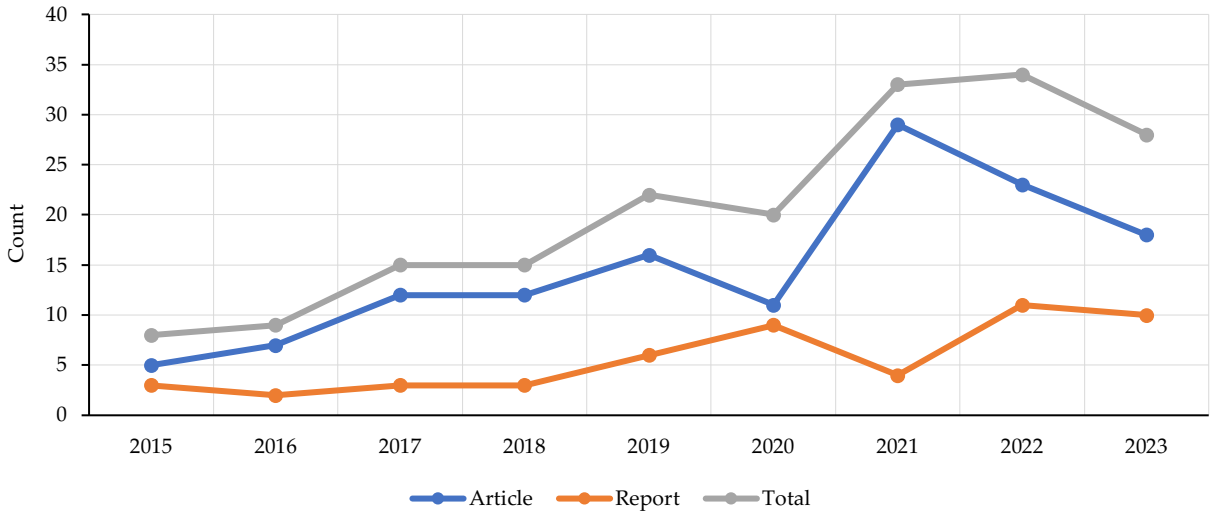

Figure 2-3: Breakdown of Items by Year and Format (2015-2023)

In temporal terms, there is a general upward trend in works published from 2015 to the end of 2023 (Figure 2-3). This is not too surprising given the increasing interest over time in the decarbonization of transportation in all its forms. The figure provides a breakdown between articles and reports. Peer-reviewed articles seem to show a significant spike in 2021. This could be an artificial spike in the sense that due to the pandemic, many works that might otherwise have appeared in 2020 appeared in 2021 instead. Perhaps the pattern reflects delays in completing manuscripts or in the review process. Regardless, the pattern is not replicated for reports with 2021 actually being a quieter year. It does appear that peer-reviewed activity relating to ZEV medium- and heavy-duty trucks may have peaked. This is something that we will monitor to see if certain recent 2023 works have been excluded that perhaps should not have been. The newness of the works can make inclusion and classification processes more challenging.

2.1.4. Primary Theme Categorization

This report is being executed on the basis of one important thematic classification, which has proven effective in past work. There are four categories assicated with this classification as follows:

1. **Barriers & TCO** – this theme is associated with barriers that get in the way of procuring ZEV trucks and is also associated with efforts that take place to assess the total cost of ownership associated with such trucks.
2. **Logistics** – this theme is associated with aspects of operational feasibility, constraints that are in play and the ability of ZEV trucks to meet existing logistical needs.
3. **Energy** – this theme is associated with the "energy pathway" of ZEV adoption scenarios. While TCO above may be focused on the economics of adoption, this theme is aligned with natural science aspects in terms of flows of energy and/or emissions.
4. **Infrastructure** – this theme takes account of the supporting infrastructure, external to the ZEVs themselves, that are required for ZEV fleets to operate.

Not all works can be conclusively assigned to just one of these themes as there are a number of items in the database that cover a lot of ground. Nevertheless, an attempt is made to choose the most appropriate option among the four. As can be seen in Figure 2-4, the classification of items by primary theme is relatively well-balanced with the operational/logistics theme being the leading one. Energy-oriented items are not far behind in prominence.

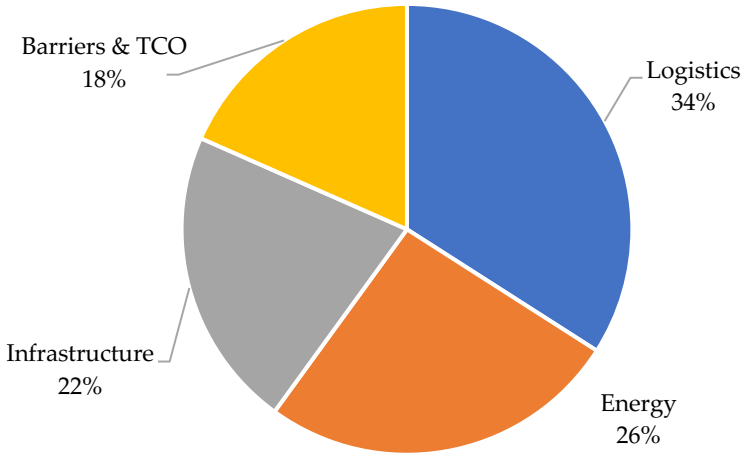

Figure 2-4: Breakdown of Items by Primary Theme

2.1.5. Vehicle Size Classification

As Figure 2-5 indicates, the works in the archive are quite focused on heavy-duty trucks, either as the sole truck size being investigated or in combination with medium trucks. 88% of the works have a focus on aspects related to heavy trucks while the total is 51% for medium-duty trucks. Only 8% of the items focus solely on medium-duty trucks. For a small share of the works, the truck size is not a prominent component of what is done.

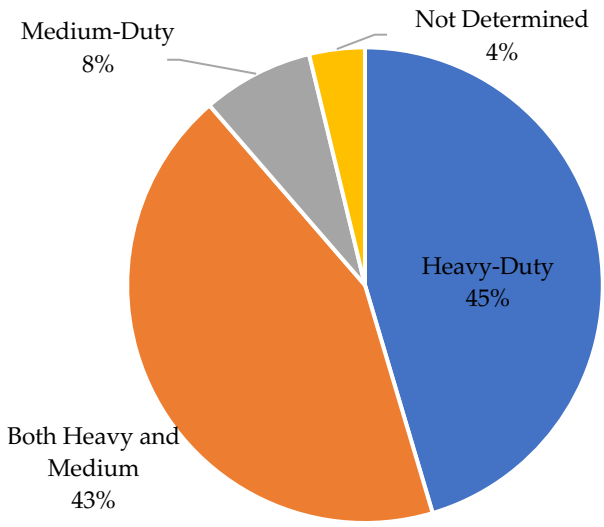

Figure 2-5: Breakdown of Items by Truck Size

The comparative lack of direct focus on medium-duty trucks is interesting considering that the medium classes encompass a wide range of vehicles that are prominent in the movement of goods. Such vehicles are more locally-oriented than their larger counterparts but are heavily involved in

urban distribution functions and various point-to-point movements. All but the largest of straight trucks are medium-duty vehicles and these are ubiquitous in metropolitan contexts and play a crucial role. Movements of straight trucks within the Greater Toronto Hamilton Area, for example, can easily extend over 100km and in environments where harmful emissions are more acutely felt by many people. Researchers may have assessed the situation and considered that decarbonization of heavy-duty vehicles is a more pressing matter.

2.1.6. Powertrain Technology Classification

Figure 2-6 portrays the combinations of powertrain technologies that are represented in the archive. One interesting observation is that most items in the archive (66.5%) focus on only one of the three powertrain technologies at a time. The remaining third deal with multiple technologies.

Direct tabulations with the database reveal that battery technology is involved in 71.3% of the items while hydrogen is involved with 50.2%. Natural gas is the least prominent at 20.5% with the majority of those cases being in works where multiple technologies are covered. It is noteworthy that nearly 40% of the archive is focused on decarbonization purely in the battery context, which is about twice the rate applying to hydrogen.

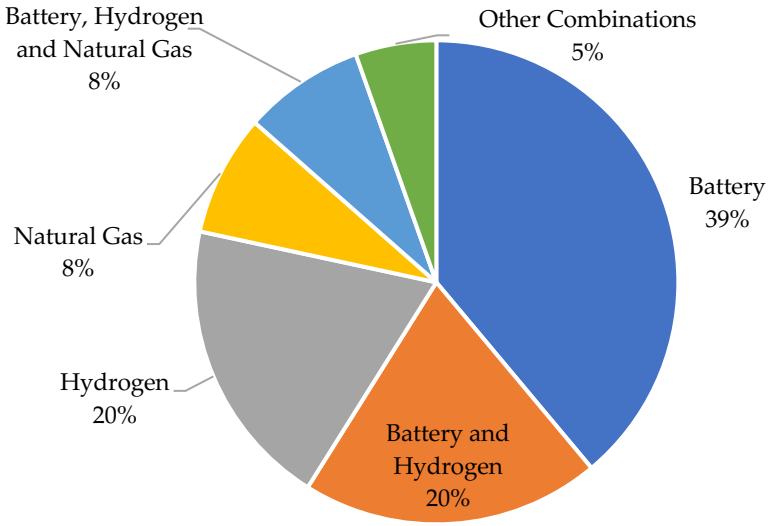

Figure 2-6: Breakdown of Items by Powertrain Focus

2.1.7. Freight or Vehicle Use Context

Figure 2-7 indicates that most items in the database are not particularly linked to a strongly defined freight context. This aspect comes across much less clearly then truck size, which was reviewed in section 2.1.5. Essentially, the implication is that many studies view freight context through the lens of the types of vehicles involved. Heavy-duty trucks, for example, do the things that heavy trucks do. Many studies do not seem to break that aspect down much further into specific use cases.

As is seen immediately below, about 1 in 3 of the items are indeed more closely linked to particular freight contexts. However, the basic classification used may not give the best clue as to the depth of the focus. About 8% of the items relate to urban freight (e.g., such as last-mile delivery or other aspects of urban distribution). Inter-city might also be seen as short-haul. It appears far less prominent than long-haul.

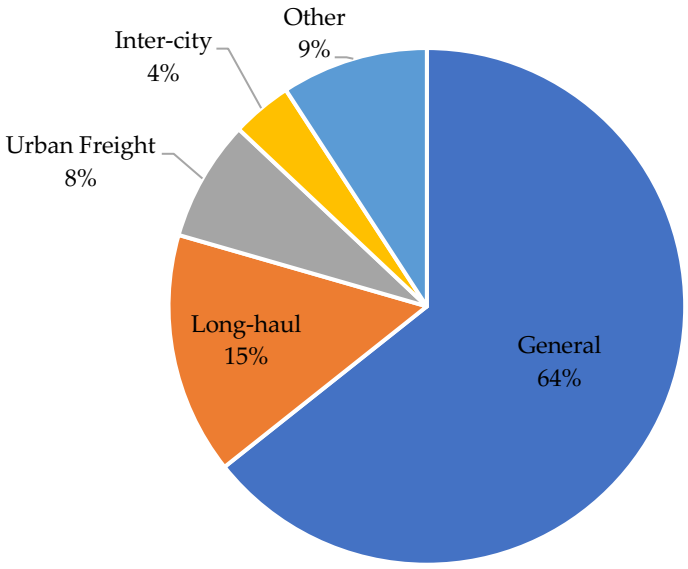

Figure 2-7: Breakdown of Items by Freight Context

In may ways, some of the most interesting contexts are hidden in the "other category". Three items examine heavy-duty vehicles in the context of mining activities, which is an important Canadian context. Isolated studies are included that focus on aspects like the use of natural gas heavy trucks in French automotive supply chains. There is a study that examines cold chain logistics (essentially the requirements of transporting perishables) in a decarbonization context.

The fact that Municipal fleets are captured in the "other" category is significant. It appears that bus transit decarbonization dominates research in municipal contexts. Municipalities operate various other medium- and heavy-duty vehicles such as full-size pick-ups, bucket trucks, refuse trucks, fire trucks and others but research efforts do not seem to focus too intently on these niche-oriented contexts.

2.1.8. Geographic Scale or Resolution of the Analysis/Item

As Figure 2-8 indicates, the database contains a field that seeks to identify the best characterization of the geographic level of resolution that applies per item. Most commonly, a national characterization is appropriate and certainly, there are many US items that take this approach. Almost as frequently, a specific geographic resolution is not readily interpretable. State or province level works are more common than items that are best described as international. Geographic scopes that are particularly linked to municipalities/cities are actually the rarest of all, which is interesting when the large magnitude of freight activity associated with cities is considered[1].

[1] Note that "municipal" in Section 2.1.8 refers to a type of geographic unit whereas "municipal" in Section 2.1.7 relates to fleets that are operated by municipal governments.

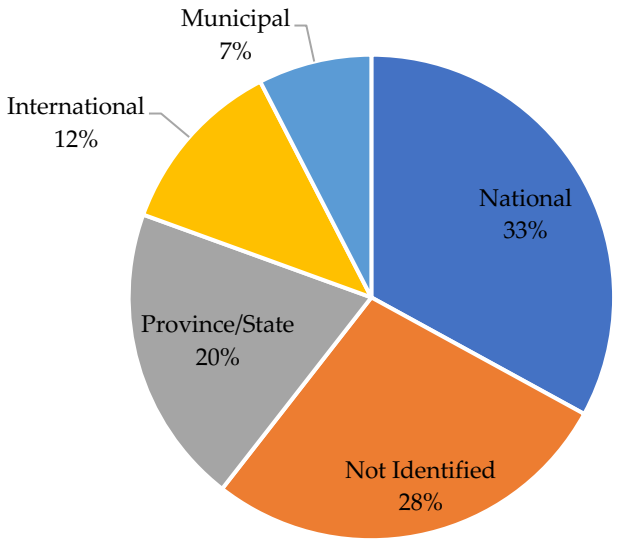

Figure 2-8: Breakdown of Items by Geographic Resolution (Scale)

Along the same lines, the result showing the continent associated with the item is fairly self-explanatory as is seen in Figure 2-9. North America, Europe and Asia, in that order, are dominant. Results are perhaps somewhat influenced by the fact that the archive is limited to items that are developed in English.

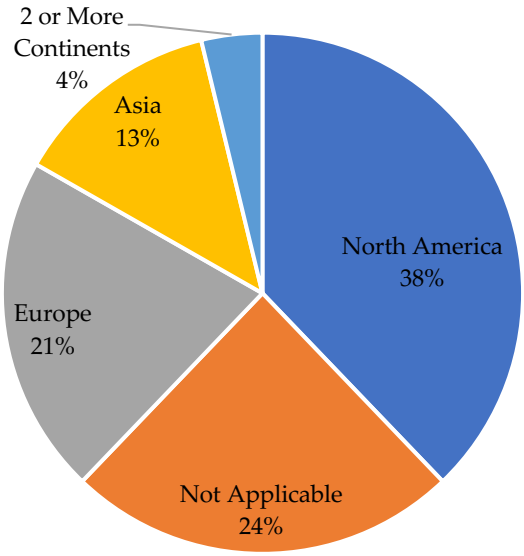

Figure 2-9: Breakdown of Items by Continent

As Figure *2-10* indicates, there are notably few countries that are heavily represented in research on the decarbonization of trucking. The fact that the United States and China are prominent is not surprising but there are more Canadian items than might be expected. To some extent, this is likely related to Canada tying into extensive US trucking networks. But there is also a need to thoroughly capture progress in Canada. Regardless, the archive contains works from 17 distinct countries, and for most of these the item count is minimal.

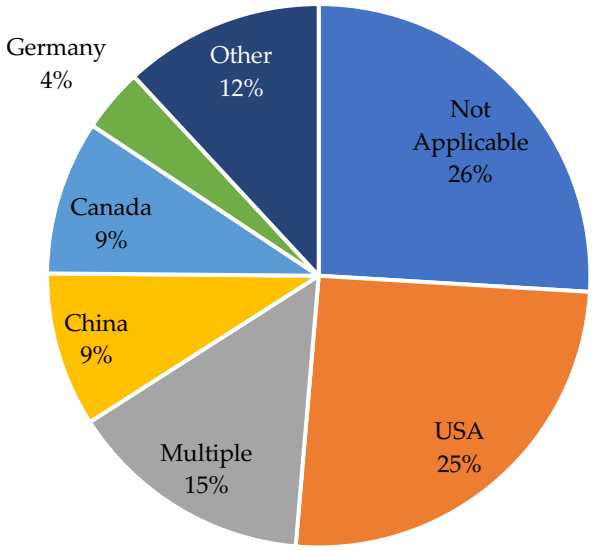

Figure 2-10: *Breakdown of Items by Subject Country*

2.2. Bivariate Analysis

Considering that there are ten core variables, and their segments, covered in the univariate analysis, many bivariate combinations of those ten variables are possible. In this sub-section, a few of the more interesting pairings of the key variables are presented.

2.2.1. Powertrain technologies over time

For some archive items only one technology is represented and others have multiple technologies that are examined. Bearing this in mind, this chart tabulates the total occurrences of each technology over time in the archive. Battery and hydrogen technologies have been on a similar upward trajectory while natural gas has stagnated and then declined.

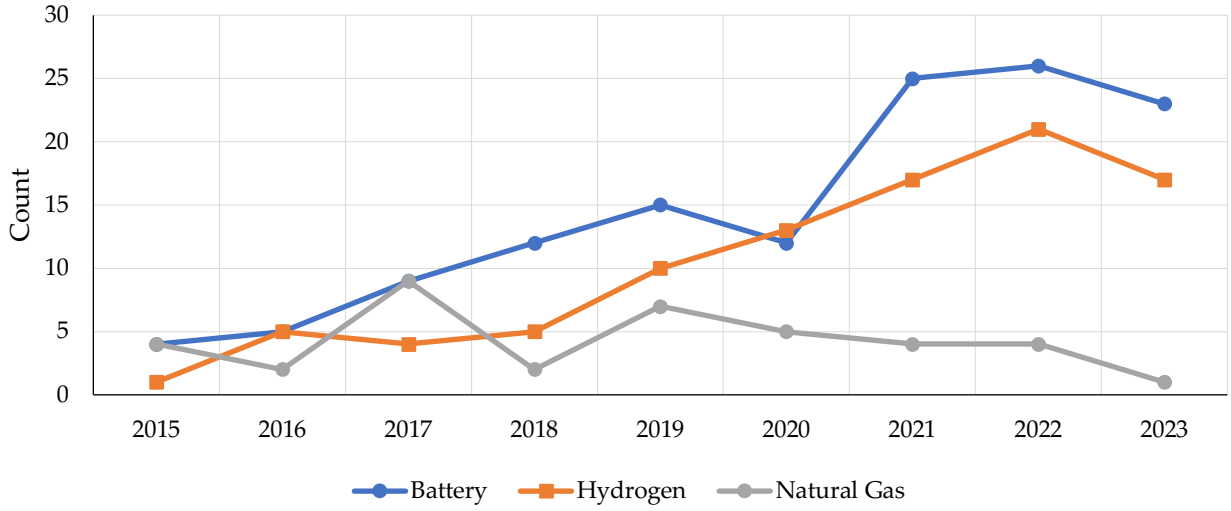

Figure 2-11: Powertrain technology appearances over time

2.2.2. *Article/Report Type Versus Primary Theme*

The primary theme distribution in the archive is quite different for peer-reviewed articles versus reports (Figure 2-12). Academic articles appear relatively much more focused on aspects of the energy pathway and emissions and logistics, whereas reports tend to emphasize energy pathway the least. Literally, the implication seems to be that the energy pathway is more a topic of academic interest. Report creators may be accepting the premise of ZEV trucks and are choosing to focus more on the infrastructure build out and the economics of adoption.

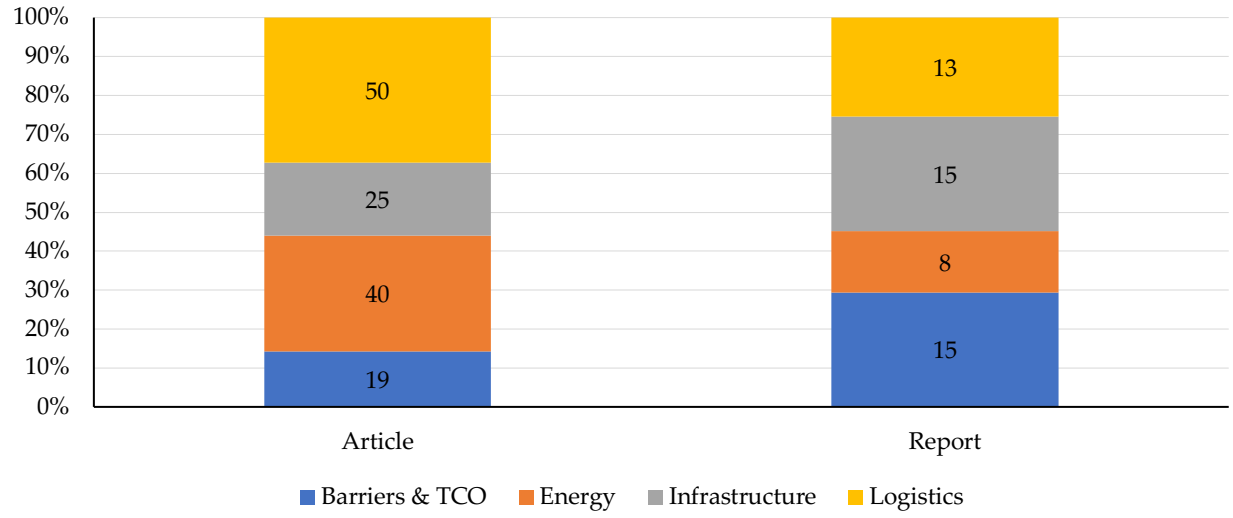

Figure 2-12*: Breakdown of Primary Theme by Item Format*

2.2.3. *Primary Theme of the Work versus Year of Publication*

In Figure 2-13 the primary themes of archive items are broken down over time. In general, there is an upward trend across all four themes with the Logistics theme being more volatile. It seems fair to say that infrastructure has gained in relative prominence over time.

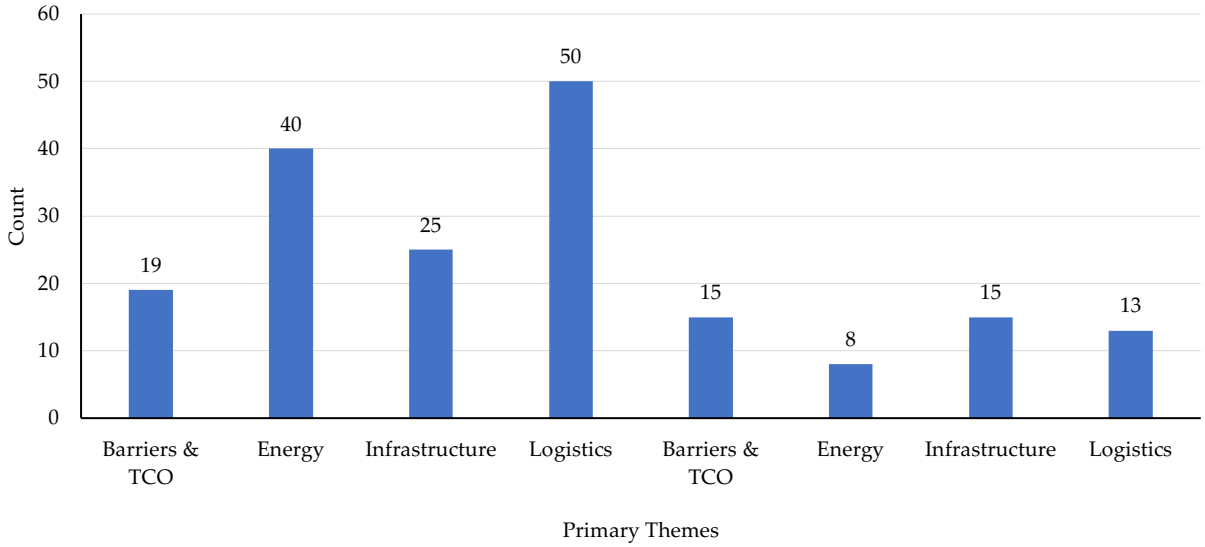

Figure 2-13: Occurrences of Primary Theme over Time

2.2.4. Vehicle Size and the Nature of the Work that gets done

Figure 2-14 shows that the most varied arrays of initiative are applied in the heavy-duty context. Conversely, the inquiry related to medium-duty vehicles is the least varied and lacking in terms of demonstrations and pilots. Most of the work on medium-duty vehicles appears to be modelling-oriented. There appears to be a severe shortage of works, focused purely on medium-duty vehicles, that are qualitative/conceptual in nature. To the extent that this is done, it is done as part of a package that includes heavy-duty vehicles as well.

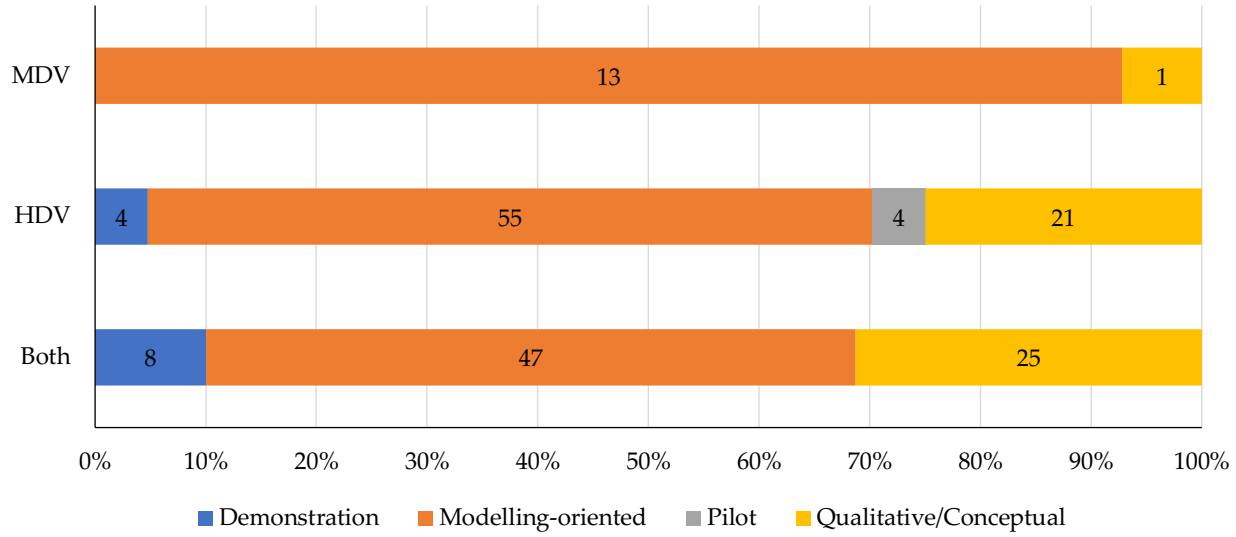

Figure 2-14: Breakdown of Initiative Types by Size of Vehicle

2.2.5. Keyword Analysis

We carried out an extensive manual keyword search and tabulation process that helped to characterize the records in the database. Each of the keywords shown below was evaluated in the archive on a record-by-record basis to see if it was meaningfully captured per record. Primarily, the title field and the abstract were assessed to determine if a record merited inclusion for the given keyword. The context in which the word was used was taken into account. For example, we validated "delivery" in relation to delivery trucks, not in relation to hydrogen delivery paths. We validated "problem" only in relation to mathematical optimization problems and not any other context.

One limitation of the manual keyword process used was that there was not a new binary field specifically created for each keyword assessment process. This was to keep the time committed to the exercise to reasonable levels. As such, the analysis is a univariate one as opposed to examining occurrences of multiple keywords in the same record (which no doubt would be of value). Nevertheless, the outcomes seem quite worthwhile. Searches were conducted in such a way as to minimize the impact of words being in slightly different forms (e.g., optimize,optimise).

Table 2-1: Significant Presence of Selected Keywords in the Archive per Record/Item

Keyword	Count	Percent	Keyword	Count	Percent
Energy	80	43.7	Feasibility	15	8.2
Fleet	64	35.0	Delivery	15	8.2
Charging	49	26.8	Interview	10	5.5
Model	48	26.2	Van	9	4.9
GHG	44	24.0	Particulate	9	4.9
Policy	40	21.9	Optimize	9	4.9
Total Cost of Ownership	34	18.6	Routing	7	3.8
Scenario	33	18.0	Problem (optimization)	7	3.8
Life-cycle	31	16.9	Refuse	4	2.2
Long-haul, short-haul	29	15.8	Nitrogen	4	2.2
California	24	13.1	Caternary	4	2.2
Class	23	12.6	Depot	3	1.6
Refuel	22	12.0	Food	2	1.1
Barriers	20	10.9	GPS	1	0.5
Incentive	19	10.4	Truckload	0	0.0
Operational	17	9.3	For-Hire	0	0.0
Well-to-Wheel	16	8.7			

There is a lot of information in

Table 2-1 that is both explicit and implicit in nature and the outcomes from the analysis say a lot about the achive that we seek to characterize. The keywords are sorted in the table by descending order of the number of occurrences. Ocurrences as a percentage of the total number of records is captured as well. It perhaps suggests something positive about the diversity of the archive that no keyword assessed appeared more than 44% of the time.

In the discussion below, a series of sub-headings is used to organize the main takeaways from the analysis. The sub-headings will typically include groupings of words that are related in ways that will be pointed out.

Energy,GHG, Life-cycle, Well-to-wheel

The word "energy" is the most significant keyword captured in the archive at about a 44% hit rate. Many of the works are focused on some aspect of energy and the related keyword "GHG" does not rank far behind. The word life-cycle is also a frequently occurring keyword that is a close relative. "Well-to-wheel" analysis is very much related but less frequently occurring due to its specificity. Overall, these keywords help to characterize the "Energy Pathway" theme.

Fleet

The word "fleet" is highly prominent and occurs 35% of the time. The implication is that if trucks and/or vans are being discussed, which is always the case in this archive, that there is likely to be a connection made to the concept of a vehicle fleet in the study.

Charging, Refuel, Caternary

"Charging" is clearly related to charging infrastructure for the battery context while "Refuel" is linked to hydrogen fuel cell vehicles. The former is more than twice as prevalent in the archive as the latter, indicating that battery propulsion, and associated infrastructure needs, have been more top-of-mind for trucking applications. Much less prominent as a keyword is "Catenary" which refers to overhead wires on major thoroughfares as an infrastructure solution to power trucks. This has been mentioned in about 2% of the archive and mostly in European contexts.

Model

The word "Model" was evaluated strictly for its use. We sought to identify whether the analysis associated with an item was specifically identified as a mathematical modelling structure of some type. Using this approach, 26% of the items met the criterion. There are several types of models and varied associated approaches that made up this total.

Policy, Incentive

The keyword "Policy" is prominent in the archive but related policy keywords (e.g., related to policy tools) are not clearly prominent, which suggests that the word is more often used in a fairly high-level sense. One associated keyword is "Incentive" which occurs about half as often as policy.

Total Cost of Ownership

This concept was investigated through keywords such "ownership" and "TCO" to arrive at 19% of the archive records that explicitly undertook or alluded to a TCO type of analysis. This is probably the dominant concept in terms of assessing the economics of potential ZEV truck adoption.

Scenario

The scenario keyword appears for 18% of the records. While "scenario" is definitely connected to the "energy" theme mentioned above, there are a variety of scenario-based analyses that are portrayed in the archive.

Long-haul, Short-haul, Delivery

These three keywords give some sense of the usage of trucks under study as portrayed by the archive. Using this measure, long-haul and short-haul truck movements are collectively investigated about twice as much as urban delivery contexts. Note that the first two keywords focused on searches involving "haul."

California

The database did not have a field that specifically identified the state for US items, but it is well-known that California is a leading jurisdiction in matters related to the decarbonization of freight. Approximately 13% of the items are clearly linked to California in the archive. There may be additional works where California gets mentioned in the body of the document, perhaps along with other US states

Class

The keyword "Class" was examined in relation to its use as an identifier for specific vehicle classes (e,g,, Class 7, Class 8 and others) and not in any other context. It is noteworthy that only about 13% of the works used the keyword in this way. It does suggest some lack of specificity about the nature

of the truck or van in most works and perhaps an associated tendency to group into the broader terms of medium- and heavy-duty.

Barriers
About 11% of works are focused on barriers in the adoption context. Barriers often get examined in qualitative works that may include interviews.

Feasibility, Operational
As an average, these two keywords, which are quite associated with the "Logistics" major theme, occur about 9% of the time.

Interview
Actual tabulation of the keyword "interview" reveals that the method is associated with about 5% of the records. So, the investigation of barriers, as shown above, is more general than what is provided via qualitative interviews.

Optimize, Routing, Depot, Problem
These keywords are quite well associated with optimization methods and lines of inquiry. These keywords are all occurring at rates well less than 5% indicating that optimization techniques overall have not been heavily used in the archive. It is one component forming a subset of the "Models" keyword which appears much more often.

Van
Vehicles best described as "Vans" are certainly in scope for this archive, mostly in urban delivery contexts, but appear only 5% of the time. This finding is aligned with the earlier observation that there is not such a focus on medium-duty trucks. Vans are highly secondary to the keyword "Truck" which is too fundamental to merit detailed examination.

Refuse, Food
The keyword "refuse" yielded a 2% hit rate in the archive. This is a good example of extensive heavy truck movements that are quite ubiquitous but perhaps are somewhat "under the radar" in a decarbonization context. In addition, a small number of items explored ZEV trucks in the context of food supply chains.

Nitrogen, Particulate
These two keywords were tested to assess the depth of items in terms of harmful emissions (nitrogen oxides, particulate matter) as opposed to GHG's only. GHG's occur nearly five times more often then these two emission types in the archive, indicating a much stronger focus on climate change relative to direct human health impacts.

GPS
The acronym GPS, related to data derived from the global positioning system, only appears once in the archive. This result suggests that the use of such data appears to be underrepresented in decarbonization research contexts.

For-Hire, Private,Truckload
While the "fleet" keyword is very prominent in the archive it is interesting to note that no apparent distinction is made between For-hire and private fleets in the archive. These three keywords do not appear in the archive based on the current search criteria. "For-hire" fleets are in the business of

carrying goods for other parties whereas private fleets relate to companies that move their own goods. Keyword searches based on “hire” and “private” did not reveal any results or revealed results that related to another context. Certainly, the decarbonization context differs between private and for-hire fleets but this does not seem to be a significant research focus in the archive.

In closing this chapter, we note that the discussion above has been about the description of basic quantitative results that have been derived from the archive. The concluding Chapter 3 seeks to synthesize and discuss some implications from the results presented here.

McMASTER INSTITUTE FOR TRANSPORTATION & LOGISTICS

Conclusions

3. Chapter 3 - Conclusions

This scoping review exercise has permitted nuanced perspective on the nature of the progress on medium- and heavy-duty ZEV trucking research since 2015. Decarbonization of trucking remains in its early stages but a fairly mature literature on the topic has developed. Meanwhile, there are several good examples of demonstration and pilot projects that help to make ZEV trucking more tangible and practical in the eyes of potential adopters.

As a consequence of developing the archive and preparing the previous chapter in this report that analyzes the archive, a few useful conclusion are evident which are outlined below. The discussion is organized on the basis of the archive's primary thematic classification as shown below:

1. **Barriers & TCO** – this theme is associated with barriers that get in the way of procuring ZEV trucks and is also associated with efforts that take place to assess the total cost of ownership associated with such trucks.
2. **Logistics** – this theme is associated with aspects of operational feasibility, constraints that are in play and the ability of ZEV trucks to meet existing logistical needs.
3. **Energy** – this theme is associated with the "energy pathway" of ZEV adoption scenarios. While TCO above may be focused on the economics of adoption, this theme is aligned with natural science aspects in terms of flows of energy and/or emissions.
4. **Infrastructure** – this theme takes account of the supporting infrastructure, external to the ZEVs themselves, that are required for ZEV fleets to operate.

Initially, a few general conclusions are offered before moving into outcomes that are more closely linked to these four primary themes.

3.1. General Conclusions/Observations

A few general conclusions/observations are presented in this section as follows:

- Some individual reports, such as ones released by the North American Council on Freight Efficiency (NACFE) are extremely important for understanding real-world trucking and electrification contexts. Related to this conclusion is that all items in the archive, realistically, are not (or should not be) weighted equally - some are much more important and influential than others. This has to be borne in mind in light of some of the simple summaries that have been created in Chapter 2 based on equal weighting of archive items.
- There are indications of duplication of research effort in the archive. In the peer-reviewed academic realm, for example, there are many articles on energy pathway concepts that seem to have overlap and in the realm of reports, there are several which offer similar broad coverage on an array of ZEV adoption issues.
- It was discovered that while truck fleets is a well-covered topic across the archive, there appears to be minimal distinction being made between two major types of truck fleets: for-hire fleets versus private fleets. Decisions about decarbonization look quite different depending on the type of fleet linked to the decision. Along similar lines, the archive contains only one work that focuses specifically on the topic of small truck fleets (in terms of number

of vehicles) and yet the vast majority of trucks fleets are very small and in many cases are owner-operated with no employees.

- There is very little coverage in the archive at the extreme of small fleets which is the truck owner-operators, who actually account for a large share of the ZEV adoption decisions that ultimately need to be made. In many ways, the owner-operator is a trucking counterpart to the consumer adoption of light duty vehicles at the household level. The latter is a centrepiece of electric vehicle research but the owner-operator in trucking is comparatively very much neglected.
- The body of works captured in the archive are skewed toward heavy-duty trucking. For example, it is interesting to note that the qualitative/conceptual class of archive item was heavily underrepresented for medium-duty trucks relative to heavy-duty. There appears to be a gap where examination of medium-duty trucking in the qualitative/conceptual sense could add value. Medium-duty trucking simply is not attracting the same level of attention.
- A related thought is that trucking in the archive is often viewed in an aggregated sense (e.g., medium and heavy) as opposed to the particular class of vehicle that is involved. To the extent that particular classes are analyzed in isolation, it often turns out to be Class 7 or 8, which highlights the emphasis on heavy-trucking. Perhaps there is a researcher notion that solving the issues of heavy trucking decarbonization implies the solving of medium-trucking issues.
- Another under-explored dimension is the contrast between truckload and less-than-truckoad (LTL) services. Both of these rely quite heavily on heavy-duty trucks but the service type is associated with quite different logistics.
- In some studies there may be an implicit assumption that heavy trucking is long-haul trucking. A handful of studies showed that this is not truly the case and that many heavy truck movements are 200-300 km and less. This reality has implications for ZEV trucking and could make BEV trucks more attractive in more contexts then many might think.
- It is very striking that the academic literature covered in the archive does not have many industry-specific elements or cases at all. There are isolated studies that deal with the retailing sector or trucking related aspects of the automotive industry in Europe but there has not been a concerted effort to study industry-specific nuances. Automotive supply chains, with their extensive dependence on trucking to operationalize just-in-time assembly operations is a very interesting and specific context in which ZEV trucking should be studies in more detail.

3.2. Barriers and TCO

Many of the general conclusions highlighted above have implications for the Barriers and TCO theme. The general sense that emerges from these is that a lot of academic analysis has tended to be somewhat aggregate across key dimensions such as truck size or across very different trucking contexts. TCO calculations, for example, will tend to be most accurate when underlying assumptions are based on usage contexts that are most closely aligned with reality.

The prior keyword analysis made clear that ZEV procurement barriers are very much related to the "interview" form of qualitative data collection, though the former appears to be more broadly dispersed throughout the archive. The archive has revealed that a good qualitative interview study for Canada that covers procurement barriers and other aspects will be a good addition to the international literature and also to the domestic scene. The timing is good for such a study in Canada and this type of study, of course, is a key component of the current project.

Analysis of the archive reveals opportunity for more nuance on the policy front. Policy measures are very much intertwined with the Barriers and TCO theme. The term "incentive" is prominent in the archive, which is perhaps not surprising, but other policy measures are much less so. European policy, for example, emphasizes the zero-emission zone as a tool to assist in the decarbonization of trucking. The intersection of the zero-emission zone with ZEV trucking in the archive is not an aspect centrally covered in studies and no doubt there are other policy examples.

3.3. Logistics

There are several observations/conclusions related to operational aspects of ZEV trucking that have emerged:

- The topic of trucks functioning collaboratively with drones to make delivery more efficient is rapidly rising to prominence in the literature but ties to electrification that are required for membership in this archive are not present. This suggests a gap concerning research on the intersection of electric trucks and drones in delivery contexts.
- It was noteworthy that the archive captures very little research activity in the realm of applying GPS data. Powerful GPS data sources that document the actual movements of thousands of trucks are available nowadays and give considerable insight about how trucks are deployed across varied contexts. This appears to be an area in need of further investigation for the potential to better understand the implications for decarbonization.
- Research on the potential implications of operating ZEV trucks in a cross-border sense is relatively quite important in the Canadian trucking context. Connections between Ontario and the US Midwest is one importance example. The cross-border dimension of ZEV trucking is not readily apparent in the archive.
- There is no real coverage in the archive of the importance of logistics clusters and how this concentrated form of land use determines a lot about the movement of goods by trucks that takes place, whether for urban distribution or inter-city movements. There is likely some inter-play between land use and decarbonization of trucking that needs further investigation.

3.4. Energy

The Energy Pathway theme is quite extensively covered in the academic literature. Properly answering the related research questions is seen as one of the key building blocks in understanding which powertrain technologies appear most promising and in which contexts. The theme is stressed relatively less in many non-academic reports. A few observations that emerge are as follows:

- GHGs are highlighted in the archive much more than criteria air contaminants (CACs), which suggests that more work may be needed to showcase the role of electrification in reducing CACs and why this matters a lot in highly populated areas.
- It cannot be disputed that heavy trucks require a lot of attention on the decarbonization front but medium trucks are enormously important in many intra-urban and some inter-city, short-haul contexts. Again, in such potentially heavily populated areas, harmful emissions are at play.
- Province-by-province energy pathway implications considering varying electricity generation profiles is an interesting Canadian topic for consideration. Luckily, provinces that are most densely populated and have the largest trucking operations tend to be associated with relatively clean generation profiles.

3.5. Infrastructure

It is perhaps not surprising that the archive pays a lot of attention to charging infrastructure in the case of BEV trucks and refuelling infrastructure in the case of hydrogen fuel cell trucks. The battery solution is much more prominent in the literature and especially in the domain of non-academic reports.

Infrastructure is certainly intertwined with logistics and operational aspects, which in turn often links to optimization research. Mathematical optimization is a powerful modelling technique which seems to be relatively under-represented in ZEV trucking contexts. There have been some efforts that generalize the vehicle routing problem (which typically assumes trucks) to the electric vehicle routing problem (where concepts such as range limitation and access to required infrastructure is incorporated). Of course, there are some potential stumbling blocks. One is that the required data to drive such models tends to be quite private sector oriented – more so than would be the case with ZEV transit buses (as a comparative example).

BEV truck optimizations are more tied to pure goods movement than is the case with hydrogen. The hydrogen literature is also forced to focus on the infrastructure associated with hydrogen storage and the actual transport of hydrogen to refuelling stations.

There is evidence of alternative infrastructure approaches that appear to be gaining momentum, particularly in Europe. These emerged as minor themes in the archive. The concept, which has appeared in electric bus contexts, is that charging takes place as vehicle movement takes place. In Europe the concept of electric road systems appears to be gaining traction in the trucking context and especially so for corridors that are more heavily travelled. Prospects of such an approach for Canada appear to be worthy of investigation.

McMASTER INSTITUTE FOR TRANSPORTATION & LOGISTICS

References

4. References

[1] L.-P. Tardif and M. Ferguson, "The Transformative Role of the Trucking Industry: Federal Policy Questions," McMaster Institute for Transportation and Logistics, 2022.

[2] G. Eldeeb, S. Tasnim and M. Mohamed, "Mobility and Public Transit: A Renaissance for the Experience Age," McMaster University: Transit Research-Informed Practice Lab, 2021.

[3] H. Daudt, C. van Mossel and S. Scott, "Enhancing the scoping study methodology: a large, inter-professional team's experience with Arksey and O'Malley's framework," *BMC Medical Research Methodolgy,* vol. 13, no. 48, 2013.

[4] M. Pham, A. Rajic, J. Greig, J. Sargeant and A. M. S. Papadopoulos, "A scoping review of scoping reviews: advancing the approach and enhancing consistency," *Research Synthesis Methods,* vol. 5, pp. 371-385, 2014.