ANALYZING EXPECTED OPERATING GROSS VEHICLE WEIGHT OF BATTERY ELECTRIC TRUCKS: IMPLICATIONS FOR REGULATORY AND FLEET ELECTRIFICATION STRATEGIES

						
AHMED LASISI Postdoctoral Research Fellow, University of Manitoba, Winnipeg. PhD in Civil Infrastructure Systems, University of Delaware, USA	JYOTI MANDHANI Postdoctoral Research Fellow at University of Manitoba, Winnipeg. Obtained Ph.D. in Transportation Systems from Indian Institute of Technology Roorkee, India.	PHANI KUMAR PATNALA Research Fellow at University of Manitoba, Winnipeg. Obtained Ph.D. in Transportation Systems from Indian Institute of Technology Roorkee, India.	DAVID LINTON Policy Analyst, Manitoba Trucking Association, Winnipeg	BABAK MEHRAN Professor, Urban Mobility and Transportation Informatics Group, Department of Civil Engineering, University of Manitoba	CARL HO Professor Department of Electrical and Computer Engineering, University of Manitoba	JONATHAN D. REGEHR Professor, Urban Mobility and Transportation Informatics Group, Department of Civil Engineering, University of Manitoba

Abstract

The transition to battery electric trucks (BETs) requires an understanding of the relationship between gross vehicle weight (GVW) (mass, kg) and battery weight, as increased battery capacity reduces payload. This study examines the impact of battery capacity on carrying capacity using real-world data from weigh scales in Manitoba, Canada. We analyze GVW distributions from conventional diesel trucks using Gaussian Mixture Models (GMM) to predict future compliance challenges for BEVs. By decomposing GVW into empty, partially loaded, and fully-loaded states, and adjusting for incremental battery weight, we estimate the proportion of trucks that may exceed GVW limits and assess the need for configuration adjustments. The analysis focuses on four common truck configurations in Manitoba: five- and six-axle tractor semitrailers (3-S2s and 3-S3s), eight-axle B-doubles (3-S3-S2s), and nine-axle A-doubles (3-S2-4s, which operate under special permit). Alternative scenarios explore increased GVW limits and the implications of electric truck adoption. These findings provide insights into weight adjustments, necessary configuration changes, and the potential impact on fleet electrification, helping shape adaptive regulations for sustainable transportation in line with global decarbonization goals.

Keywords: Battery Electric Trucks, Gross Vehicle Weight, Regulations, Compliance, Gaussian Mixture Models

1. Introduction

The electrification of heavy-duty trucking represents a critical step in Canada's broader efforts to achieve its national and international climate targets. As a country with vast geography and an economy heavily reliant on road freight transport, a transition to battery electric trucks (BETs) offers both significant challenges and opportunities. Heavy-duty trucks are responsible for a disproportionate share of greenhouse gas (GHG) emissions within the transportation sector, so the examination of decarbonization through truck electrification is essential for moving towards a more sustainable future (Link and Plötz 2022). In the Canadian context, the push towards electrifying heavy-duty trucks is not only driven by environmental imperatives but also by economic and operational considerations, where the latter is influenced by technical feasibilities and the realities of the trucking business (Nykvist and Olsson 2021). With the federal government committing to ambitious net-zero targets by 2050, there is a growing need to align regulatory frameworks, infrastructure development, and industry practices with these goals (Canada 2023). However, the transition to BETs is complex, particularly given the technical limitations associated with battery weight (mass), range, and the impact on carrying capacity. As battery capacity increases to extend the range of electric trucks, the battery's weight grows significantly, impacting the operating gross vehicle weight (GVW).

In this study, we explore different scenarios of BET penetration and the corresponding influence on truck GVW and regulatory compliance. Specifically, the study pursues the following questions:

- How does the penetration of BETs in the Canadian trucking fleet influence GVW distributions?
- How do those influences vary for different truck configurations and body types?
- What impact might the introduction of BETs have on productivity and regulatory compliance, and how should that inform policy?

The analysis of percentage penetration scenarios aligns with Canada's net-zero goals, offering strategic insights into how the gradual integration of electric trucks could be managed effectively. While different jurisdictions have proposed additional weight allowances and financial incentives to facilitate a smooth transition, significant issues around practicability, economic viability, and payload restrictions need to be addressed. The electrification of heavy-duty trucking in Canada is a multifaceted issue that requires careful consideration of regulatory, operational, and environmental factors. This paper contributes to the growing body of knowledge on BET adoption by providing a data-driven analysis of GVW implications, ultimately supporting the development of informed policies and strategies for a more sustainable transportation system.

2. Regulatory Incentives and Target Penetration Rates for Zero-Emission Trucks

To support the adoption of zero-emission trucks (ZETs), several regions have introduced weight allowances to offset the additional weight of electric and hydrogen-powered trucks. These policies ensure that ZETs can maintain similar payload capacities as diesel trucks without exceeding legal weight limits. In Europe, a weight allowance of up to 4 tonnes is provided for both electric and hydrogen trucks to account for the added weight of their propulsion systems (Earl et al. 2018; Soone 2024). Similarly, in the UK, certain ZETs are allowed an increase in their GVW by 2 tonnes, and alternatively fueled vehicles (AFVs) can have up to 1 tonne added, to account for the extra weight of their powertrains. However, no vehicle, including ZETs and AFVs, can exceed the overall maximum weight limit of 44 tonnes, and individual axle weight limits stay the same. (Department for Transport 2020; HM Government 2021; The UK Government 2023). Australia has taken an axle-based approach, allowing up to 8 tonnes (from 6.5-7 tonnes) on a single steer axle and 18.5 tonnes (from 16.5-17 tonnes) on the drive axle for ZETs, supporting operational efficiency (Government 2023; NSW Transport 2023). In the United States, California offers an additional weight allowance of 2,000 pounds (approximately 0.9 tonnes) for zero-emission trucks, reinforcing the state's efforts to lower greenhouse gas emissions and improve air quality (Board 2023). In British Columbia, Canada, electric trucks benefit from a 1.5-tonne weight allowance, while hydrogen-powered trucks receive a 1 tonne allowance (Ministry of Transportation and Infrastructure 2023).

In addition, several countries have set targets to achieve significant penetration of ZETs within their heavy-duty fleets. The following table summarizes key targets for ZET penetration in heavy-duty fleets and market share of new ZETs across various regions, highlighting the progressive target milestones leading up to 2050. These targets reflect the growing commitment of governments to align their transportation sectors with decarbonization goals and climate action strategies, with early milestones set for 2025 and more aggressive adoption rates by 2030 and beyond. While regions like the UK and Europe have clearly defined their targets for complete ZET adoption, other countries, such as the U.S., Germany, and Singapore, aim to gradually increase their market share of new ZETs over the coming decades. Table 1 provides an overview of target ZET fleet penetration and market share goals for different nations. Notably, the Canada market share goal of 10% by 2030 for ZETs is less aggressive than the other countries identified.

Table 1 – Overview of ZET Fleet Penetration and Market Share Goals by Jurisdiction

Country	**Target Year**				
ZET fleet penetration					
	2025	2030	2035	2040	2050
UK		15%		100%	
Europe	0-7%	4-22%			
Market share of new ZETs					
Global (COP26)		30%		100%	
Germany	50%	100%			
Norway		100%			
Japan			100%		
UK	2%	15%	39%		
Singapore					85%
Canada		10% (2032)		100% (2045)	
U.S.		46%		100%	

3. Methodology

3.1 Source Data

Weight (mass) data for 17 truck configuration-body type pairs were collected at four static weigh scales located on primary highways in Manitoba, Canada. There are four main truck configurations under consideration:

1. **Five-axle tractor semitrailer (3-S2):** This configuration falls under class 9 of the 13-vehicle Federal Highway Administration (FHWA) classification scheme. It has a GVW limit of 40,000 kg at the data collection sites.
2. **Six-axle tractor semitrailer (3-S3):** Classified as FHWA class 10, this configuration has a GVW limit of 47,000 kg at the data collection sites.
3. **Eight-axle B-double (3-S3-S2):** This class 13 configuration has a GVW limit of 63,500 kg.
4. **Nine-axle turnpike double (3-S2-4)**: Like 3-S3-S2s, this configuration falls into class 13 and has a GVW limit of 63,500 kg. The configuration operates only on divided highways, subject to annual overlength permits.

Notably, this study excluded truck configuration-body type pairs having fewer than 100 observations, as highlighted in Table 2. A full data description can be found in a previous study that used Gaussian Mixture Models (GMMs) to characterize payload distributions for predominant truck configurations and body types (Regehr et al. 2020). Next, we introduce the application of GMMs in GVW analysis.

Table 2 – Data Summary of Observations per Truck Configuration-Body Type Pair

Truck config-body type pair	Observations	Truck config-body type pair	Observations	Truck config-body type pair	Observations
3-S2 Container	36 (X)	3-S3 Container	74 (X)	3-S3-S2 Dump	43 (X)
3-S2 Dump	219	3-S3 Dump	78 (X)	3-S3-S2 Hopper	126
3-S2 Hopper	165	3-S3 Hopper	83 (X)	3-S3-S2 Tanker	91 (X)
3-S2 Van	2798	3-S3 Van	432	3-S3-S2 Flat Deck	180
3-S2 Flat Deck	425	3-S3 Flat Deck	386	3-S2-4 Van	506
3-S2 Tanker	89 (X)	3-S3 Tanker	46 (X)		

(X) – Excluded from Analysis

3.2 Application of Gaussian Mixture Models (GMMs)

Previous studies, such as those by (Hernandez 2017; Nichols and Cetin 2007; Regehr et al. 2020), have successfully demonstrated the use of GMMs for modeling truck weight distributions. A GMM is a statistical approach commonly used to identify and distinguish normally distributed components within a dataset, such as the distribution of truck weights. Mathematically, a GMM represents the data as a linear combination of multiple Gaussian distribution components, each weighted by a mixing proportion. This method allows us to decompose the GVW data into its underlying components: empty, partially loaded, and fully loaded trucks. For our study, GMM analysis was employed to characterize the GVW distribution for each scenario and truck configuration–body type pair. This approach enabled us to capture the variability in the load conditions and provided insights into the different loading states of trucks operating in Manitoba. By distinguishing these components, we were able to estimate the proportion of trucks in each load category and evaluate the potential impact of battery weight on productivity and compliance for future BET fleets.

3.3 Additional battery weight calculation

In long-haul scenarios, where larger battery packs are necessary, the impact of battery weight is pronounced. A case in point: for a truck with a battery capacity of 800 kWh, the battery alone weighs 4,301 kg, which, when combined with the electric motor and other components weighs nearly 5,000 kg (see Table 3). If no weight allowances were in place, this would substantially reduce payload capacity, assuming the truck remained within allowable weight limits. To account for the additional battery weight, this study makes the following assumptions:

- The electric truck has a capacity to cover long-haul trips (more than 160 km one way) for all truck configuration-body type pairs.
- For on-time delivery in long hauls without consideration for charging between trips, the truck operates 640 km per day (i.e., four 160-km one-way trips).
- Battery swapping on board is not allowed but overnight charging is permissible.
- The proposed truck has the specifications of the Tesla Semi 800 kWh model, namely: storage capacity = 800 kWh; maximum gross combination weight = 37,300 kg (82,000 lb); range = 480-800 km (300-500 miles); tractor unladen weight = 11,800 kg (26,000 lb); energy consumption less than 1.2 kWh/km; and energy density = 0.186 kWh/kg (Johnson 2023).

Table 3 below outlines the steps and corresponding calculations needed to calculate the net additional weight to the GVW data as an input to the GMM model.

Table 3 – Additional weight to be added to GVW data

Steps	Calculation
Battery Weight Calculation	**Battery Weight** $\alpha = \frac{Battery\ Capacity}{Energy\ Density} = \frac{800}{0.186} = 4301kg$
Total Electric Component Weight	Combined weight of electric motor and gearbox ≈ 618 kg (Sharpe 2019), hence total electric component weight = 4919 kg
Net Additional Weight to GVW Data	$W_{add} = Combined\ Weight - Diesel\ Engine\ Weight = 4919 - 1700 = 3219\ kg \approx 3220\ kg$

*Weight of Diesel Engine ≈ $1700kg$ (Mareev, Becker, and Sauer 2017)

For all the truck configuration-body type pairs identified in Table 2, a net additional weight of **3220 kg** would be added resulting in a maximum GVW of 37,300 kg. However, for heavier configurations like the 3-S2, which has a GVW of 40,000 kg, it is imperative to increase battery capacity to meet this additional weight requirement. This adjustment is crucial for ensuring compliance with regulatory standards while maintaining the performance and efficiency of the fleet. For our analysis, we utilized the GMM approach to characterize GVW distributions and its underlying components (i.e., empty, partially loaded, and fully loaded components) for each truck configuration-body type pair.

Based on data from Table 1, the following scenarios were developed for the GVW analysis considered in this study: **7%, 15%, 30%, 50% and 100 %** BET penetration rates. This analysis considers three regulatory incentive levels (additional weight allowance): no incentive, 1.5 tonnes (British Columbia), and 4 tonnes (Europe).

4. Results

Figure 1 shows the plotted GVW distributions with GMM components for a 3-S2 flat deck truck configuration body-type pair scenario with 425 observations with randomly added additional weight of 3220 kg to the dataset. This was also repeated for different scenarios as shown in Figure 2. The GMM components (blue dashed lines) represent the different loading states (empty, partially loaded, fully loaded). As ET penetration increases, the curve shifts rightward, indicating higher overall GVW due to the additional weight of batteries and electric components. Table 4 shows that the GMM estimated mean GVW exhibits a nuanced trend with increasing ET penetration. For instance, at 15% ET penetration, there's a notable jump in the mean for Components 2 and 3 compared to the base, suggesting that specific truck configurations or routes might be more susceptible to increased weights due to battery inclusion. At 50% ET penetration, Component 3 has the highest mean GVW, indicating that longer hauls or larger trucks could be disproportionately affected. Still on Figure 1, we illustrate the estimated GVW distributions for 3-S2 flat decks under different penetration levels for BETs. An anticipated 3.76% of trucks would need to reduce their payload to comply with the existing GVW limit at 100% penetration with a corresponding expectation of 1.1% violation rate at 15% penetration rate assuming no intervention.

Figure 2 illustrates the Gaussian Mixture Model (GMM) distributions of GVW for various truck configurations and body types, including 3-S2 Dump, Hopper, and Van, as well as 3-S3 and 3-S2-4 configurations for Flat Decks and Hoppers. Each distribution includes distinct sample sets and highlights variations in GVW profiles across configurations. Notably, the 3-S2 configurations, especially Dump and Hopper trucks, show significant peaks in GVW that align with regulatory GVW limits for that class, while 3-S3 configurations, like the Flat Deck, display broader distributions, indicating higher GVW variability. The density peaks reveal the tendency for each truck type to cluster around certain weight values, likely tied to operational loading patterns, with heavier configurations, such as 3-S2-4 Hoppers, showing broader distributions that extend to higher GVWs.

The data from Table 5 highlights the complexities and challenges associated with the electrification of heavy-duty trucks, particularly as it relates to GVW compliance and the broader implications for fleet productivity and regulatory frameworks. The analysis reveals that increasing the penetration of BETs without corresponding weight allowances could lead to a significant rise in non-compliance with GVW limits across most truck-body types, particularly for configurations like the 3-S2 dump and 3-S3-S2 hopper, where non-compliance could potentially exceed 37% and 26% respectively at full BET penetration, if nothing is done. Even with additional weight allowances, compliance challenges persist, suggesting that while regulatory measures such as weight allowances (e.g., 1,500 kg or 4,000 kg) can mitigate some of these issues, they may not be sufficient across all truck types. This points to a potential need for more flexible and tailored regulatory approaches.

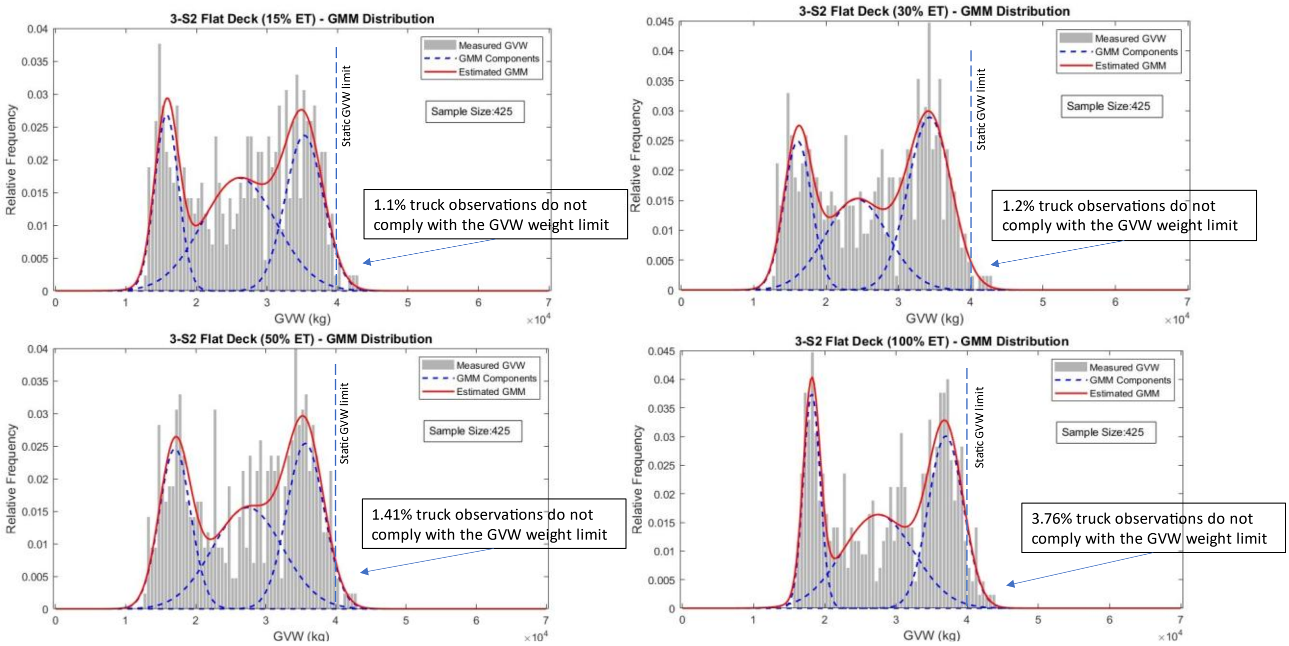

Figure 1 – 3-S2 Flat Deck – GMM Distribution with different penetration rates and corresponding rate of non-compliance.

Table 4 – GMM Artefacts for 3-S2 Flat Deck – Combined GMM Distribution with different penetration rates and corresponding rates of non-compliance

Scenario	**% of non-complying trucks**	**Mean GVW (in kg)**			**Mean Payload (kg)**	***Avail. Payload (1500kg)**	****Avail. Payload (4000kg)**
		Component 1	**Component 2**	**Component 3**			
Base	0.2	14900	24200	33800	14300	26600	29000
7% ET	0.2	15200	24200	33900	14300	26200	28700
15% ET	1.2	15800	26100	35300	14700	25600	28100
30% ET	1.2	16000	24200	34300	14500	21800	24300
50% ET	1.41	17000	27300	35600	14700	24300	26800
100% ET	3.76	18100	27400	37000	14300	23300	25800

***Available payload under full compliance with additional weight allowance of 1500 kg (weight limit - 41500kg)**
****Available payload under full compliance with additional weight allowance of 4000 kg (weight limit - 44000kg)**

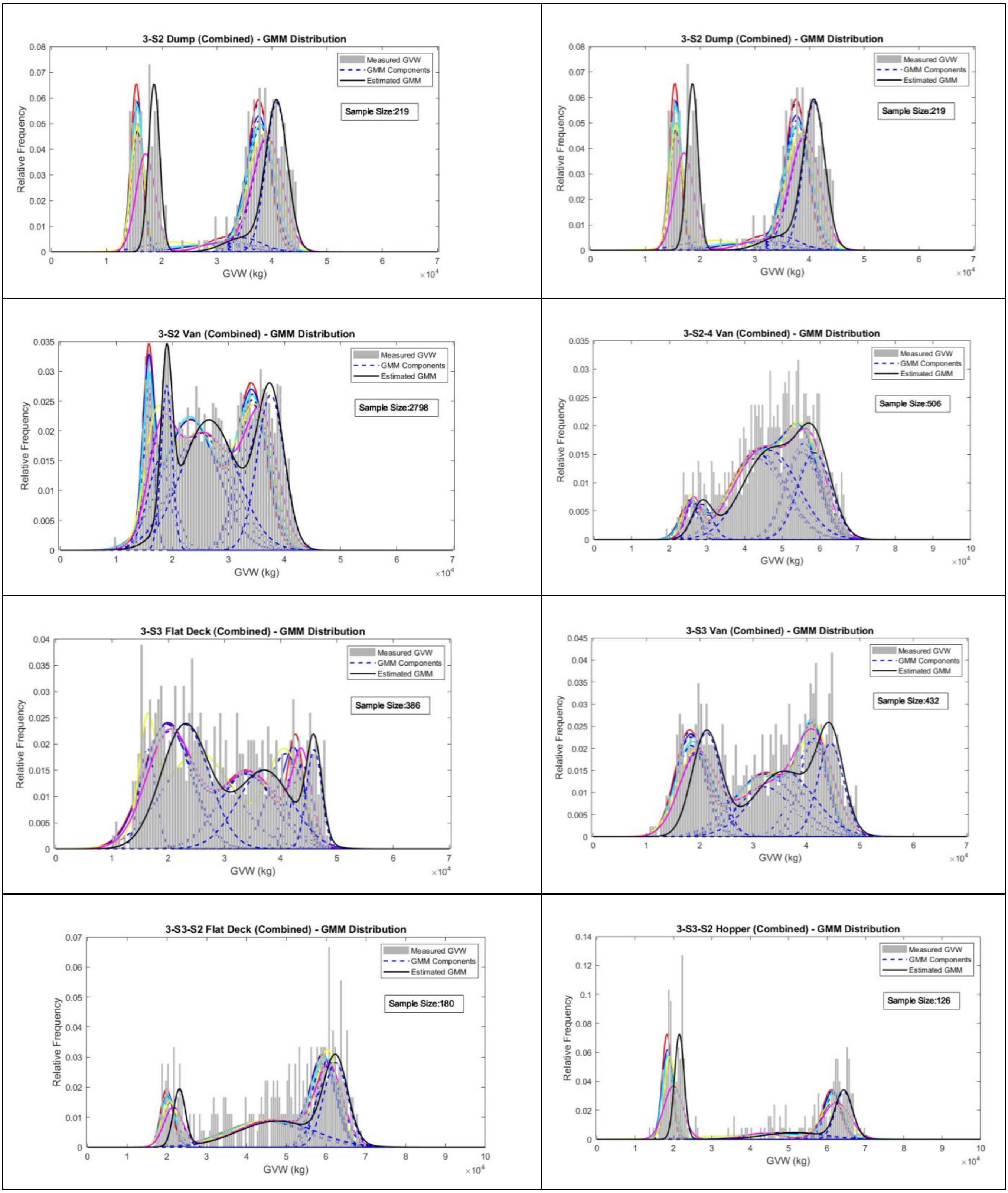

Figure 2 –Combined GMM Distribution with different penetration rates and corresponding rates of non-compliance for 3-S2 Dump, 3-S2 Hopper, 3-S2 Van, 3-S3 and 3-S2-4 configurations for Flat Decks and Hoppers.

Table 5 – Compliance for different truck scenarios at varying levels of penetration

Truck-body type pair	% truck observations not complying with GVW limit											
	No additional weight allowance (wt limit- 40,000kg)				Additional allowance of 1,500kg (wt limit – 41,500kg)				Additional allowance of 4,000kg (wt limit – 44,000kg)			
	Base	30% ET	50% ET	100% ET	Base	30% ET	50% ET	100% ET	Base	30% ET	50% ET	100% ET
3-S2 Dump	7.8%	16.9%	23.3%	37.4%	0.4	7.8%	12.8%	21.9%	-	1.8%	2.3%	3.2%
3-S2 Hopper	-	-	-	-	-	-	-	-	-	-	-	-
3-S2 Van	0.2%	1.8%	2.7%	5.1%	-	0.4%	0.6%	1.4%	-	-	-	0.1%
3-S2 Flat Deck	0.2%	1.2%	1.41%	3.76%	0%	0%	0.7%	1.41%	-	-	-	-
Weighted Sum	0.6%	2.5%	3.7%	6.7%	0.05%	0.8%	1.3%	2.6%	-	0.1%	0.1%	0.3%
Weighted Sum	0.6%	2.5%	3.7%	6.7%	0.05%	0.8%	1.3%	2.6%	-	0.1%	0.1%	0.3%
3-S3 Container	-	-	-	-	-	-	-	-	-	-	-	-
3-S3 Van	-	1.6%	2.8%	4.6%	-	0.5%	0.9%	2.1%	-	-	-	-
3-S3 Flat Deck	-	0.3%	0.8%	4.2%	-	-	-	0.3%	-	-	-	-
Weighted Sum	-	1.0%	1.8%	3.9%	-	0.2%	0.5%	1.2%	-	-	-	-
3-S3-S2 Hopper	3.2%	12.7%	17.4%	26.2%	0.8%	6.3%	11.9%	19.8%	-	1.6%	1.6%	1.6%
3-S3-S2 Flat Deck	2.8%	6.7%	11.7%	20%	1.11%	1.7%	4.4%	10%	-	-	0.6%	2.2%
3-S2-4 Van	0.6%	1.6%	2.8%	5.3%	-	0.9%	1.6%	3.2%	-	0.2%	0.2%	0.2%
Weighted Sum	1.5%	4.4%	7.0%	11.8%	0.3%	1.9%	3.8%	7.3%	-	0.4%	0.5%	0.9%

5. Discussion & Conclusion

The series of GMM distributions presented in this study underscores the complex interplay between truck configurations, battery weights, and regulatory compliance. Across various truck body types and configurations, the introduction of BETs reveals distinct shifts in GVW distributions, as indicated by the spread and shape of the curves. The data demonstrate that as battery weights increase, GVW distributions increasingly deviate from the static limits, particularly for configurations with higher tare weights. This shift suggests that without appropriate regulatory adjustments, a significant portion of trucks would face productivity losses owing to reduced payload capacity. From a policy perspective, these findings highlight the necessity for tailored weight allowances that consider the specific characteristics of different truck types, ensuring that the transition to BETs does not unduly compromise payload capacity or fleet productivity. Additionally, the nuanced differences in how each truck type responds to added battery weight suggest that a one-size-fits-all approach to regulation may be insufficient. Instead, adaptive policies that provide flexible weight allowances or incentives for lighter, higher energy density battery technologies could better align with both the operational realities of the trucking industry and the broader goals of emissions reduction. We summarize the main takeaways in the following points:

- **Economic and Operational Considerations:** From an economic and operational perspective, companies are unlikely to simply exceed GVW limits. Instead, in the absence of weight allowances, companies that choose to operate a BET may opt to reduce cargo capacity to remain compliant. This reduced cargo capacity impacts productivity for cargo types that would cause a vehicle to "weigh-out" (i.e., loads that would be constrained by the GVW limit). The weighted sum analysis from Table 5 illustrates that even with additional allowances, some truck configurations still face significant productivity losses resulting from compliance. This reduction in cargo capacity translates to decreased operational efficiency, as companies may need to run more trips to transport the same volume of goods, which increases costs. If incentives and allowances do not adequately compensate for this reduced productivity, the economic viability of BET adoption may be compromised.
- **Implications of Practical Nuances:** The practical reality of operating BETs depends on numerous geographic and weather-related variables (e.g., vertical and horizontal alignment, temperature, wind direction and speed). These variables influence the operational range and GVW dynamics of BETs, and present risk factors that trucking companies would consider on a route-by-route basis when making purchasing decisions. Relevant tools (e.g., MapEUR) have been developed to study the influence of these variables on operating range (Levesque et al. 2023), with a particular need to better understand energy consumption of heavy-duty trucks in cold climates. This underscores the importance of improving energy density to reduce battery weight and ensure efficiency in demanding operational environments. However, the energy density improvements and any resulting reductions in battery weight might not fully address the issue, as trucks operating in such challenging conditions may require larger, heavier batteries to maintain range and power, potentially exacerbating GVW compliance issues.
- **Industry Adaptation and Regulatory Implications:** The data suggests that rather than all companies adhering to a uniform compliance strategy, there might be a shift towards higher allowable limits by transitioning to configurations such as 3-S3s from 3-S2s. This shift would allow companies to accommodate the additional weight without sacrificing payload, though it may also lead to increased wear and tear on infrastructure, particularly in regions with weaker subgrades. In a previous study, it was shown that these sorts of shifts require a

lag time (up to 8 years) between regulatory changes and when trucking companies take full advantage of a new allowance (Pushka and Regehr 2021).

This study assumes a constant battery weight across truck configurations, which does not reflect potential advancements in battery technology or variations in battery size. Such an assumption could oversimplify the impacts of battery weight on GVW and regulatory compliance. Additionally, while our analysis focuses on GVW, axle load limits—particularly in relation to battery placement and truck configurations—also play a critical role in regulatory compliance and operational feasibility. Future research could explore these aspects to provide a more comprehensive understanding of the implications of BETs for fleet operations and infrastructure management.

From a policy standpoint, as with any regulatory change, future work will be needed to harmonize potential weight incentives amongst provinces/states and across international borders. More broadly, future studies could also consider the holistic economic impacts of incremental battery weight on productivity loss (in the event of down weighting) compared to potentially increased infrastructure repair costs (caused by heavier trucks). Other socio-economic factors, such as the full-cost assessment of emission savings versus charging infrastructure provision, are also worth evaluating.

In conclusion, while BETs represent a critical pathway towards decarbonization, the findings reported in this study underscore the need for nuanced, flexible regulatory approaches that consider the diversity of operational environments and truck configurations. The assumption that incremental increases in battery energy density will solve potential productivity losses arising from increased tare weight overlooks the practical challenges posed by different operational demands. Policymakers must balance the incentives for BET adoption with realistic allowances that prevent a decline in productivity, ensuring that the transition to electric heavy-duty truck fleets is both economically viable and operationally feasible. Without careful consideration of these factors, the industry could face significant disruptions, with potential shifts in fleet configurations and operational strategies that could have broader implications for both the trucking industry and infrastructure management.

6. Acknowledgement

The authors gratefully acknowledge the financial support of Natural Resources Canada through its Zero-Emission Vehicle Awareness Initiative.

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