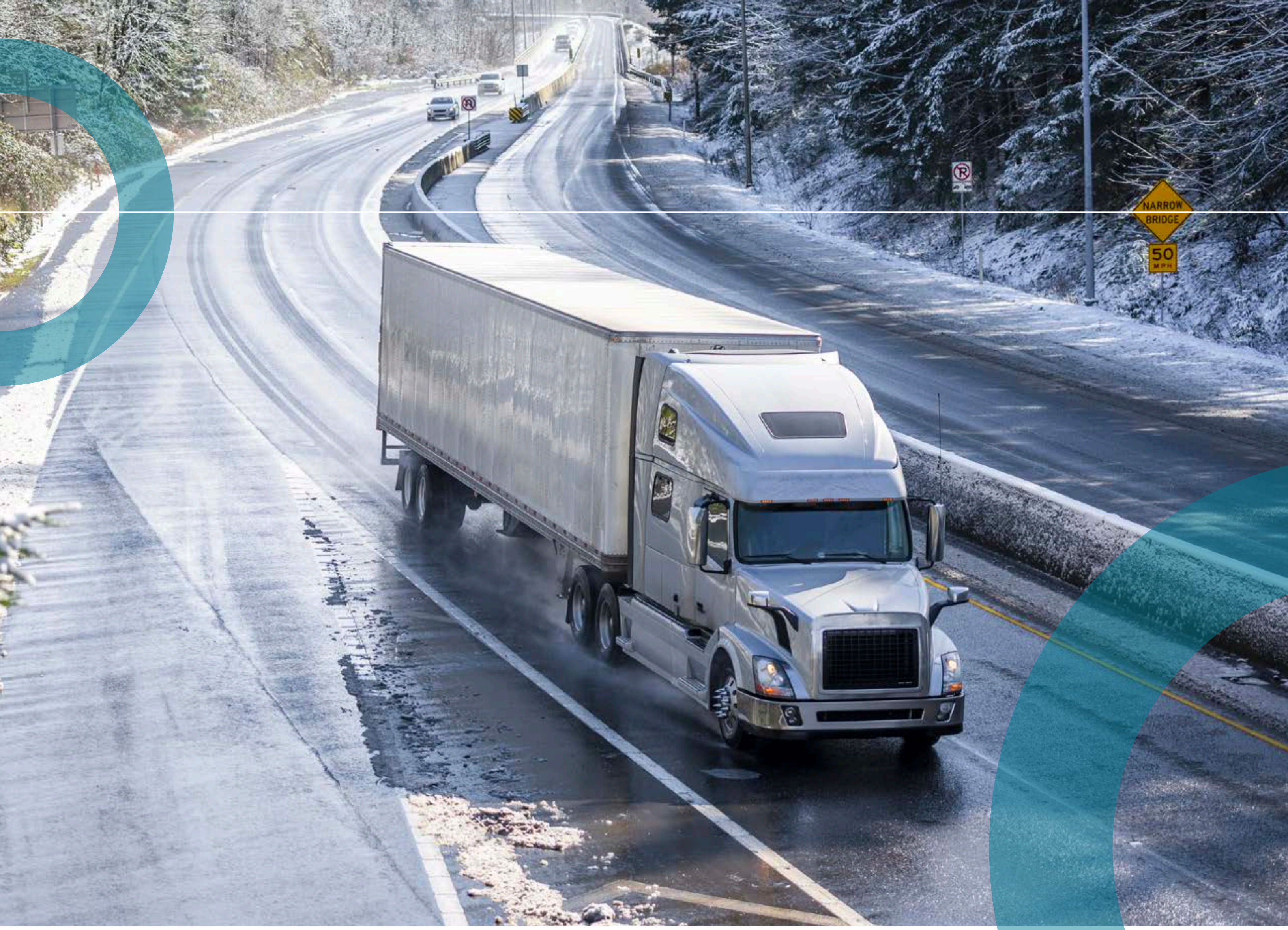


# HEAVY-DUTY EMISSIONS CONTROL TAMPERING IN CANADA

CALEB BRAUN, HUZEIFA BADSHAH, VAHID HOSSEINI, LINGZHI JIN, JOSH MILLER, FELIPE RODRÍGUEZ

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International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

# EXECUTIVE SUMMARY

Emission controls tampering in heavy-duty vehicles can have serious consequences for public health, warranting proactive regulatory action to eliminate such practices.

In this study, we provide a holistic assessment of the issues that motivate and facilitate tampering with the emission control systems of heavy-duty vehicles in Canada. We gained insights into these issues from a legislative perspective, an analysis of the technology vulnerabilities of modern heavy-duty vehicles, the market for tampering devices and services, the views of fleet operators, and the analysis of the excess emissions and health impacts that tampering can have.

While tampering with emission control systems is explicitly prohibited in most Canadian provinces, Alberta being a notable exception, there is a general lack of regulatory means to enforce such prohibition. Currently, inspection and maintenance programs are the only regulatory lever available with some potential to address tampering in Canada. However, these programs—which are only used in British Columbia, Ontario and Québec—focus on identifying issues related to maintenance and are not designed to deter tampering. As a result, our market assessment reveals that several providers exist in Canada which offer the deactivation of emission control systems through, most typically, a combination of hardware removal and re-flashing of the control units. Still, the prevalence of tampering in Canada is not well known, and there are no robust estimates of the prevalence of tampering in heavy-duty vehicles operating in Canada, nor on the impact of tampering on the tailpipe emissions of those vehicles.

Given these knowledge gaps, we used best-available data to develop modeling scenarios that enable us to estimate the impacts on the emissions inventory from heavy-duty vehicles in Canada and the respective health impacts as a function of the prevalence of tampering. In our emissions inventory models, tampering was found to significantly increase emissions from a counterfactual case where no tampering occurs. We find that in the year 2020, each percentage-point increase in the tampering incidence—defined as the fraction of tampered vehicles on the road—increases fleetwide PM and $NO_x$ emissions by 2%–3% (Figure ES 1). Yet in 2040, by which point nearly all vehicles in the fleet should meet US 2010 or later standards, we project that each percentage-point increase in the tampering incidence would increase fleetwide PM emissions by 14%–16% and $NO_x$ by 48%–67%, depending on the province.

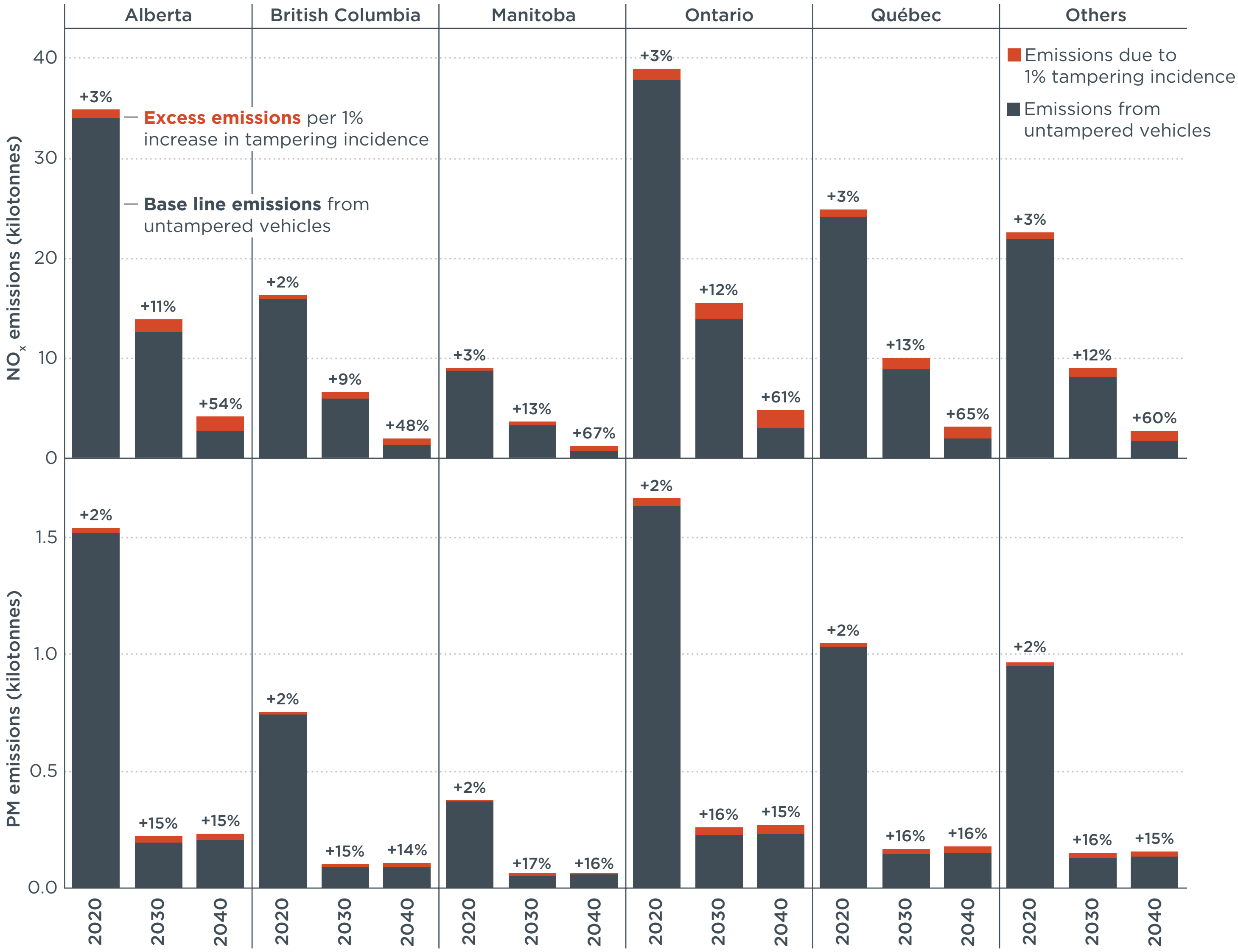


**Figure ES 1.** Tailpipe NOx and PM emissions from medium- and heavy-duty vehicles by province in 2020, 2030, and 2040 (kilotonnes). Dark segments show baseline emissions under a scenario without tampering. Light segments indicate the percent increase in emissions associated with a 1% increase in the number of tampered vehicles on the road.

The health impacts of such disproportionate impacts of tampering on pollutant emissions are substantial. We estimate that excess emissions from tampering can lead to a large number of premature deaths. Compared to the case where no tampering occurs, a tampering incidence of 1% is associated with 690 (330–1,190) excess premature deaths and 11,700 (6,000–19,200) years of life lost over the next 20 years. People over the age of 70 account for 74% of estimated premature deaths, with the main causes being heart disease, chronic obstructive pulmonary disease, and cancer; yet younger people are also at risk and account for 48% of estimated years of life lost. It is also expected that these health impacts will be disproportionately borne by disadvantaged communities living near high-traffic freight corridors.

Public policy can have a crucial role in avoiding such ominous consequences from tampering. The explicit prohibition of tampering at the federal level, combined with adequate market surveillance and persuasive penalties, can serve as a strong deterrent against tampering.

Inspection and maintenance programs with technical designs coherent with modern emission control systems—for example, substituting opacity measurements with particle counting in the evaluation of particle filters—have the potential to be an effective hurdle against tampering. Additional targeted market surveillance activities, such as the combination of remote sensing screening with subsequent roadside inspections, can be an effective measure to identify and penalize tamperers. Furthermore, setting steep financial penalties to those offering such services or products can reduce the supply of tampering devices into the market.

Lastly, technology-forcing regulations that mandate the development and deployment of anti-tampering technologies can increase the technology barrier required to tamper with vehicles. Such technologies include data authentication of emissions control components, anomaly detection through enhanced on-board diagnostics systems, and on-board monitoring and reporting of emissions related data, as already adopted in California and China.

The upcoming next round of federal $NO_x$ regulations in the United States and Canada represents an opportunity to address the tampering issue from technical and in-use testing perspectives. The coordinated action of the aforementioned policy tools has the potential to mitigate the tampering of heavy-duty vehicles.

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# INTRODUCTION

In 2018, heavy-duty diesel vehicles[1] (HDVs) in Canada emitted 260,000 tonnes of nitrogen oxides ($NO_x$) and 9,300 tonnes of particulate matter (PM). There has been a 38% reduction in PM emissions since 1990; however, $NO_x$ emissions have only been reduced by 10% in the same time period (ECCC, 2020). Tailpipe exhaust from diesel trucks contributes significantly to local air pollution in cities across Canada. Recent studies indicate that heavy-duty diesel trucks are the largest contributors to roadside black carbon, a key component of PM, and that a small portion of trucks are responsible for most of the emissions in Canada (Wang et al., 2015, 2018).

Heavy-duty vehicles were responsible for 86% of on-road diesel $NO_x$ emissions globally in 2015 (Anenberg et al., 2017) and 78% of on-road diesel black carbon emissions in 2017, despite accounting for less than a quarter of the diesel vehicle fleet (Miller & Jin, 2018). Other assessments in the United States have also found that high-emitting HDVs can substantially increase fleet-wide emissions (Pan et al., 2019). This disproportionate impact that high emitting HDVs can have on the Canadian emissions inventory warrants a closer look at the emissions and health impacts of tampering. In 2012, the Canadian Council of Ministers of the Environment (CCME) agreed to implement a comprehensive new Air Quality Management System. As part of this initiative, CCME developed a guideline to assist jurisdictions, raise awareness, and increase understanding of environmental and health concerns related to tampering (CCME, 2016).

## WHAT IS TAMPERING?

Pollutant emission standards have been successful in driving the development and deployment of complex emissions control systems to reduce tailpipe pollutant emissions, thus decreasing the environmental and health impacts of HDV exhaust. Pollutant emission standards typically include several provisions to ensure that emission control systems are performing adequately, not only during vehicle certification, but also throughout the vehicle's life.[2] However, such standards regulate manufacturers and do not include sufficient provisions to address the negative emissions impacts that vehicle operators can have through improper maintenance or the purposeful modification of emission control systems.

Tampering, in its broadest definition, is the act of removing or rendering inoperative an emission control component on a certified motor vehicle or engine. CCME's guidelines define tampering as the removal, bypassing, defeating or deactivation of emission control systems or of software designed to monitor or control emissions. The definition also covers the modification of vehicles in any way that results in increased emissions from the level to which it was originally certified to (CCME, 2016).

In the United States, it is illegal to knowingly falsify, tamper with, render inaccurate, or fail to install any emission control component or monitoring device or method; this is legislated under Clean Air Act (U.S. Environmental Protection Agency, 2017). Despite these prohibitions, recent market studies have revealed a significant presence of emission control system tampering in the U.S. heavy-duty diesel fleet (U.S. Environmental Protection Agency, 2020).

1 HDVs are defined as those having a gross vehicle weight rating above 4.5 tonnes

2 Examples of such provisions are the *Manufacturer-Run In-Use Testing Program* and the *Durability Demonstration Program*

In contrast, anti-tampering legislation in several Canadian jurisdictions is either non-existent or lacks enforcement. The extent of this problem, the impacts on pollutant emissions, the possible health impacts of the practice, and the policy avenues to address it need to be studied. Hence, this study sheds light on these topics by assessing the current and future outlook of emissions from diesel vehicles as a result of tampering.

## RESEARCH QUESTIONS

This study aims to provide a comprehensive assessment of the tampering of HDVs in the Canadian context. Specifically, the research seeks to answer the following questions:

1. What is the existing anti-tampering legislation in Canada?
2. What is the prevalence of tampering in the HDV fleet?
3. What are the views and opinions of fleets operating in Canada around tampering?
4. What are the current tampering practices and how vulnerable are HDV emission control systems?
5. How can emission control systems be hardened against tampering?
6. What is the impact of HDV tampering on the Canadian emissions inventory?
7. What are the air quality and health impacts of HDV tampering?
8. What policy interventions are appropriate to address tampering?

Our answers to these questions, in the same order as outlined above, are contained in the following sections.

## LEGISLATIVE BACKGROUND IN CANADA

Tampering can be addressed through a number of regulatory measures, including inspection and maintenance (I/M) programs, emission standards that mandate the adoption of anti-tampering technologies, roadside monitoring, and the prosecution of those engaged in tampering. In Canada, legislation prohibiting tampering and enabling its detection is not centralized at the national level, falling within the jurisdiction of provinces and territories. Anti-tampering legislation in Canada is summarized in Table 1, based on previously published work (D. Cope Enterprises, 2004) and updated with recent information on related Acts in Canadian jurisdictions.

**Table 1**. Anti-tampering legislation in each Canadian province or territory (ordered by population).

| Province or territory | Details | Source |
|---|---|---|
| **Ontario** | Anti-tampering legislation is contained in the Ontario Environmental Protection Act. This legislation was in place prior to the implementation in 1999 of Drive Clean, the province's mandatory I/M program for light- and heavy-duty vehicles. A new vehicle emission regulation under the Environmental Protection Act and amendments to the Vehicle Permits Regulation under the Highway Traffic Act is in effect since January 1, 2020 to clarify and strengthen on-road vehicle emissions requirements and set out rules around the testing of emissions from heavy-diesel commercial vehicles. | (Ontario, 2020) |
| **Québec** | Québec's anti-tampering legislation is enabled by the powers of the Environment Quality Act. The specific provisions for heavy-vehicles are contained in article 7 of the Regulation Respecting Environmental Standards for Heavy Vehicles. This regulation, in effect since 2006, makes it illegal to remove or tamper with emissions control equipment. It is also the basis of the roadside inspection program. The latter is conducted by Contrôle routier Québec (CRQ), a law enforcement agency part of the Ministère des Transports du Québec, with the mandate to enforce these provisions. | (Gouvernement du Québec, 2021) |
| **British Columbia** | British Columbia's Motor Vehicle Act Regulations (B.C. Reg. 26/58) explicitly prohibits the operation of diesel heavy-vehicles that do not meet emission standards. The regulation also enables the enforcement of this tampering prohibition through roadside inspections. Peace officers can stop vehicles for a diesel emission inspection, if there's suspicion to believe the vehicle does not meet the pollutant emission standards. | (British Columbia, 2021) |
| **Alberta** | Alberta's Commercial Vehicle Inspection Program (CVIP) requires commercial trucks above 11,794 kg to have an annual safety inspection, but it does not include a check of emissions control equipment. Alberta's Traffic Safety Act and its regulations do not prohibit tampering with the emission control systems. | (Alberta, 2021) |
| **Manitoba** | At present, there is no specific emission control equipment and anti-tampering in the Manitoba Highway Traffic Act (C.C.S.M. c. H60). | (Manitoba, 2019) |
| **Saskatchewan** | There is no in-use vehicle, emissions control system, or anti-tampering legislation in Saskatchewan. While the Saskatchewan government does have a safety check for imported vehicles, it does not include a check of emissions control equipment. In 2016, Saskatchewan adopted National Safety Code Standard 11 into regulations that requires all heavy vehicles to meet emission control systems and devices in accordance with that standard. | (Saskatchewan, 2004, 2016) |
| **Nova Scotia** | In Nova Scotia, anti-tampering legislation is under the Motor Vehicles Act and is the responsibility of Service Nova Scotia and Municipal Relations. The anti-tampering clause is under the Standards of Vehicle Equipment Regulations made under Section 200 of the Motor Vehicle Act R.S.N.S. 1989, c. 293 O.I.C. 85-216 (March 12, 1985), N.S. Reg. 51/85 as amended up to and including O.I.C. 97-752 (Dec. 2, 1997), N.S. Reg. 165/97 and prohibits any exhaust tampering. | (Nova Scotia, 1997) |
| **New Brunswick** | Under their Motor Vehicle Act, New Brunswick has legislation for the inspection of vehicles that is related to tampering with emissions control systems. Changing the muffler or exhaust pipe is prohibited under the Motor Vehicle Act, RSNB 1973, c M-17 act. | (New Brunswick, 1996) |
| **Newfoundland and Labrador** | The Highway Traffic Act, Licensing and Equipment Regulations contain anti-tampering provisions. Enforcement of anti-tampering is the responsibility of the Government Services and Lands Department. The province has a mandatory, annual safety inspection for commercial HDVs.<br><br>Consolidated Newfoundland and Labrador regulation 100/96 under Licensing and Equipment Regulations of the Highway Traffic Act (O.C. 96-211) prohibits any alteration of the vehicle exhaust system. | (Newfoundland and Labrador, Canada, 2015) |
| **Prince Edward Island** | Provincial legislation contains an anti-tampering provision related to the presence of the catalytic converter. The province requires both light- and heavy-duty vehicles to undergo an annual inspection. The regulation governing those inspections states that the catalytic converter is one of the components to be inspected annually. The current annual vehicle inspection for renewal of the license plate only covers safety and mechanical parts. | (Prince Edward Island, 2018) |
| **Northwest Territories** | There is no current or proposed anti-tampering legislation in the territories. | |
| **Yukon** | Air Emission Regulations were developed in 1998 and, because of requests to develop controls for in-use vehicles, an anti-tampering clause was included. The clause is in Air Emissions Regulations, YOIC 1998/207. | (Yukon, 2015) |
| **Nunavut** | There is no current or proposed anti-tampering legislation in the territories. | |

Currently, the only regulatory levers with some potential to deter tampering in Canada are limited to I/M programs and the few anti-tampering policies shown in Table 1. Most of the legal provisions aimed at ensuring adequate in-use performance of HDVs have manufacturers as the regulated entity. The regulations include the on-road demonstration at certification, conformity of production testing, and market surveillance activities, among others. Inspection and maintenance programs are fundamentally different, as the regulated entity is not the vehicle manufacturer but the owner and operator of the vehicle. As such, I/M programs provide an existing regulatory framework to develop further anti-tampering provisions. Still, these programs focus on identifying issues related to maintenance and are not explicitly designed to identify and deter tampering. These limitations are best exemplified by the lack of $NO_x$ measurements in I/M programs and the use of opacity measurements for identifying faults in the particle control systems, a technique that is not sensitive enough for modern vehicles.[3] The different instances where vehicle emissions can be measured are shown in Figure 1.

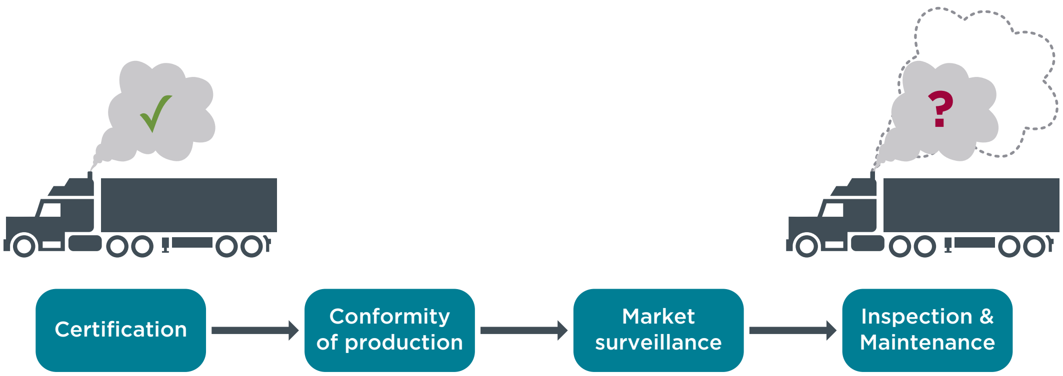


**Figure 1.** Emission control steps from type approval to the conformity of production, market surveillance, emission inspection.

Existing I/M programs in Canada are not run by the federal government and lie within the jurisdiction of individual provinces and territories. Only British Columbia, Ontario and Québec have emissions testing for HDVs as part of I/M programs. The Drive Clean program in Ontario, started in 1999, requires HDVs to have an emission test for exhaust opacity. In British Columbia, the AirCare program, started in 1992 with additional improvement in 1999 (AirCare II), requires that only trucks with visible smoke need to perform a free acceleration smoke test. The AirCare On-Road program (ACOR), which implements random testing of trucks, measures the smoke of HDVs with visible black exhaust. Loaded chassis dynamometer testing is also part of both Drive Clean and AirCare programs. In Québec, the program includes free acceleration smoke testing of trucks with visible smoke.

3 In response to these limitations, Netherlands, Belgium and Germany are implementing the use of particulate number counting instruments for inspection and maintenance programs. There are able to detect particulate filter removal/tampering or other DPF malfunctions.

# LITERATURE REVIEW

It is challenging to identify tampered exhaust systems in newer vehicles because, even with the tampered particle control systems, the dynamic combustion control eliminates most visible smoke and large particles. Vehicle inspection needs to be done by an expert eye as emulators, closed EGR valves, or SCR catalysts removed without removing the housing requires technical training to detect the alteration.

Techniques such as random roadside emission inspection, remote sensing with optical or extractive sampling measurement, and plume chasing are often used to identify high-emitting vehicles. Plume chasing is a method in which emission sampling probes are performed by a mobile laboratory driven in the normal traffic flow to collect emissions data from the exhaust fumes of target vehicles. Remote sensing is done using roadside emission measurement devices in a fixed location at the sides of the road while a large sample size of vehicles passes through the test section (Bernard et al., 2019).

## STUDIES OF HIGH EMITTING VEHICLES IN CANADA

A number of studies in Canada have focused on identifying high-emitting vehicles, which can exhibit high emissions as a consequence of poor maintenance or failures and do not necessarily have tampered emission control systems.

In Alberta, a study was conducted in two parts (1999 and 2006) by the Clean Air Strategic Alliance of Alberta using remote sensing methods. The survey found 5% of the fleet classified as high emitters based on one or more of HC, CO, $NO_x$, or smoke emissions.[4] In addition, 20% of the light-duty fleet was found to be responsible for 80% of emissions (ESP & McClintock, 2007).

Another remote sensing study, conducted in 2012 in Vancouver, British Columbia, found that 26% of the over 6,000 heavy-duty vehicles measured were high emitters, contributing 42% of the PM and 38% of the $NO_x$ emissions from the vehicles tested. The study established that 8% to 26% of vehicles can be categorized as high emitters (Envirotest Canada, 2013).

## ESTIMATION OF EXHAUST TAMPERING IN THE UNITED STATES

In 2020, the Air Enforcement Division of the U.S. Environmental Protection Agency (U.S. EPA) released a study quantifying the prevalence of tampering in Class 2b and Class 3 diesel pickups—those weighing between 3,856 and 6,350 kg. The study found that more than half a million diesel pickup trucks have had emissions controls removed within the last decade (U.S. Environmental Protection Agency, 2020). In the United States, this corresponds to approximately 15% of Class 2b and 3 diesel trucks newer than model year 2003.

The study also provided estimates on the level of emissions increase when the emission control system is removed in these vehicles:

- $NO_x$ increased by 30 to 300 times
- Non-methane hydrocarbons (NMHC) increased by over three orders of magnitude

4 The identification of a vehicle as high emitter using remote sensing depends on the selection of cut-points in grams of pollutant emissions per kilogram of fuel consumed, or per kilogram of $CO_2$. The selection of these cut-points depends on the emissions standards the vehicles are certified to and vary across the different remote sensing studies,

- Carbon monoxide (CO) increased by over two orders of magnitude
- PM increased by 15 to 40 times

U.S. EPA estimated that 570,000 tons of $NO_x$ and 5,000 of PM will be emitted by tampered with medium-duty diesel pickup trucks over their lifetime, which is the equivalent to adding more than 9 million additional well-functioning diesel pickup trucks to the on-road fleet.

The U.S. EPA study also provides further insight into the total number of diesel pickup trucks in the United States with tampered emission controls by model year and state. For the 2016 on-road fleet, the study estimates the tampering prevalence to be 15% among vehicles that are 2003 model year or newer. The highest tampering incidence is observed in North Dakota at 18.6%, followed by Idaho at 15.0% and Wyoming at 14.0%. The lowest incidence was obveserved in California at 1.8% and New Jersey at 5.6%. The study does not provide further examination on the regulatory differences that led to the wide range of tampering incidences observed in the different states.

## ESTIMATION OF EXHAUST TAMPERING IN EUROPE

A study conducted by AVL for the Danish Road Traffic Authority showed the plume chasing method's validity to identify high emitters and tampered exhaust systems (Janssen, 2020). Using this technique, researchers in Germany (Pöhler & Engel, 2018) measured the real-world driving emissions of 185 trucks to identify high emitters and emissions control systems that were possibly tampered with. Overall, 27% of trucks have higher $NO_x$ emissions over the Euro V and Euro VI limits. Specifically, 35% of Euro V trucks (16 out of 46) and 25% of Euro VI trucks (34 out of 136) measured were over the $NO_x$ tolerance limits.

A similar study which measured 284 trucks on German, Austrian, and Slovakian highways using plume chasing (Annen & Helmerich, 2020) showed that 50% of Euro V and 43% of Euro VI trucks exceeded the tolerance limits of the study for $NO_x$ emissions. The authors estimated that entire truck fleet $NO_x$ emissions were doubled compared to emission regulations limits. No subsequent validation was performed to determine the actual percentage of high-emitting vehicles had exhaust systems that were tampered with.

A plume chasing study on a Czech motorway (Vojtisek-Lom et al., 2020) measured the NOx emissions of a total of 222 unique, mostly Euro VI and Euro V trucks. About 10%–15% of Euro V and about 10%–25% of Euro VI trucks were identified as high emitters, with no SCR functionality on about 10%–15% of Euro VI trucks.

Using remote sensing, a study in Scotland (Hager Environmental & Atmospheric Technologies, 2017) showed that vehicles certified to Euro VI exhibited four to five times higher emissions than the limit values. The study reported that 8% of the close to 6,000 readings from heavy-duty diesel trucks were identified as high emitters.

In Denmark, an assessment of 874 trucks using remote sensing (Ellermann et al., 2018) found that the fraction of high-emitting vehicles differs according to the country of origin, with emissions from the non-Danish Euro V and VI heavy-duty vehicles reported to be 50% and 31% higher than the Danish heavy-duty vehicles, respectively. Still, the fraction of trucks with tampered SCR systems was estimated to be less than 25%. A separate Danish study found that 10% of the fleet were estimated to have malfunctioning SCR systems (Hertel et al., 2020).

In 2017, enforcement teams of the Driver and Vehicle Standards Agency (DVSA) of the UK Department for Transport inspected 2,900 lorries on strategic routes issuing 238 prohibition notices. One in twelve lorries checked by DVSA examiners were fitted with tampering devices (Department for Transport, 2018).

Table 2 shows a summary of studies reviewed in Europe.

**Table 2**. Summary of literature review of high-emitter HDVs in Europe

| High emitter incidence | Region | Technique | Source |
|---|---|---|---|
| **25% - 35%** | Germany | Plume chasing | Pöhler and Engel (2018) |
| **43% - 50%** | Germany, Austria, Slovakia | Plume chasing | Annen and Helmerich (2020) |
| **10% - 25%** | Czech Republic | Plume chasing | Vojtisek-Lom et al. (2020) |
| **8%** | Scotland | Remote sensing | Hager Environmental & Atmospheric Technologies (2017) |
| **Up to 25%** | Denmark | Remote sensing | Ellermann et al. (2018) |
| **15%** | Spain | Remote sensing | Opus RSE (2019) |
| **10%** | Denmark | Remote sensing | Hertel et al. (2020) |
| **8.2%** | United Kingdom | Roadside inspection | Department for Transport (2018) |

## HDV EMISSION CONTROL SYSTEMS: AN OVERVIEW

The power output for a diesel engine is controlled by the amount of fuel injected, therefore, the engine draws air unthrottled. An overall lean air-fuel ratio, high compression ratio, and high volumetric efficiency due to the lack of an air throttle valve give diesel engines a torque advantage in heavy-duty applications. However, the nature of the diesel combustion process causes high $NO_x$ formation in high-temperature regions of the cylinder and diesel soot in areas with oxygen deficiency due to challenges in air-fuel mixing.

Advances in engine design have led to many in-cylinder measures to minimize the formation of pollutants and thereby reduce engine-out emissions. Parameters such as temperature, speed of combustion, fuel delivery timing, and chemical composition of the air/fuel mix entering the combustion chamber directly influence the combustion process. Fuel injection, air handling, and exhaust gas recirculation (EGR) strategies are traditionally implemented and calibrated to achieve an optimal balance of power, fuel economy, and emissions. The engine control module stores these calibration settings and ensures appropriate operation over a variety of operating conditions. However, the $NO_x$-PM trade-off, where measures to lower the formation of $NO_x$ lead to an increase in particulate formation, imposes a limit on how far both emissions can be reduced by enhancing and controlling combustion. The use of emission control systems is required to reduce both $NO_x$ and soot emissions simultaneously.

Figure 2 shows the challenges of simultaneously reducing $NO_x$ and PM emissions under the previous, current, and possible future pollutant emission standards for HDVs in the United States and Canada. The significant emissions reduction mandated from 1998 ($NO_x$ at 4.0 g/bhp-hr and PM at 0.1 g/bhp-hr) to 2010 ($NO_x$ at 0.2 g/bhp-hr and PM at 0.01 g/bhp-hr) is shown in Figure 2. The $NO_x$-PM trade-off line shows an indicative example of the engine raw emission behavior and the role of combustion control technologies and emission control systems to break-down the trade-off and reduce emissions close to zero.

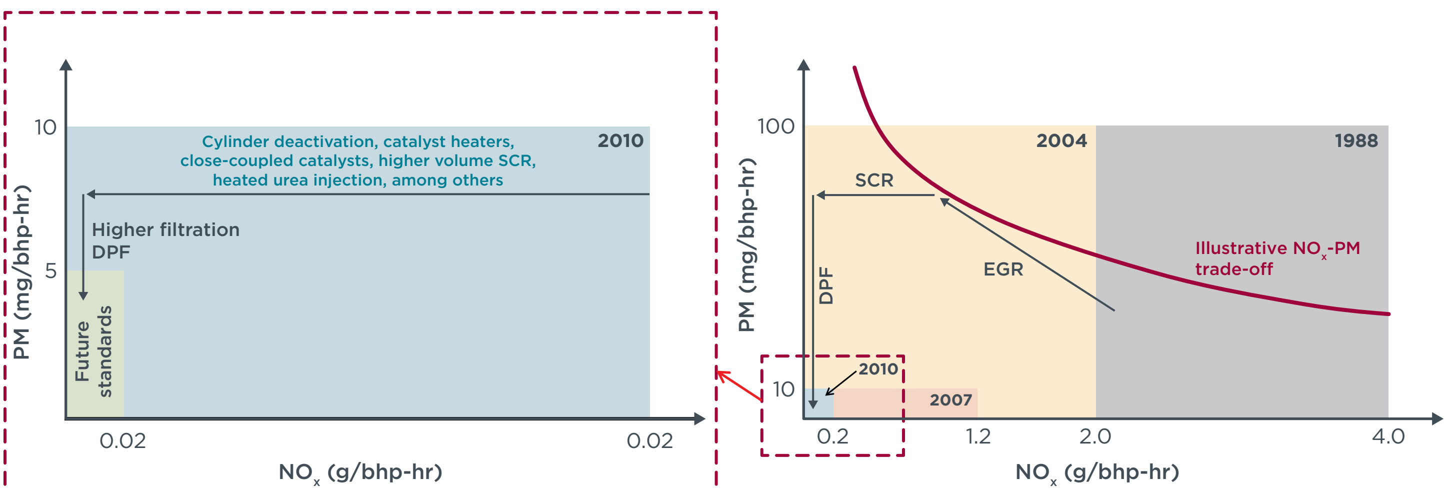


**Figure 2.** Emission limits for on-road heavy-duty diesel trucks based on U.S. EPA and Canada indicating possible paths of achieving certification levels using emission control technologies

Given that modern engine calibration seeks to optimize fuel efficiency at the cost of higher engine-out $NO_x$ emissions, diesel vehicles rely heavily on effective aftertreatment systems to comply with tailpipe emission standards. Therefore, a modern diesel truck with an aftertreatment system that has been removed or tampered with emits substantially more than a truck that was originally calibrated without any aftertreatment.

The following paragraphs present an overview of the working principles of different emission control technologies to enable the understanding of the effects of tampering on pollutant emissions.

### Fuel injection

The main function of the fuel injection system is to provide diesel fuel to the engine's cylinders, but how and when this fuel gets delivered directly impacts the engine's performance and emissions. For example, advancing an engine's timing via changes to the calibration settings causes the injection process to occur earlier, potentially leading to higher fuel economy at the expense of higher engine-out $NO_x$ emissions and noise. In addition, in modern HDV diesel engines, common-rail fuel injection enables multiple injections per cycle to better control the combustion process.

### Exhaust gas recirculation

An exhaust gas recirculation (EGR) system provides inert diluent to the air intake system by recirculating a portion of the exhaust gas back to the engine's cylinders. This prevents the formation of $NO_x$ by increasing the thermal mass of the mixture, reducing the combustion speed and ultimately lowering peak combustion temperature within the cylinder. However, this generally results in higher PM formation due to the reduced oxygen availability. Coolers are often part of EGR systems to further help in temperature control while increasing air density for improved power and emission performance. This packaged recirculation system is the most widely used technology for diesel-powered engines today for in-cylinder $NO_x$ control. The rate or fraction of exhaust being recirculated in the total intake charge is controlled according to the engine operation condition, varying anywhere from zero to 50% of the incoming air. However, the EGR rate control valves and EGR coolers are prone to soot deposits and require periodic cleaning and maintenance.

### Diesel oxidation catalysts

Diesel oxidation catalysts (DOCs) control the soluble organic PM fraction and reduce HC and CO emissions. In addition, DOCs also oxidize NO, increasing the $NO_2$ content of the exhaust gas to support the performance of SCR catalysts and the passive regeneration of diesel particulate filters.

### Diesel particulate filters

Diesel particulate filters (DPFs) control soot by physically capturing diesel particulates of 20 nm to 300 nm with more than 99% filtration efficiency. In addition, DPFs also reduce other non-criteria pollutants such as polycyclic aromatic hydrocarbons and formaldehyde, ash produced by oil burning, and engine wear metals. After a certain amount of particle accumulation, DPFs regenerate to avoid excessive backpressure on the engine. Passive or active thermal regeneration is often employed to oxidize the soot particulates to gaseous products, restoring the DPFs soot collection capacity.

Reliance on passive regeneration implementation is critical in catalyzed DPFs, which require the presence of $NO_2$. Regeneration rates with oxygen occur at high exhaust temperatures of around 550°C. On the other hand, $NO_2$ regeneration can occur at much lower temperatures of around 350°C. This event, termed as passive regeneration, is critical in cold temperature as well as prolonged idling conditions where high exhaust temperatures are not typically achieved.

### Selective catalytic reduction

Selective catalytic reduction (SCR) is a technique for reducing $NO_x$ via injection of a reducing solution known as diesel exhaust fluid (DEF) directly in the exhaust stream. At appropriate temperatures, usually greater than 200°C, urea is converted to ammonia which then serves as a reducing agent in the SCR catalyst converting $NO_x$ into nitrogen and water. This requires very precise DEF dosing control to maximize $NO_x$ conversion while avoiding excess ammonia emissions. Ammonia slip catalysts control the amount of ammonia being emitted by oxidizing ammonia, a precursor to secondary particle formation, downstream of the SCR catalyst.

# CURRENT TAMPERING PRACTICES

## WHAT IS THE MOTIVATION FOR TAMPERING?

Tightened pollutant emission standards have resulted in the deployment of effective emission control systems that feature a large number of components, as presented in the previous section. Although these systems have been optimized to comply with the regulatory requirements for pollutant emissions while mitigating any adverse effects on fuel economy or power, proper and timely maintenance are required for optimal operation.

Perverse incentives, however, can lead fleets and truck owners to remove or modify these emission control systems. Despite the vast societal benefits of these systems, individual vehicle operators can see immediate benefits from this practice, such as savings in operational and maintenance cost, reducing downtime, and increasing engine power or fuel economy. These are described in more detail in Table 3.

**Table 3.** Motivations for tampering.

| | |
|---|---|
| **Operational cost savings** | The deactivation or removal of the SCR system eliminates the use of DEF, which at a typical consumption rate represents an annual cost savings of between CA$ 1,500 and CA$ 3,000. |
| **Decreased maintenance and downtime** | The ash accumulation in the DPF which does not burn during regeneration, needs to be cleaned at regular intervals of approximately 200,000 km. However, extended idling for the thermal management of the cabin, as is common in Canada, reduces this maintenance interval.<br><br>Over time, particularly in extreme cold temperatures, the DEF can crystalize in the exhaust system, causing blockages in the injection nozzle, filters, pumps, and on the SCR system. To avoid it, proper and continuous maintenance of the tanks, heaters, and nozzles is required. |
| **Decreased fuel consumption** | EGR systems, required to lower the engine out $NO_x$, can have a negative impact on fuel consumption. Similarly, DPFs can have negative consequences for fuel consumption due to the periodic regeneration and backpressure they generate on the exhaust. In modern engines, these negative effects are minimized through the careful calibration of the engine and a heavier reliance on SCR systems, which do not have adverse effects on fuel consumption. |

## HOW ARE THE SYSTEMS VULNERABLE TO TAMPERING?

Each of the emission control systems introduced in the prior section are vulnerable to tampering. In this section, we provide possible paths for tampering to occur and some of the possible advantages and disadvantages for each. Table 4 and Figure 3 provide a summary of the individual emission control components that are vulnerable to tampering.

**Table 4.** Tampering practices, associated changes, and related emission impacts

| Tampering practice | Associated hardware change | Associated software change | Emissions impact |
|---|---|---|---|
| **SCR removal** | SCR filter and DEF injection system including pumps, lines, and injector are removed. It is replaced by an empty pipe. Alternatively, a large bore hole is drilled in the filter substrate. | Engine control module and OBD calibration is required. Not having SCR, all signals to the engine control module are disrupted and OBD functionality results in engine malfunction indicator light to be active. This is purposefully disabled by software changes. | $NO_x$ increase |
| **DPF removal** | Complete removal of DPF from exhaust and replacement with an empty pipe | Change of engine control module calibration and OBD | PM increase |
| **EGR blocking** | Block-off plates to physically block the EGR ports on the intake manifold | Alter expected valve position for optimized performance and emissions. | $NO_x$ increase |
| **Tuning of engine control units** | May involve accompanying hardware changes or removal | Modify emission control systems: disable sensors, injection timing, EGR targets, rail pressure, etc. | $NO_x$ or PM increase |
| **Exhaust temperature sensor insert** | Insertion of a spacer between the exhaust and the sensor such that the measured temperature is lower and DEF injection is halted by engine control module. | No change in ECU software is required. Incorrect temperature sensing results in reduced or no DEF injection. | $NO_x$ increase |
| **Urea emulator installation** | Urea emulator is installed on the vehicle providing false signals to engine control module. | No change in engine control module or OBD is required. The emulator mimics signals to the engine control module, pretending the proper operation of the SCR. Also overrides $NO_x$ sensor and exhaust temperature feedback. | $NO_x$ increase |

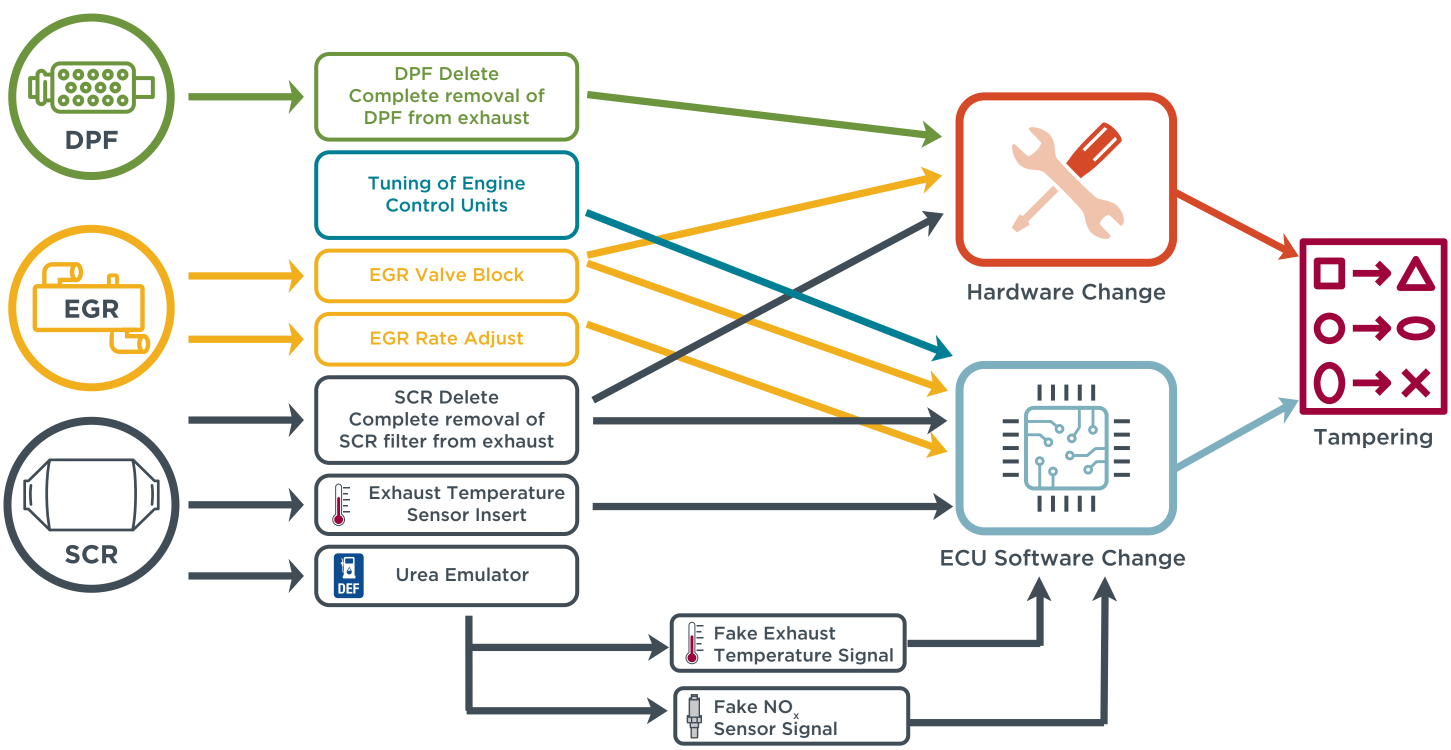


**Figure 3.** Schematic representation of possible tampering approaches.

Tampering can take the form of software modifications, hardware removals, or a combination of both. The sections below provide further insight into the different tampering techniques and the associated emission control components.

### Tuning of engine control units

The software approach most commonly targets the engine control module, whereby the current engine calibration is "tuned" for positive fuel consumption and/or power in lieu of higher regulated pollutant emissions. Tuning can also alter the functioning emission control systems or render them useless. The OBD system, which consists of sensors designed to detect, record, and report malfunctions of all monitored emission-related powertrain systems or components are the main target of any software-based tampering. On the other hand, almost all hardware controls in modern heavy-duty diesel engines are integrated via the engine control module and monitored by the OBD system. Therefore, it is a necessary step to also modify the engine control module to allow for any physical or operational hardware changes. Modifying the original manufacturer configurations and operation settings that are stored in the engine control module are illegal in many countries.

Those choosing to only modify the injection timing to increase in power or improve fuel economy can attempt a re-flashing of the engine control unit. An advanced injection event leads to higher peak cylinder pressure and temperature. Conversely, the time spent during the expansion stroke is hereby increased as well, allowing for higher rates of cooling and leading to lower exhaust temperatures. However, the higher in-cylinder combustion temperatures cause high $NO_x$ emissions and the low exhaust temperatures leads to inefficient operation of aftertreatment systems.

### Tampering of SCR systems

The main components of an SCR system are a metering module to control the amount of urea delivered, an injector for urea injection into the exhaust, appropriate urea lines, and sensors for measuring $NO_x$ and temperature. Most SCR systems are based on a closed loop sensor-based strategy, where two $NO_x$ sensors (one upstream and another downstream of the SCR) are used. As such, this enables the determination of a setpoint that can always be measured in real-time, leading to precise control of urea injection. This control strategy is programmed in the engine control module and the urea control unit. Due to the complex nature of this system, SCR systems maintenance can lead to significant down-time and costs.

The individual components of the SCR system all work in unison; therefore, each input and output from the various sensors and devices are needed for its operation. It is difficult to "tamper" with any one individual component without triggering a malfunction indication in the OBD system. For this reason, the most preferred routes to tamper with the SCR systems is to either install a urea emulator or remove the entire system from the aftertreatment altogether.

Deletion of the SCR system involves the removal of the SCR catalyst and the DEF injection components from the aftertreatment system, and replacing them with an empty canister or a straight pipe. This practice is accompanied by an extensive tune that deletes the SCR, DEF injection, $NO_x$ sensor, and temperature control logic from the engine control module.

An SCR can also be tampered with through DEF emulators without the removal of any component. These external devices are designed to override the controls of the original on-board SCR system and are usually installed in the junction box under the hood on the driver's side of the truck. The main function of the emulator is to imitate the work of the SCR system for the engine control module and the OBD system. By disabling the actual SCR system and still sending active data to the engine control module, the device makes the engine control module think that the SCR is functioning according to its intended purpose. The emulator also overrides exhaust temperature and $NO_x$ sensor feedback, which is necessary for closed-loop urea control. The emulator renders the SCR useless, as the catalytic activity is suppressed due to the absence of the reacting agent, DEF. As such, the engine is able to operate at its usual settings, but emits significantly higher amount of $NO_x$, comparable to engine out $NO_x$ levels.

Another set of important parameters directly affecting the efficiency of $NO_x$ conversion are the temperatures of the various components of the SCR system. Catalytic conversion of $NO_x$ decreases at low temperatures; therefore, urea dosing must also be reduced to prevent high emissions of ammonia. In a functioning aftertreatment system, this is controlled by an upstream temperature sensor. This feature is especially critical in vehicles that frequently operate in low temperatures. The low temperature limit for urea dosing is set by fouling considerations, where crystallization of solid urea and byproducts of uncomplete urea decomposition occur. The temperature cut-off point is typically 200 °C–250°C. Although this is sufficient for regulatory type test, events such as low speed/low load operation as well as cold temperature operation can severely impact optimal SCR performance. The upstream temperature sensor that controls urea dosing is also prone to tampering. Temperature spacers are another avenue to "trick" the aftertreatment engine control module. By inserting the spacer, there is a reduction in the measured temperature. Depending on the spacer's length, the temperature threshold for urea injection is delayed or not reached at all during operation. This practice is a passive form of tampering, since it requires no electricity/power, can be readily manufactured, and easily installed.

### Tampering of particle control systems

The principal purpose of the DPF is to remove soot from the exhaust stream. Generally, the only sensors employed on the DPF are for temperature and PM and/or differential pressure. Due to soot accumulation, a filter must regenerate either passively or actively during a defined period. Feedback from the PM sensor identifying high soot levels downstream of the DPF or a high-pressure delta across the DPF are signs that it must regenerate. Once this is registered in the engine control module, the regeneration cycle is actively triggered, and the temperature of the exhaust is raised via a secondary fuel injection before the filter. This additional fuel injection results in lower fuel economy and thus increases the motivation for tampering. The complete removal of DPFs from the aftertreatment path allows for a decrease in system backpressure, higher power gains, and a better fuel economy.

### Tampering of the exhaust gas recirculation system

Modified software can alter the expected valve position that was optimized for performance and emissions. Lowering the amount of EGR can be achieved via changes in the EGR valve position. Deleting the EGR altogether is usually accomplished via plates that physically block the EGR port on the intake manifold. By blocking any exhaust re-entry into the intake, the charge is undiluted and free of particulates, making combustion faster and more powerful where higher in-cylinder temperatures and pressures are achieved. This practice directly leads to a boost in engine power in lieu of higher $NO_x$ production and lower particulate formation. The lower PM levels mean there is less accumulation on the DPF which may reduce the number of regeneration events, further helping with fuel economy. While the increases in power and fuel economy sound very promising to any truck owner, the high in-cylinder temperature also translates to low exhaust temperatures and higher $NO_x$ emissions. A reduced or no EGR flow can also lead to a higher intake air flow for the same in-cylinder air target, thereby allowing more air dilution and thus a lower exhaust temperature. This can also ruin the turbo charger due to high rotational speeds and deteriorate the engine block due to high peak pressures.

## MARKET SURVEY OF TAMPERING PROVIDERS IN NORTH AMERICA

We conducted qualitative research to evaluate the availability of devices or delete kits as well as the most commonly found pathways for vehicle tampering. We found readily accessible media and websites that catered to customized tampering options as well as companies that marketed their services and equipment for customized tuning. Table B1 in Appendix B includes a non-exhaustive list of tampering and tuning service providers in North America identified as part of this research.

One of the most common tampering methods found in North America is the installation of straight pipes that completely eliminate the aftertreatment emission control system from the truck. This method of tampering is accompanied by an engine control module "tune" that deletes the presence of these components from the calibration settings as well as implementation of logic to disable the appropriate aftertreatment OBD system that would otherwise trigger the malfunction indicator.

Most popular options for tampering, based on market survey are:

» Online: The tampering service provider connects remotely to the vehicle and makes direct changes to the engine's control module.

» Dealer: The tampering service provider caters to customers on-site. Certain providers have as many as 500 local dealers spread across North America.

» Shipping of components: The original engine control module is shipped to the tampering service provider to modify the engine's control module. Options also exist for the customer to purchase a new preprogramed module with the tampering software that disables the emission control system.

The method of "delete and tune" is one of the more popular tampering approaches in the North American market according to our evaluation. Although sources for DEF emulators for SCR tampering do exist in North America, these seem to be more in demand in the European market. Due to the wide cross-border travel of heavy-duty trucks across different provinces, it is anticipated that fleet owners and operators would be reluctant to tamper their aftertreatment systems. In comparison, medium-duty trucks have more of a local/regional vocation, where trucks owners are more at ease about tampering, especially in provinces without any I/M programs to detect tampering.

Also, the prevalence of the number of sources available in the market for the everyday pickup truck owner to modify their emission control systems is significant. Owners of the most popular pickup trucks, the Ford Powerstroke, GM Duramax, and Dodge Ram, are able to easily order tampering kits from a multitude of online sources. Most of these are ready-made kits that involve some extent of tuning in combination with removal of an aftertreatment part (e.g., DPF or SCR). Some of these are relatively moderate in cost, ranging anywhere from $200 to $1,500. For a technically apt individual, they might be willing to take the risks and attempt the "delete" themselves, saving additional labor costs.

A wide range of tampering service providers exist in the market today, some of the most common ones that are found on the worldwide web are shown in Table B1.

Although most of the ready-made tuning products are for medium-duty trucks, suppliers often offer customized solutions for heavy-duty applications.

All of the above are well-established businesses. These companies are cited frequently among bloggers and “do-it yourself” truck owners that encourage others to lead down the path of tampering.

Certain truck owners are inclined to pay for a new, tampered engine control module and save their existing factory engine control module for the future. Since any tampering is a cause for the engine warranty to be voided, certain owners will go to high extents to circumvent this. For example, installing a new engine control module in lieu of modifying the current one is an easier path to pursue if one was to reinstall emission control systems on their vehicles. For any service claims, the straight pipe can be replaced with the original aftertreatment system and the engine control module can be swapped for the original factory calibrated one.

Many providers advertise tampering services or devices via affiliate links on personal websites, blogs, and service shops. In addition, many blog posts also contain detailed tampering instructions, provide step-by-step guides for the tampering of the engine control module and the removal of emission control components.

We also found websites that sell “diagnostic laptops” that come preloaded with a series of tuning software applicable for all major heavy-duty engine manufacturers as well as pickup trucks. Many such providers similarly offer remote tampering services. These providers are able to either ship a tampered engine control module to the customer or remotely connect to the existing one for tampering.

It is evident from the research above that there are many options currently available for the average truck owner to tamper with or fully delete its emission control system. The vulnerabilities in the modern emission control system are common knowledge among many truck enthusiasts who are not afraid to seek paths to reap the benefits. However, as tampering practices become known and spread among the fleet, manufacturers and regulars are also learning more about those vulnerabilities. Likewise, several options and technological innovations in combination with regulatory efforts are active today to overcome these vulnerabilities. We present an overview of these in the following section.

# TECHNOLOGY MEASURES TO PREVENT TAMPERING

Emission control systems have a number of vulnerabilities that currently make them susceptible to tampering, as outlined in the previous section. However, the removal of emission controls, the manipulation of vehicle sensors, and the reprogramming of control units can be disincentivized through the deployment of anti-tampering technologies. While no technology can completely render emission control systems tamper-proof, the combination of several anti-tampering technologies can significantly increase the barriers to tampering while reducing the benefits from doing so. Table 5 and Table 6 present an overview of such desirable effects of anti-tampering technologies.

**Table 5.** Increased barriers from anti-tampering technologies

| Barrier | Desirable feature of anti-tampering technology |
| --- | --- |
| **Required expertise** | Tampering can only be performed by multiple experts collaborating together |
| **Required information** | The system information and data streams needed for a tampering attempt are inaccessible to tamperers |
| **Required equipment** | The hardware and software needed for a tampering attempt is hard to acquire and not accessible to tamperers |
| **Required time** | The time required for a tampering attempt is long enough to discourage tamperers from targeting the system |

**Table 6.** Decreased benefits from anti-tampering technologies

| Benefit | Desirable feature of anti-tampering technology |
| --- | --- |
| **Financial return** | The increased barriers make the tampering attempt significantly more expensive, decreasing the financial benefit. |
| **Legal consequences** | The likeliness of authorities discovering the tampering increases substantially |
| **Down-time** | The tampering attempt requires significant down-time of the vehicle |
| **Vehicle functionality** | Tampering attempts are recognized by the vehicle prompting *limp-home mode* (e.g., engine derating and speed limitation), the immobilization of the vehicle, and the voidance of the warranty |

The following sections present select anti-tampering technologies that can potentially disincentivize tampering attempts. While many of them rely on the effective use of information technology security, the focus is on the challenges and opportunities for their use in securing emission control systems.

## INTELLIGENT SENSORS AND ACTUATORS

Emission control systems rely on the data collected by a large number of sensors and actuators to control and diagnose individual components of the vehicle. These sensors measure, among others, the temperature, pressure, and composition of the air, fuel, diesel exhaust fluid (DEF), and exhaust gases. The location of some of these sensors are illustrated in Figure 4.

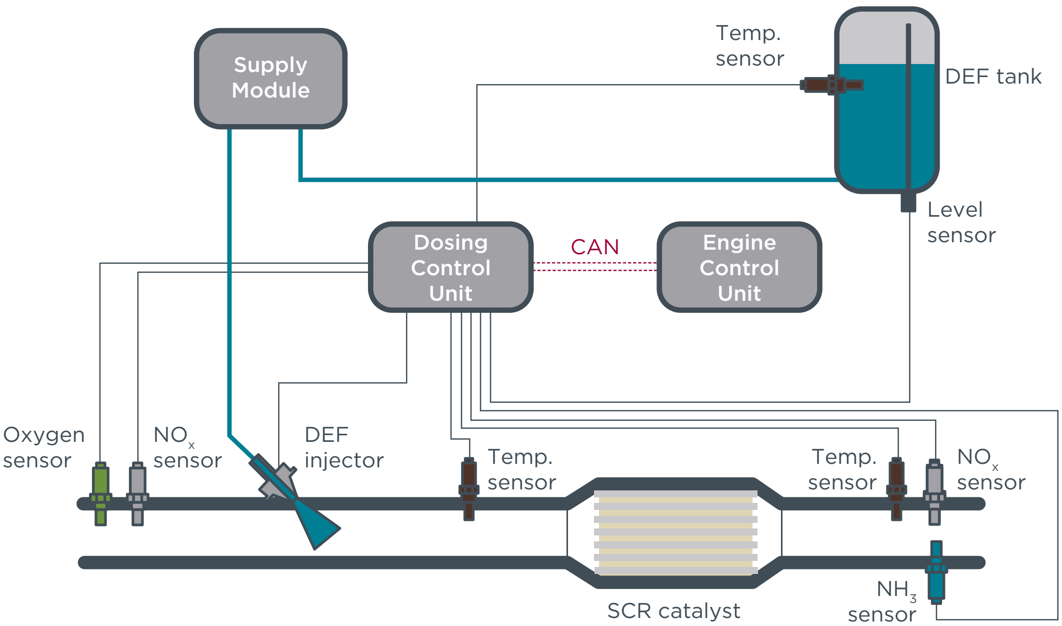


**Figure 4.** Schematic of sensors, actuators, and control units in an SCR system

Several tampering approaches rely on the manipulation of the signals coming from these sensors, or on their replacement with malicious devices. The sophistication of these attacks range from the manipulation of the signal of a single analog sensor to the complete emulation of the emissions control system. Vehicle sensors can be categorized into three groups depending on the way they communicate with the control units. These are summarized in Table 7.

**Table 7.** Automotive sensor categorization by communication protocol

| Type | Example of implementation | Description |
|---|---|---|
| **Analog** | - | Produce a continuous output signal, generally proportional to the quantity being measured, which is directly transferred to the control unit. |
| **Point-to-point digital sensors** | SENT protocol[a] | Digital sensors with limited computational resources, that provide an output-only communication with control units. Compared to analogue sensors, SENT sensors can report multiple pieces of additional information per message, and allow the transfer multiple signals from one sensor. |
| **BUS connected sensors** | CAN protocol[b] | Have the ability to send and receive messages over the CAN bus. These sensors have a dedicated control unit, connected to the probe, for signal processing. |

[a] The Single Edge Nibble Transmission (SENT) is a protocol for the transmission of accurate, high-resolution sensor data to control units. SENT was developed as a simpler alternative to CAN sensors, while improving on the limitations of analog sensors.

[b] The Controller Area Network (CAN) is a message-based protocol that allows microcontrollers and devices to communicate with each other over a multiplexed network.

To hinder tampering, sensors must provide sufficient information to control units to ensure the data integrity—that is, the data are complete and have not been modified—and the data authenticity—that is, the data can positively be proved to originate from the sensor in question.

Analog sensors alone cannot ensure the integrity or authenticity of the data, as they only communicate a continuous output signal or voltage. As a result, analog sensors are intrinsically vulnerable to tampering. However, the data from analog sensors can be validated through plausibility checks done at the control unit through a process called anomaly detection. This is described further in the *Enhanced on-board diagnostics* section.

Digital sensors and actuators communicating over the CAN protocol include several information fields in each data frame that is bidirectionally transferred. As such, CAN sensors can provide some information on the data integrity but cannot prove their authenticity. To do so, it would be necessary to implement secure cryptographic approaches, which can be computationally intensive and out of reach for the processing power of most current sensors (Lokman et al., 2019).

Digital sensors and actuators communicating over the SENT protocol have limited computational resources, and do not allow bidirectional communication—that is, they are output only. The SENT protocol includes the most common implementation of data integrity verification, called a checksum (SAE, 2016). However, checksums cannot verify the data authenticity, making them easy targets to be replaced by emulators.

Regardless of the communication protocol, future automotive sensors and actuators with key roles in the functioning of emission control systems should enable the verification of the integrity and authenticity of the data transferred. To do so, however, it is necessary that not only the sensors, but also the complete information network of the emissions control system enables the use of cybersecurity techniques developed in the past decade. This is explored in more detail in the following section.

## SECURED COMMUNICATION

The CAN protocol is the most widely used communication standard to allow sensors and control units to communicate among each other. However, the CAN protocol was conceived with little concern about security and does not contain direct support for secure communications (Lin & Sangiovanni-Vincentelli, 2012). In the CAN protocol, data is broadcasted to all nodes in the network, with limited information on the data origin. Thus, receiving nodes in the network cannot discern whether the data received is legitimate or not.

While modern security mechanisms are readily available to address the current vulnerabilities of automotive communication, the challenge resides in their integration into current architectures, their production, and cryptographic programing of spare parts. Retrofitting the CAN protocol with such security mechanisms poses challenges due to the lack of processing power and memory storage of the network nodes, and the limited data rates available (Lokman et al., 2019). However, it has been shown that data authentication is still achievable under those constraints using lightweight message authentication protocol designed specifically for the application in CAN networks. These protocols include, among others, CANAuth (Herrewege et al., 2011), LiBrA-CAN (Groza et al., 2012), CaCAN (Kurachi et al., 2014), and LeiA (Radu & Garcia, 2016).

The CAN protocol, developed between 1983 and 1986 by the automotive component supplier Robert Bosch GmbH, was first brought into production for automotive applications in 1991, and was standardized by the International Organization for Standardization in 1993 (Hartwich, 2017). Recent efforts have been made to update the technology. In 2012, Robert Bosch GmbH released an upgrade of the protocol, called

CAN-FD, which increases the data transfer rates eight-fold and is expected to become the norm in cars and trucks (CAN in Automation GmbH, 2018), This update eliminates one of the key constraints for implementing cryptographic schemes for authentication (Groza & Murvay, 2019). Furthermore, a new update to the CAN protocol, called CAN-XL is currently being developed with a stronger focus on cyber security. CAN-XL, which will again increase the data rate, will likely feature a security layer with node-to-node protection protocols to enable modern data encryption approaches (Yao, 2020). The different generations of CAN protocols are summarized in Figure 5.


**Figure 5.** Evolution of the CAN communication protocol

In summary, the implementation of secure communication is technically feasible in current and future emission control systems, although trade-offs between security, data transfer rate, and cost exist. Anti-tampering regulations, with clear requirements for data authentication, can be a significant driver to accelerate the development and adoption of modern communications protocols.

## ENHANCED ON-BOARD DIAGNOSTICS

On-board diagnostic (OBD) systems are a fundamental element of emission control systems. Since the OBD system can pinpoint malfunctioning components, it is a useful complementary tool for a number of emission standards programs, such as warranty, defect reporting, and inspection and maintenance. The effectiveness of OBD systems in diagnosing emission controls depends on which components and pollutants are monitored, the frequency of the monitoring, the definitions of what constitutes a malfunction, among other factors.

Traditional OBD systems are designed to inform about malfunctions of systems and components and notify the users of repair needs. Due to their nature, and the respective provisions set in the OBD regulations, ill-intentioned users can circumvent the OBD monitors through signal emulation and periodic deletions of error codes so that tampering attempts go unnoticed to the various control units.

Still, OBD systems are well positioned to assist in identifying tampering attempts through enhanced anomaly detection, or the identification of rare observations which differ significantly from the way that the system is expected to behave. By monitoring various physical measurements—like temperature, pressures, exhaust gas composition, among others—as well as the characteristics of the signals transmitted in the communication networks, enhanced anomaly detection algorithms can trigger a malfunction indication by the OBD system, with the respective inducement consequences.[5]

Manufacturers are increasingly moving toward the implementation of virtual sensors—that is, model-based predictions of the systems' performance. Such accurate predictions of the engine and aftertreatment behavior enable the identification of

5 The purposeful limitation of the vehicle's performance after a malfunction has been detected is called inducement.

discrepancies between the readings of physical sensors and the expected value by the model, supporting the detection of tampering. Advanced anomaly detection systems have the potential to prevent, detect, and deter future tampering attempts by making them significantly resource intensive and increasing the likelihood of downtime or derating as a consequence of a tampering attempt.

## ON BOARD MONITORING AND LOGGING

California has adopted an on-board emissions monitoring (OBM) regulation, called Real Emissions Assessment Logging (REAL), requiring the heavy-duty OBD systems to collect and store $NO_x$ emissions and fuel consumption data from the vehicle's sensors (California Air Resources Board, 2018). China's stage VI emission standards, largely based on Euro VI, include requirements for vehicles to be equipped with a remote on-board terminal for monitoring key emission-related parameters. Real-time engine data from the engine control module, $NO_x$ sensor, DPF, and other emission-related data are required to be reported remotely to the monitoring center of the regulatory agency (Yang & He, 2018).

Figure 6 shows different options for transmitting OBM data from the vehicle to the regulatory agencies. Of the different data transmission possibilities, over-the-air (OTA) technology, as is used in China, is the only solution that realistically allows for regular fleetwide collection of the OBM data. Its implementation can rely on existing telematics hardware, minimizing introduction lead time and cost. The tampering of the OBM data transmission can be prevented through the cybersecurity approaches described in previous sections, as well as with distributed ledger technologies, such as blockchain, which ensures that data stored cannot be manipulated. This approach is being explored in a project called *DIAS, Smart Adaptive Remote Diagnostic Antitampering Systems,* funded by the European Commission (DIAS Consortium, 2021).

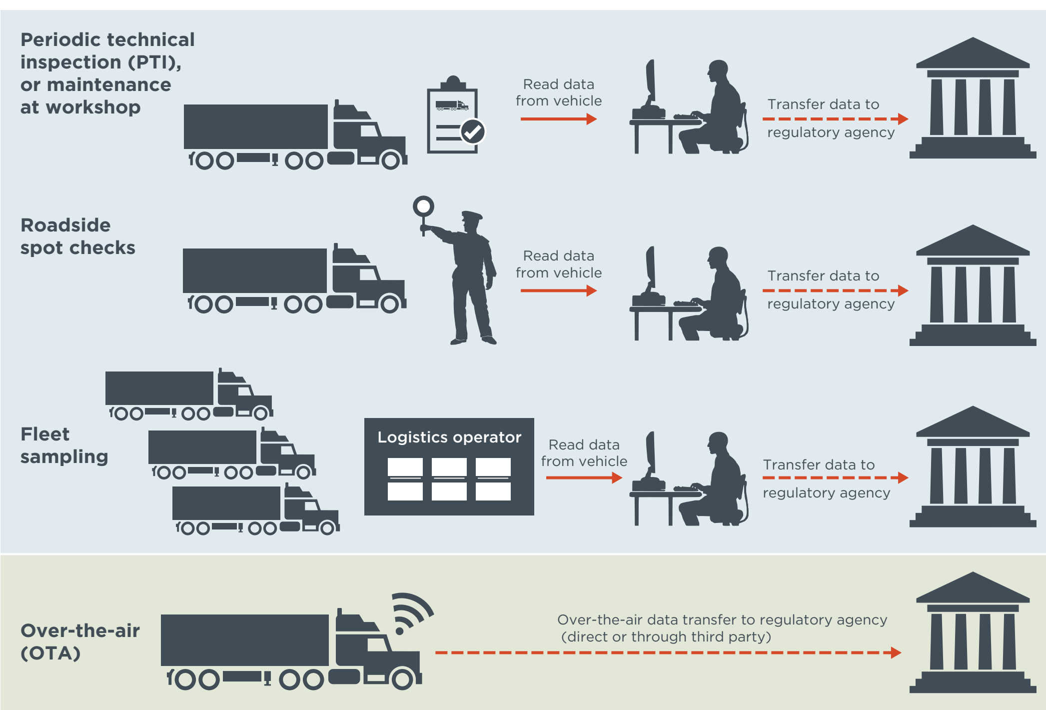


**Figure 6.** Options for transmitting OBM data from the vehicle to regulatory agencies. Adapted from Dornoff (2019).

Requiring vehicles to collect and store the vehicle performance and pollutant emission measurements[6] and estimates from the vehicle's own sensors and models, with subsequent evaluation of the data through statistical methods, would enable regulators to identify vehicles behaving abnormally. As a result, not only tampering, but other durability issues can be detected, helping ensure that vehicles maintain low emissions throughout their full lives, with the potential of triggering demand-based periodic technical inspections. OBM can be a valuable tool for assessing the limitations of the emission certification procedures and addressing emissions tampering, by increasing the likeliness of authorities discovering the tampered vehicles.

6 Such parameters include, for example, the engine speed, engine load, air or exhaust flow rate, fuel rate, $NO_x$ engine out concentration, $NO_x$ concentration, DEF injection rate, catalyst temperature, DEF tank level, DPF pressure, and EGR rate, among others.

## TAMPERING FROM THE PERSPECTIVE OF COMMERCIAL FLEETS

To understand the perceptions of fleet operators concerning tampering, we sought the support of Canadian trucking and transport associates to disseminate a target survey to their members. We obtained 13 individual responses and the collective response of a fleet association, obtained during a live panel discussion. To encourage participation, we ensured that no responses would be attributable to any individuals or companies.

Collectively the participants represented a total 90,000 trucks, including 5 small fleets (less than 500 trucks), 3 medium-sized fleets (500 to 5,000 trucks) and 3 large fleets (more than 5,000 trucks). The survey covered different business types, including 8 responses from for-hire fleets, 2 responses from less-than-truckload fleets, a response from a private fleet, 2 responses from technology suppliers, and the collective response of a fleet association.

Figure 7 shows the estimates of the survey respondents on the prevalence of aftermarket devices or services to tamper with emission control systems.

**As an estimate, what percentage of fleets do you think are using aftermarket devices or services to tamper with emission control systems to either reduce fuel consumption, urea costs, or to avoid repairs of aged or malfunctioning equipment?**

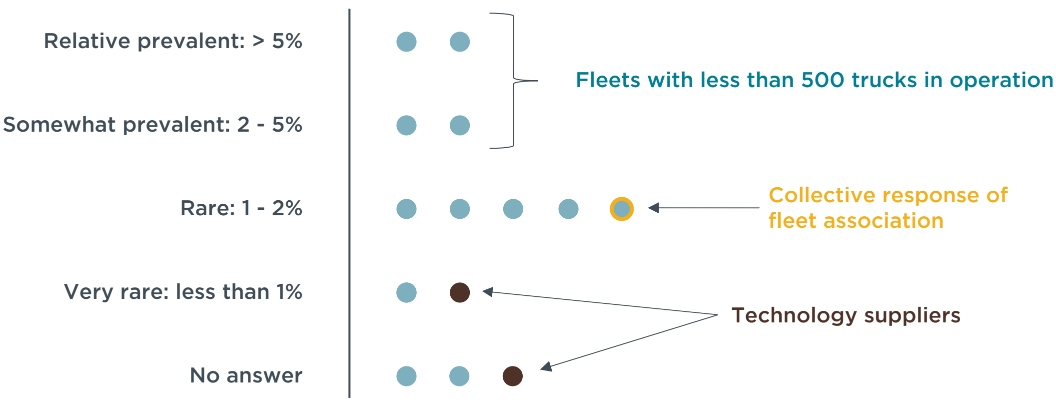


**Figure 7.** Estimates for the prevalence of tampering according to the survey respondents

Four respondents, all fleets with less than 500 trucks in operation, estimated the prevalence of tampering to be above 2%. Larger fleets, and the fleet association—in total 6 responses—estimate that tampering is rare (1%-2%) or very rare (less than 1%). In particular, during the panel discussion, participants noted that owner-operators were more likely to engage in tampering to minimize the risk of any down-time on their single source of income. Furthermore, the participants also noted that minimizing the risk of failures in the extreme low temperatures of northern regions, where a stranded vehicle can endanger the operator, is also a strong motivation.

The majority of respondents were in agreement on the limitations of on-board diagnostics (OBD) systems to prevent tampering, as shown in Figure 8. Five fleets, and the two technology suppliers expressed a neutral opinion. Most of the responses also agreed on the need for strengthened regulations to prevent tampering. Interestingly, a respondent who estimated the tampering incidence to be over 5%, strongly disagreed with the need for additional regulations to address the unlevel playing field that tampering creates.

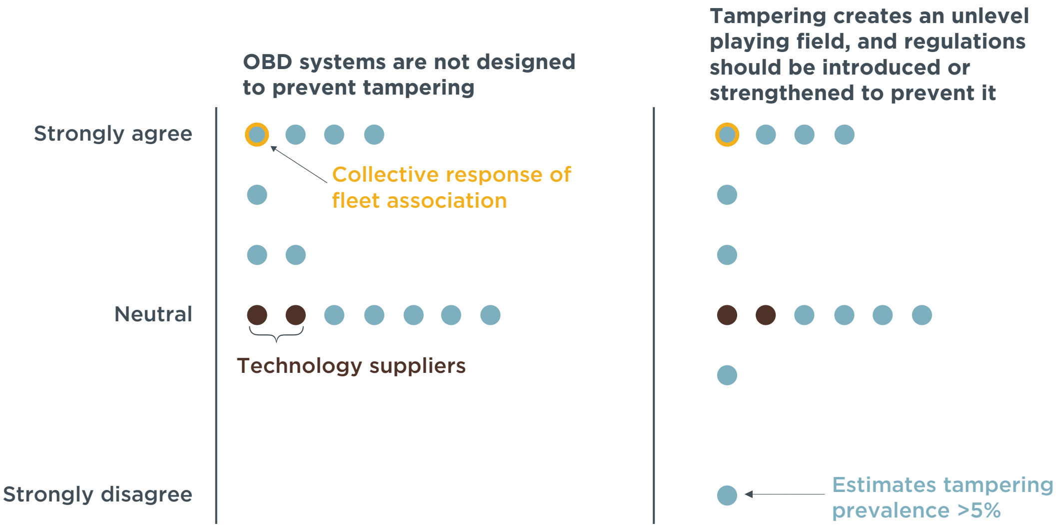


**Figure 8.** Respondents' opinions on the effectiveness of OBD systems to prevent tampering, and on the need of additional regulatory intervention to address tampering.

In the final section of the survey, participants were asked to rank the effectiveness of different measures to address tampering. The results, shown in Figure 9, exhibit a large spread, highlighting the lack of consensus among fleets on the most effective measures to prevent tampering.

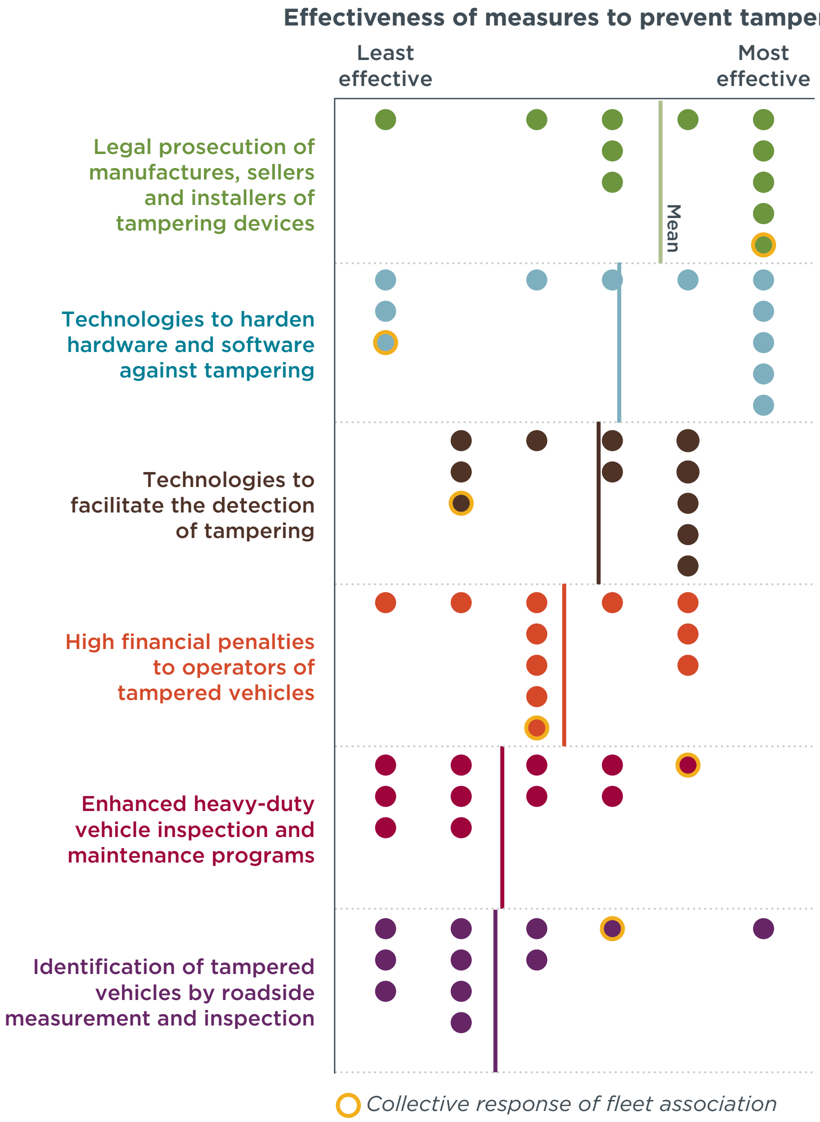


**Figure 9.** Respondents' opinions on the effectiveness of different measures to address tampering.

The two measures with the highest mean ranking were the legal prosecution of providers of tampering services or devices and the introduction of technologies to make tampering more difficult and to identify those who tamper. A clear split regarding technology-based measures can be identified, with a large number of respondents clearly favoring them and another group rejecting them as an effective measure. Participants in the fleet association panel noted that "to create additional technology to address what is in effect a technology problem, likely would not have the desired impact."

The lowest-ranked measures were roadside identification of tampering and the introduction of enhanced inspection and maintenance programs. While there seems to be consensus around this evaluation, the fleet association ranked these two measures more positively than other respondents. Participants in the fleet association panel noted that it would be more effective to police tampering providers than to attempt to police individual trucks due to, in their view, the rare occurrence of tampering.

## EMISSIONS AND HEALTH IMPACTS MODELING METHODOLOGY

For this study, we modeled the real-world effects of tampering across Canada's fleet of diesel trucks. The emissions impacts were estimated using ICCT's Roadmap model, which considers factors such as vehicle activity, sales, emission controls by country or region, vehicle type, fuel type, energy efficiency, and year. It covers on-road vehicles and can estimate both historical and projected emissions of more than a dozen air pollutants and $CO_2$ emissions.[7] This study focused on two HDV segments: medium-duty trucks (MDTs) with a gross vehicle weight (GVW) between 3.5 and 15 tonnes and heavy-duty trucks (HDTs) with a GVW of greater than 15 tonnes.

Air quality and health impacts were estimated using the Fast Assessment of Transportation Emissions (FATE) model (International Council on Clean Transportation, 2021). FATE evaluates particulate matter ($PM_{2.5}$) and ozone ($O_3$) concentrations from pollutant emissions and assesses the corresponding health impacts in terms of premature deaths and disability-adjusted life years (DALYs), typically defined as the sum of years of life lost due to premature mortality and years of healthy life lost due to disability. We only include fatal health outcomes in this analysis, so the DALYs include only years of life (YLL) lost due to premature mortality in this case. Figure 10 below shows the workflow of emissions and health impact modeling.

The key inputs developed for the emissions modeling in this analysis were emission factors, fleet tampering incidences, and provincial shares of the Canadian truck fleet. Two sets of emission factors were used, one to model vehicles with tampered emission control devices and the other for vehicles with functional emission control devices. The Roadmap model then estimated provincial air-pollutant emissions, which were further aggregated to the national-level and downscaled to serve as inputs to the FATE model. The downscaling method is based on the U.S. EPA's modeling practice (Eyth et al., 2015) and our previous study (Anenberg et al., 2017). The surrogate data used to downscale emissions to the 2° x 2.5° grid are a weighted combination of roadway length (75% share) and population (25% share). Final results from FATE include the national health burden by age, disease, and pollutant.

7 See ICCT's previous publications for more details on the model (Anenberg et al., 2017; Miller & Jin, 2018, 2019).

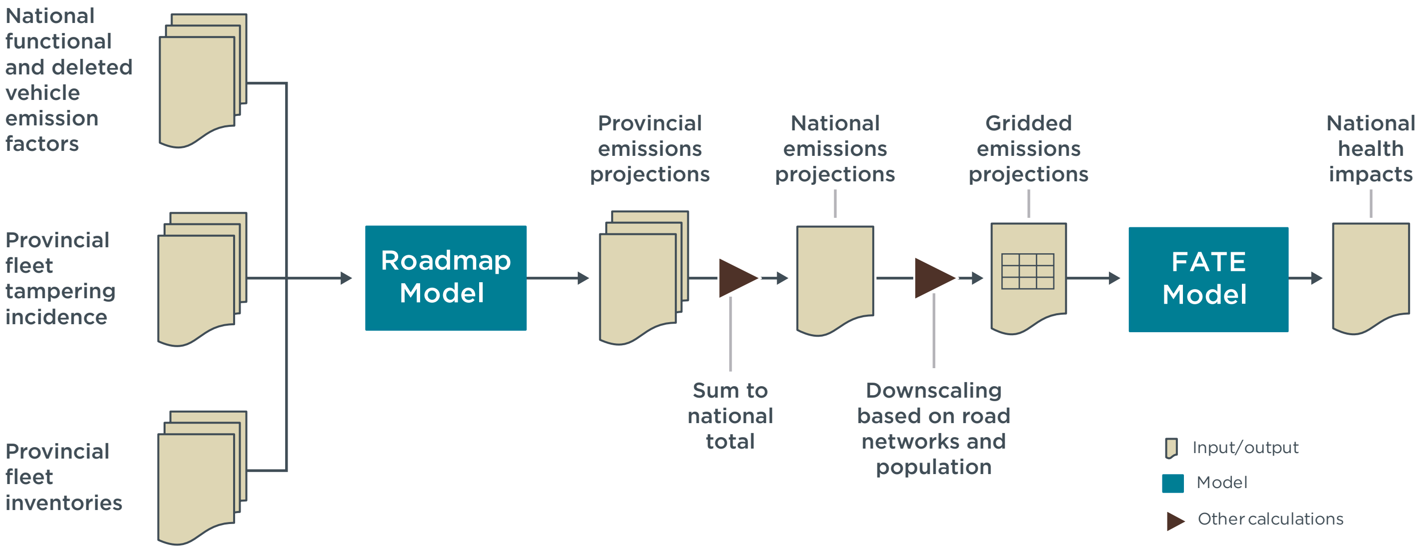


**Figure 10.** Illustration of workflow of emissions and health impact modeling

Due to a lack of concentrated studies on the effect and prevalence of tampering on heavy-duty vehicles, we rely on insights from a report recently published by the U.S. EPA, Tampered Diesel Pickup Trucks (U.S. Environmental Protection Agency, 2020), referred to as the EPA's TDPT report from here onwards. Data for the study was obtained via civil enforcement investigations and educated estimation of excess air pollution was made based on real-world and in-laboratory emissions testing.

It is important to note that the EPA's TDPT study is limited in scope to only include Class 2b and 3 diesel pickup trucks (8,500 to 14,000 lbs. gross vehicle weight rating). Also, the report only focuses on tampering that involves the complete removal or deactivation of aftertreatment and other emission control hardware/software. Although other types of tampering, such as tuners are still prevalent, "full deletes" are likely to have the greatest impact on air quality. Therefore, in sync with the EPA's TDPT report, our estimate of tampered vehicles as well as emission multipliers also focuses on tampering effects as a result of complete removal of the emissions control hardware.

In order to appropriately model the emissions impacts of tampered vehicles in Canada, we defined five key metrics:

» Untampered vehicle emission factors: The baseline emission factors of trucks with functional emission control devices.

» Cold temperature multipliers: The increase in emissions due to operation in cold ambient temperatures.

» Tampered vehicle emission multipliers: The increase in emissions due to tampering.

» Tampered vehicle share (TVS): The percent share of tampered vehicles. The TVS is a target value reached at the end of the tampered age. The TVS does not represent actual fleet-wide tampering incidence. It is a mathematical construct used in the emissions inventory modeling.

» Tampered age: The number of years its takes to reach the tampered vehicle share. Modeled as a linear increase from age 0.

Appendix A contains a detailed discussion on the development of each of the above metrics. Based on these inputs, we then outline the four scenarios modeled to assess emissions and health impacts.

## MODELING SCENARIOS

We developed three scenarios aimed at assessing a wide band of tampering incidences based on the evidence gathered in the United States, as described in the preceding sections. Additionally, we included a fourth scenario to consider the counterfactual case in which there is no tampering at all.

- **Counterfactual**: Scenario that assumes no tampering occurred historically or will occur in the future. This demonstrates a best-case scenario and highlights the relative effects of tampering.
- **Low**: Models a low tampering incidence, that is one third lower than the **Medium** scenario.
- **Medium**: Reflects a best estimate for provincial tampering incidence based on a national target tampering incidence of about 22% for MDTs, equivalent to our extrapolation from EPA's TDPT study. Provinces with inspections and maintenance programs were modeled at a tampering incidence of 15% for MDTs and 5% for HDTs. Likewise, provinces without such programs were modeled at a tampering incidence of 30% for MDTs and 10% for HDTs.
- **High**: Models a high tampering incidence that is 1/3 higher than the **Medium** scenario.

To add further granularity to our modeling approach, we broke down the targeted tampering incidence by province into the following categories: Ontario, Québec, British Columbia, Alberta, Manitoba, and others, where others includes the remaining Canadian provinces which contain less than 15% of all HDVs. As shown in Table 8, the share of MDTs and HDTs varies widely by province (StatisticsCanada, 2021). Via the Roadmap model's stock estimates, we found that the diesel share of MDTs amounts to 33% of the total MDT share, which we hold as a constant among all the provinces to calculate the total number of diesel vehicles.

Canada does not have a national level inspection and maintenance program, and each province has its own governance to implement such programs. As shown in Table 8, 47% of the MDT fleet and 45% of the HDT fleet are in provinces that currently have no such programs in place.

**Table 8.** Canada Provincial Specifications

| Vehicle Class | Category | Ontario | Québec | British Columbia | Alberta | Manitoba | Others |
|---|---|---|---|---|---|---|---|
| MDT/HDT | Anti tampering/ Emission inspection (See Table 4 for details) | Yes | Yes | Yes | No | No | No |
| MDT | Total vehicles between 4.5 and 15 tonnes | 134,789 | 65,052 | 135,691 | 192,708 | 20,226 | 85,197 |
| | Total Diesel vehicles between 4.5 and 15 tonnes | 44,930 | 21,684 | 45,230 | 64,236 | 6,742 | 28,399 |
| | % Share of Canadian Fleet | 21.3% | 10.3% | 21.4% | 30.4% | 3.2% | 13.4% |
| HDT | Total vehicles more than 15 tonnes | 134,202 | 88,277 | 46,247 | 111,415 | 32,131 | 76,630 |
| | % Share of Canadian Fleet | 27.4% | 18.1% | 9.5% | 22.8% | 6.6% | 15.7% |

Table 9 shows the target tampering incidence for each province per scenario and its effective weighted tampering incidence which is weighed according to the % Vehicle Type Share of the Canadian Fleet. Note that the Medium scenario results in a weighted tampering incidence of about 22%, which is nearly equivalent to our finding of MDT total tampering incidence in 2020 when we extrapolated the EPA TDPT study with Canada's fleet inventory data.

Due to a lack of any concrete evidence on the prevalence of HDT tampering incidence, we assume that the HDT target tampering incidence will be 1/3 of the MDTs. Once again, we note that there is significant uncertainty in the tampering incidence and base this share mainly on the different operating characteristics of medium and heavy-duty trucks. Most vehicles in the HDT classification are line haul vehicles that often cross provincial boundaries as well as international borders between Canada and the United States. In order to avoid being caught with an illegal tampering device, it is expected that many fleet operators of HDT refrain from tampering. On the other hand, MDTs are generally pickup type trucks that are characteristically operated locally or regionally. Therefore, the chances that an MDT is tampered in Alberta, for example, are significantly higher than for an HDT as well as MDTs in provinces such as Ontario and British Columbia that have an inspection and maintenance program in place.

**Table 9.** Targeted tampering incidence by province for modeling purposes

| Vehicle class | Scenario | Ontario | Québec | British Columbia | Alberta | Manitoba | Others | Weighted tampering incidence |
|---|---|---|---|---|---|---|---|---|
| MDT | Low | 10.0% | 10.0% | 10.0% | 20.0% | 20.0% | 20.0% | **14.70%** |
| | Medium | 15.0% | 15.0% | 15.0% | 30.0% | 30.0% | 30.0% | **22.06%** |
| | High | 20.0% | 20.0% | 20.0% | 40.0% | 40.0% | 40.0% | **29.41%** |
| HDT | Low | 3.3% | 3.3% | 3.3% | 6.7% | 6.7% | 6.7% | **4.83%** |
| | Medium | 5.0% | 5.0% | 5.0% | 10.0% | 10.0% | 10.0% | **7.25%** |
| | High | 6.7% | 6.7% | 6.7% | 13.3% | 13.3% | 13.3% | **9.67%** |

We assigned a target tampering incidence for each province and scenario such that the weighted average according to the percentage share of the fleet equated to our target tampering incidence. For the Medium scenario for MDTs, a 15% tampering incidence for provinces with inspection and maintenance programs and a 30% tampering incidence for provinces without such programs resulted in a weighted incidence of the entire MDT Canadian fleet of 22%. By placing a band of +/- of 5% for provinces with inspection and maintenance programs and a +/- of 10% for provinces without, the resulting weighted tampering incidence is 14.7% to 29.4%. Based on the EPA's TDPT, we considered these as reasonable hypothetical bounds for the Canadian fleet. The state level tampering incidences in the TDPT report reveals three different groups, with average tampering incidence above 20%, between 15% and 20%, and those between 10% and 15%. Only the states of California, which has an aggressive in-state inspection and maintenance program, and New Jersey have tampering incidences below 10%. Therefore, the range of tampering incidence defined in Table 9 above cover these sufficiently well and can be said to result in a reasonable bound for the modeling results.

Each of the provincial tampering incidences was further divided among different emission control levels: 1998, 2004, 2007, 2010, 2016 and next-generation. These emission control levels are defined as the technologies needed to comply with the respective pollutant emission standard. While no new emission standards were implemented in 2016, that year represent a change in compliance strategy by manufacturers to comply with US 2010 standards. Between 2010 and 2016, the average banking and trading provisions of the US 2010 standards allowed manufacturers to use banked credits to comply. As the banked credits are used or expire, manufacturers were forced to improve the emissions performance of their new engines. As a result, real-world $NO_x$ emissions gradually decreased between 2010 to 2016, warranting the introduction of the 2016 emission control level in our modeling (Badshah et al., 2019). The next-generation emissions control level represents the technologies required to meet standards equivalent with California's heavy-duty engine and vehicle omnibus regulation, assumed to be implemented in Canada in 2027. Further details on the different emission control levels can be found in Appendix A.

## AIR POLLUTION AND HEALTH IMPLICATIONS OF TAMPERING

Diesel emissions consist of many pollutants but are mainly characterized by $NO_x$ and particulates. Based on Global Burden of Disease 2019 (Institute for Health Metrics and Evaluation, 2020), ambient particulate matter air pollution is a severe public health risk that contributes to over 4.1 million premature deaths worldwide and over 118 million disability-adjusted life years lost in 2019.

Diesel exhaust is a known cause for acute inflammatory responses in the airways and peripheral blood. The World Health Organization's International Agency on Research on Cancer (WHO, 2012) has classified diesel exhaust as a carcinogen, and studies have shown the relationship between exposure to diesel exhaust and lung cancer (Garshick et al., 2012; HEI, 2015; Silverman et al., 2012). It is also a known cause of asthmatic symptoms, decreased lung function, and a significant cause of coronary artery disease leading to heart attack and stroke. A cohort study in California found significant positive associations between ischemic heart disease mortality and both fine ($PM_{2.5}$) and ultra fine particles, listing diesel vehicles as one of the sources (Ostro et al., 2015). Another study indicated mortality, due to any cause, was significantly associated with elemental carbon and $NO_2$ (Hoek et al., 2013). Both elemental carbon, or soot, and $NO_2$ are markers of combustion in general and diesel exhaust in particular.

To evaluate the health effects of tampering, this study examined the public health burden of particulates and $NO_x$ from diesel HDVs under the four scenarios outlined above. We estimated health impacts using the FATE tool, which implements methodologies developed for the Global Burden of Disease 2019 study (Institute for Health Metrics and Evaluation, 2020). In addition to estimating disability and premature deaths due to $PM_{2.5}$, we considered cases of chronic obstructive pulmonary disease from $O_3$ exposure. The following sections estimate the past and current impact of tampering on emissions and the corresponding public health burden in Canada and project its future impacts.

## IMPACTS OF TAMPERING ON CURRENT STANDARDS

The introduction of standards in 2010 requiring more stringent $NO_x$ and PM controls has significantly reduced tailpipe emissions of each pollutant. Between 2010 and 2019, annual emissions of $NO_x$ from diesel trucks reduced by 66%, while PM emissions reduced by 85%. Figure 11 and Figure 12 below show $NO_x$ and PM emissions by truck type and province in 2010 and 2019. The brown segments show the counterfactual case exploring what emissions would have been if no tampering had occurred. The blue segments represent the excess emissions estimated under the Medium tampering scenario.

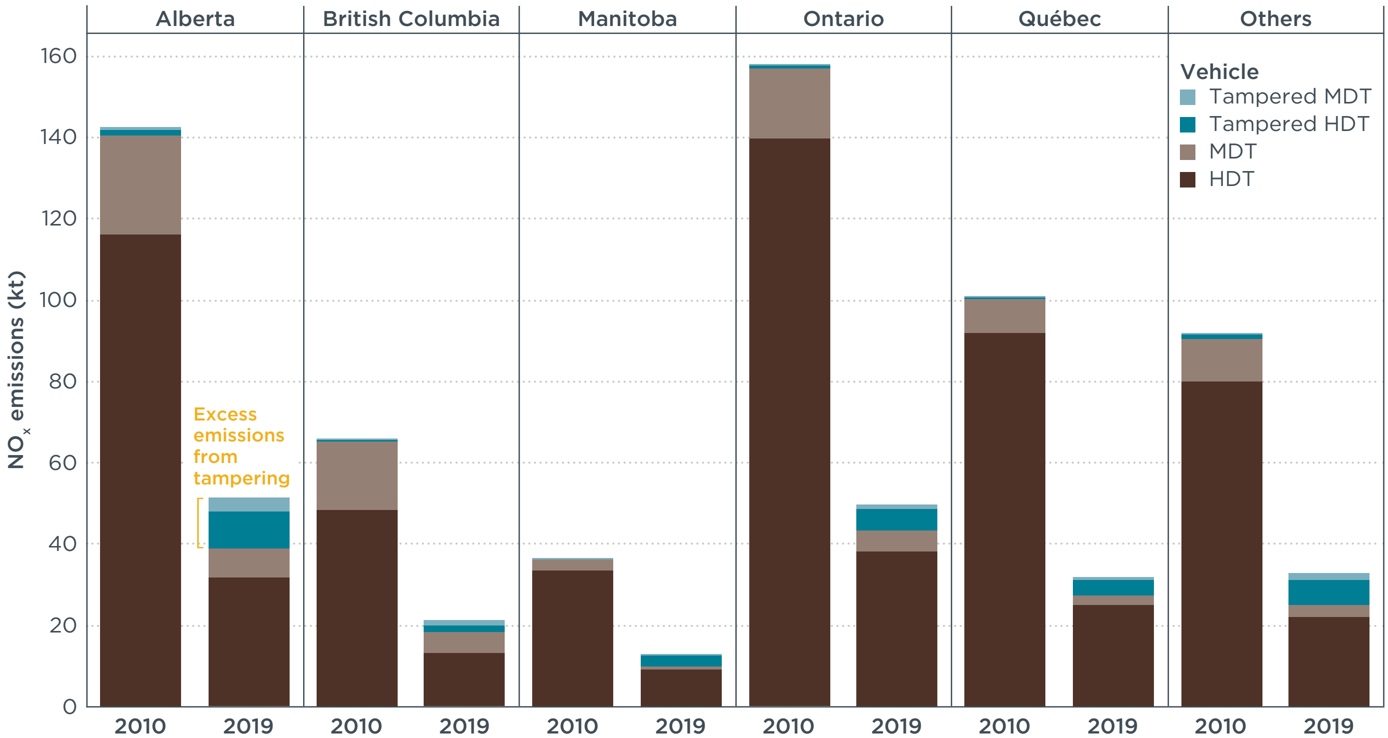


**Figure 11.** $NO_x$ emissions (kilotonnes) by vehicle type and province in 2010 and 2019. The blue segments show the excess emissions attributable to tampering under the Medium scenario.

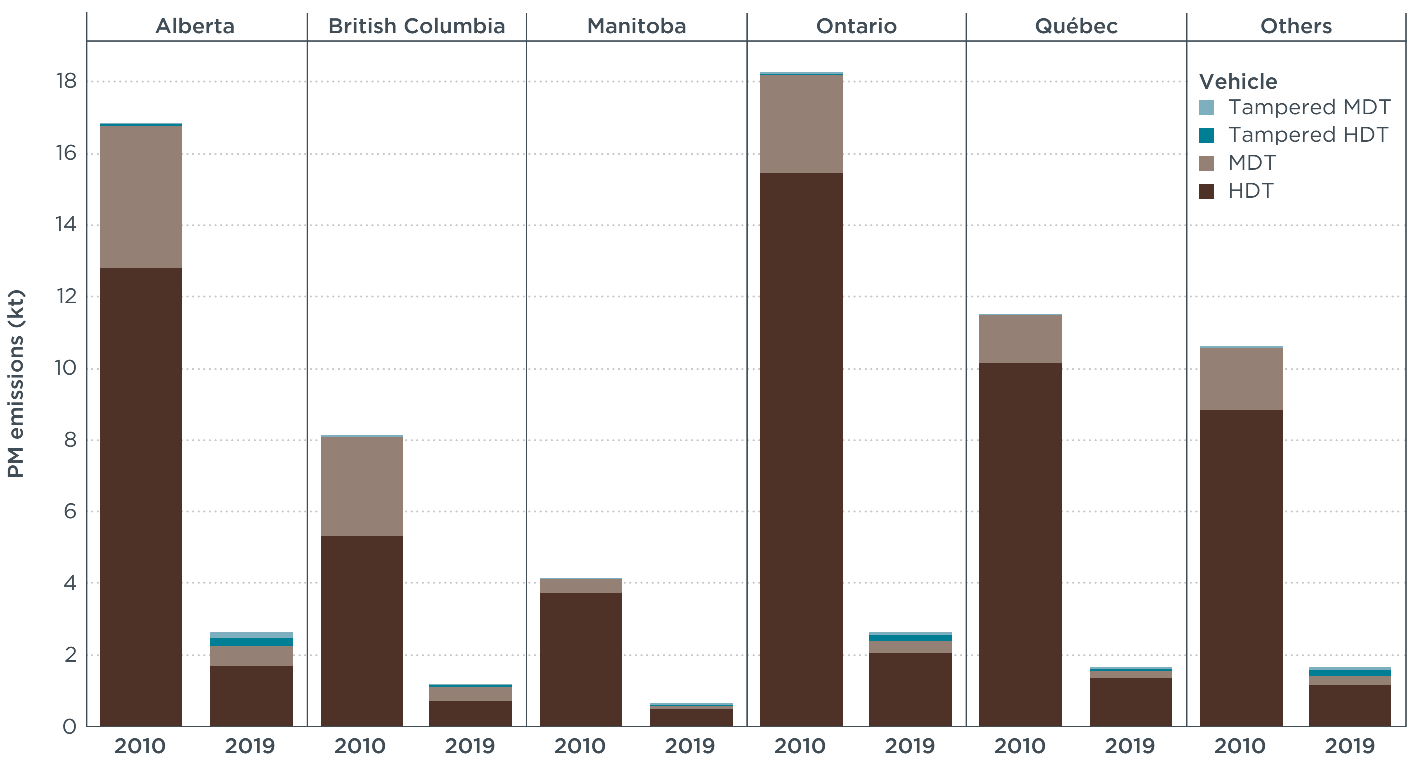


**Figure 12.** PM emissions by vehicle type and province in 2010 and 2019. The blue segments show the excess emissions attributable to tampering under the Medium scenario.

The steep decline in $NO_x$ and PM emissions over the past decade was the result of natural fleet turnover replacing older vehicles with those certified to newer standards. As turnover rates are not expected to vary greatly from province to province, differences in emissions among provinces are explained by their relative fleet sizes and presence of anti-tampering measures. Provinces that do not have anti-tampering legislation or emissions inspections are estimated to have double the amount of excess emissions. The continued operation of older vehicles remains a large contributor to current emissions. Figure 13 compares the share of total vehicle kilometers traveled (VKT) with the share of total emissions by control level in 2019. As shown, $NO_x$ and PM emissions were disproportionately attributable to pre-US 2010 certified vehicles. For example, even though US 2004 certified trucks comprised only 11% of the fleet's total activity, they were responsible for 75% of all PM emissions.

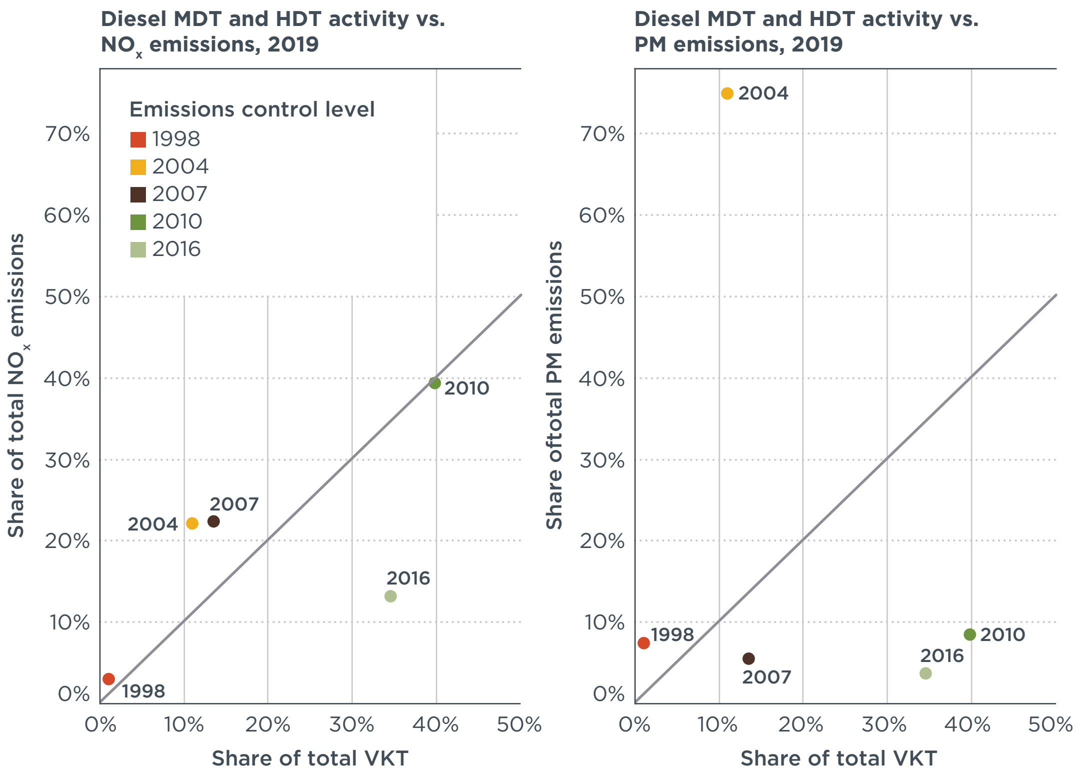


**Figure 13.** Share of vehicle kilometers traveled and pollutant emissions by emission standard under the Medium scenario, 2019. Points above the diagonal line indicate that vehicles of this standard have an outsized impact on emissions compared to their vehicle activity.

Historically, the effects of tampering have been overshadowed by the improvements due to the implementation of US 2007 and US 2010 standards. As more of the fleet transitions to newer standards, however, we estimate that tampering impacts grow in significance across Canada. Excess $NO_x$ emissions from diesel trucks due to tampering were estimated to be just 1% higher in 2010 but nearly 30% higher by 2019, contributing an estimated excess of 37,400 tonnes in that year alone. Similarly for PM, emissions were estimated to be 0.3% higher in 2010 and nearly 20% higher in 2019, resulting in an estimated excess of 1,140 tonnes.

Table 10 below shows a snapshot of the estimated number of tampered trucks (MDTs and HDTs) and their associated excess $NO_x$ and PM emissions by vehicle control level in 2019 in the Medium scenario. In total, we estimate that tampering lead to an equivalent amount of excess $NO_x$ emissions as driving nearly 220,000 additional trucks in Canada in 2019.

**Table 10.** Number of trucks with tampered emission control devices and associated excess $NO_x$ emissions, PM emissions, and vehicle-equivalents by emissions control level in 2019 in the Medium scenario.

| Emission control level | Number of trucks with tampered emission controls | Excess $NO_x$ (kt) | Excess PM (kt) | Vehicle-equivalents of excess $NO_x$ [a] |
|---|---|---|---|---|
| **2004** | 2,990 | 0.83 | 0.00 | 1,400 |
| **2007** | 15,950 | 6.58 | 0.42 | 21,700 |
| **2010** | 38,500 | 24.02 | 0.60 | 133,000 |
| **2016** | 6,830 | 5.98 | 0.13 | 63,600 |
| **Total** | **64,270** | **37.40** | **1.14** | **219,700** |

[a] Refers to the number of additional untampered vehicles that would need to be on the road to emit the equivalent amount of excess NOx.

Despite the large reduction of emissions seen since the introduction of US 2010 standards, air pollution from diesel trucks remains a burden on public health, resulting in an estimated 576 premature deaths and 11,900 disability-adjusted life years in 2019. Figure 14 below shows the breakdown of 2019 annual premature deaths from diesel MDTs and HDTs in more detail. PM contributes to the majority of the health impact we assessed, accounting for approximately 94% of the annual burden in 2019. Negative health impacts of tailpipe exhaust disproportionately affect elderly people, with over half of the health burden experienced by people from 70 to 90 years old. Ischemic heart disease was the leading cause, contributing to 36% of the total annual health burden in 2019, followed by chronic obstructive pulmonary disease (29%), and tracheal, bronchus and lung cancer (22%).

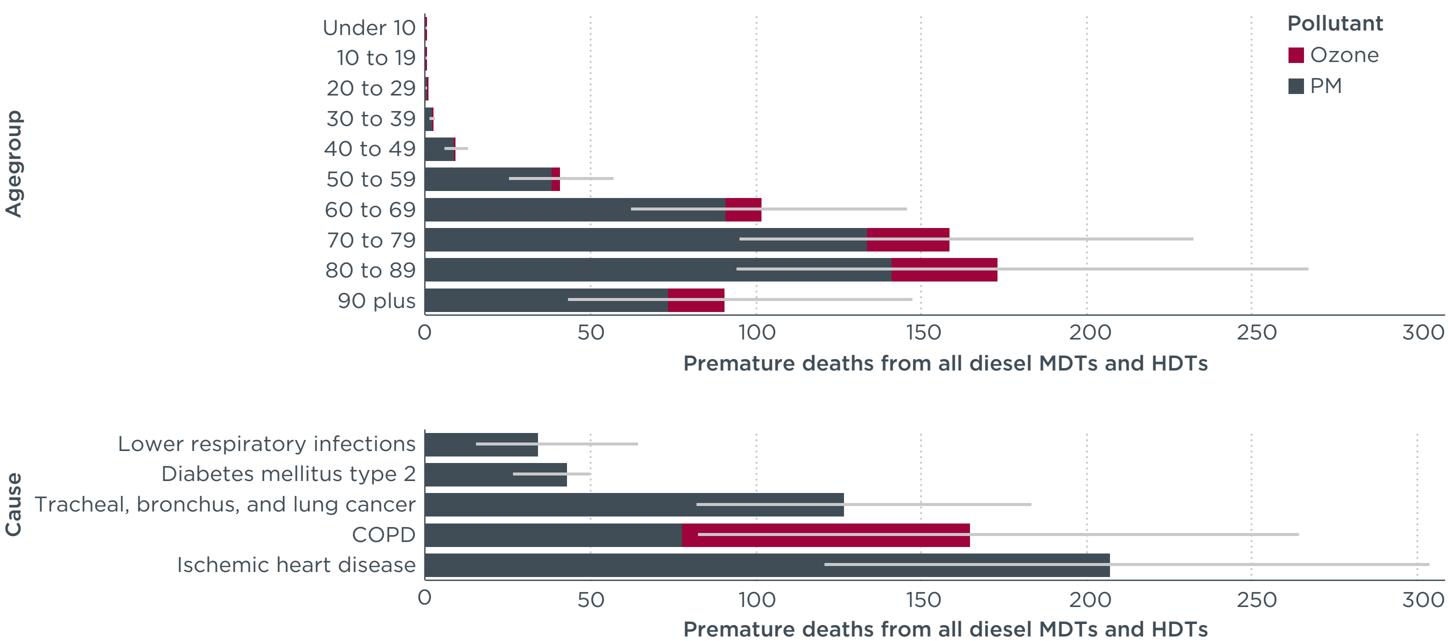


**Figure 14.** Annual health burden in 2019 from diesel MDT and HDT exhaust emissions by pollutant, age group, and cause in the Medium scenario. The health burden of ozone exposure was only considered for rates of COPD. Uncertainty bounds reflect uncertainty in relative risks only.

## FUTURE IMPACTS OF TAMPERING

As older vehicles continue to retire from Canada's MDT and HDT fleet, nearly all vehicles on the road will soon be certified to US 2010 and next-generation standards. By 2040, we estimate that 94% of trucks will be certified to next-generation standards (Figure 15) resulting in a 92% decrease in $NO_x$ emissions compared to 2020, assuming all emission control systems are functioning properly. Because the latest emission control technologies are so effective, even low levels of tampering would lead to much higher total emissions. Over the next 20 years Canada's $NO_x$ and PM emissions will be increasingly defined by the prevalence of tampering and the ability of anti-tampering measures to prevent it from occurring.

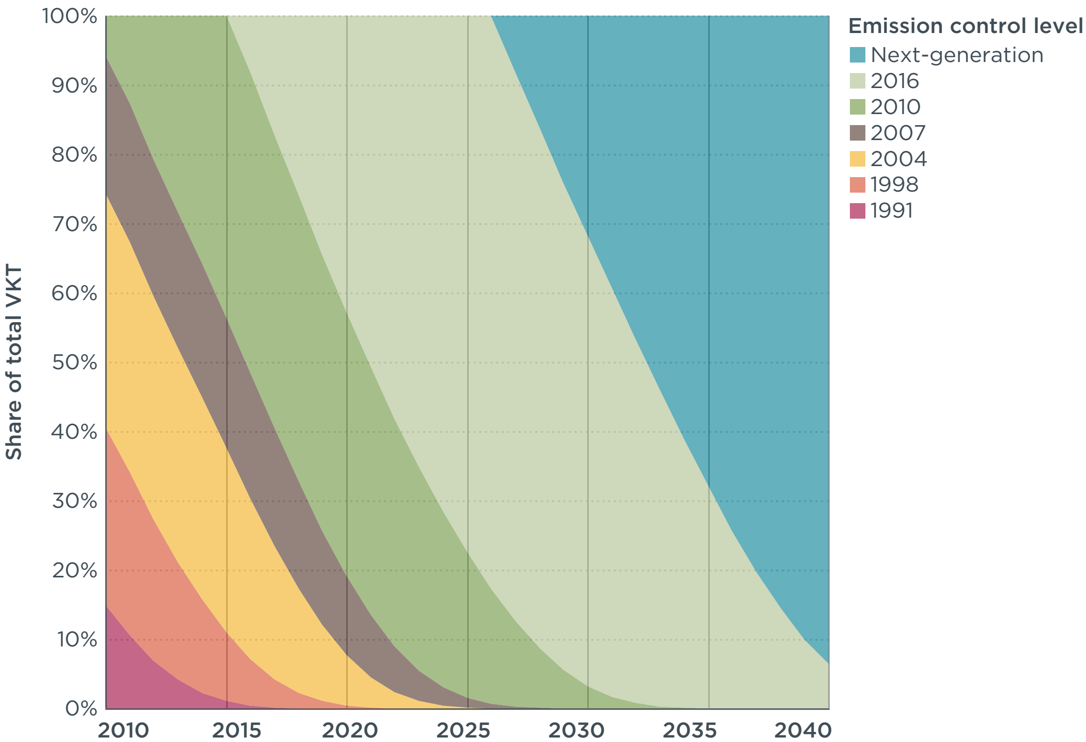


**Figure 15.** Share of diesel truck activity by emission control level, 2010-2040.

Figure 16 shows the number of tampered trucks by emission standard. As the different emission control levels are adopted following the implementation and phasing-in of the different emission standards, the effect of growing stock and increasing share of tampered vehicles as they age is dominant, resulting in an increasing number of tampered vehicles of each new vehicle control level. After these vehicles reach the share specified by the TVS, the effect of fleet turnover starts to drive the number of tampered vehicles down.

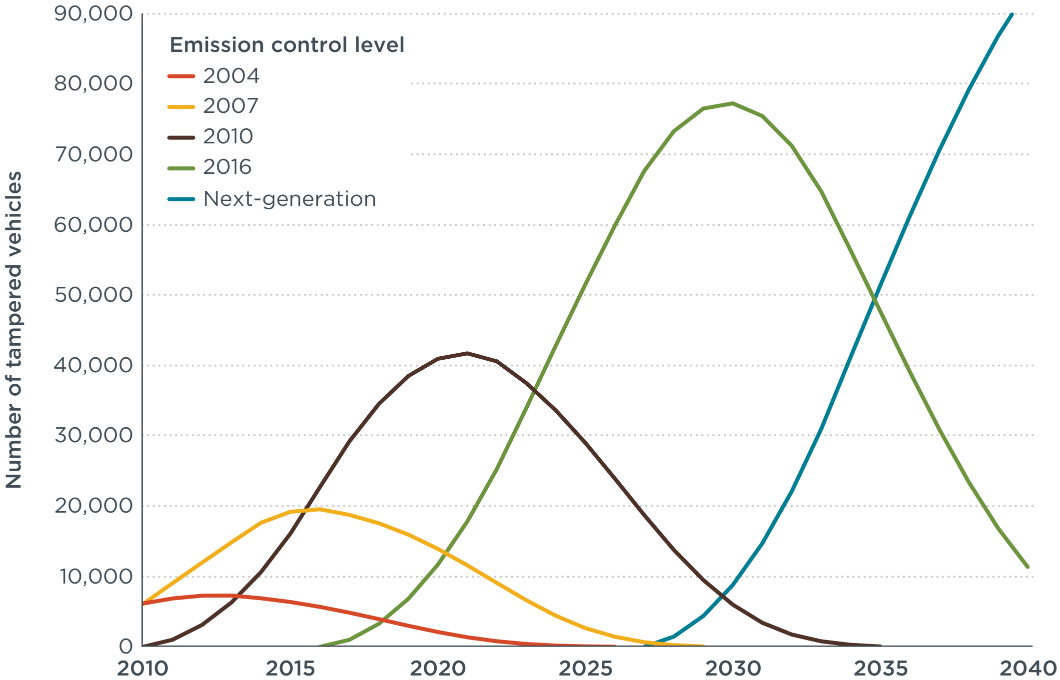


**Figure 16.** Number of tampered trucks by emission control level in the Medium scenario, 2010-2040.

Figure 17 shows $NO_x$ emissions by scenario and province from 2020 to 2040. It is clear that tampering would have a significant impact on $NO_x$ emissions across provinces. Emissions projected in the Medium scenario are 5 to 10 times that of the counterfactual scenario for HDTs and 6 to 11 times that for MDTs in 2040. Provinces with emission inspection and anti-tampering programs are expected to see a smaller emissions increase than the counterfactual compared to provinces without. The impact of next generation standards is also clear, where an accelerated decrease in $NO_x$ emissions is expected starting from 2027. Similarly, as shown in Figure 18, PM emissions in the Medium scenario are 2 to 3 times that of the counterfactual scenario for HDTs and 5 to 8 times that for MDTs in 2040.

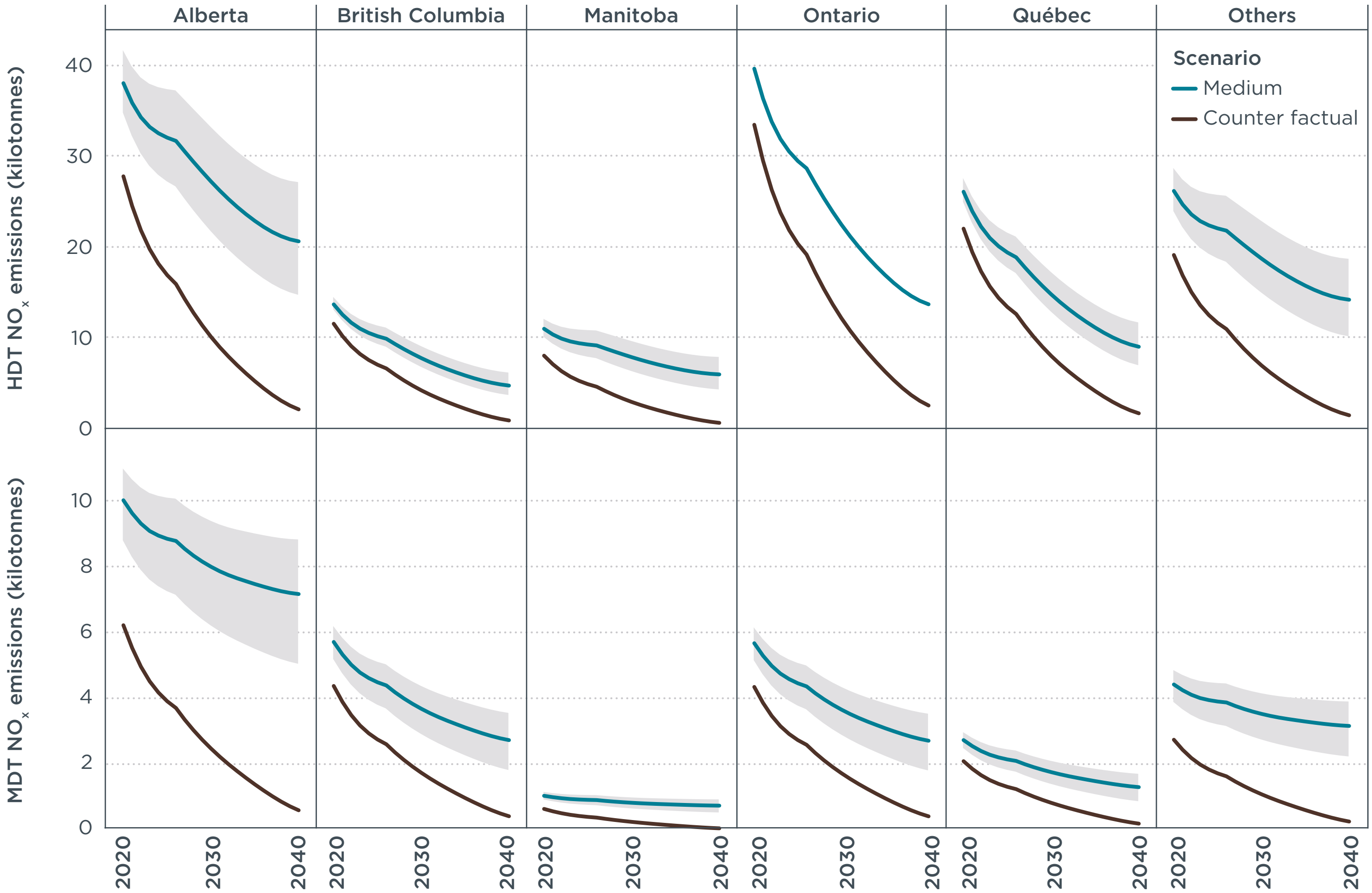


**Figure 17.** $NO_x$ emissions by vehicle type, scenario, and province, 2020-2040. Uncertainty bounds show the range given by the Low and High scenarios.

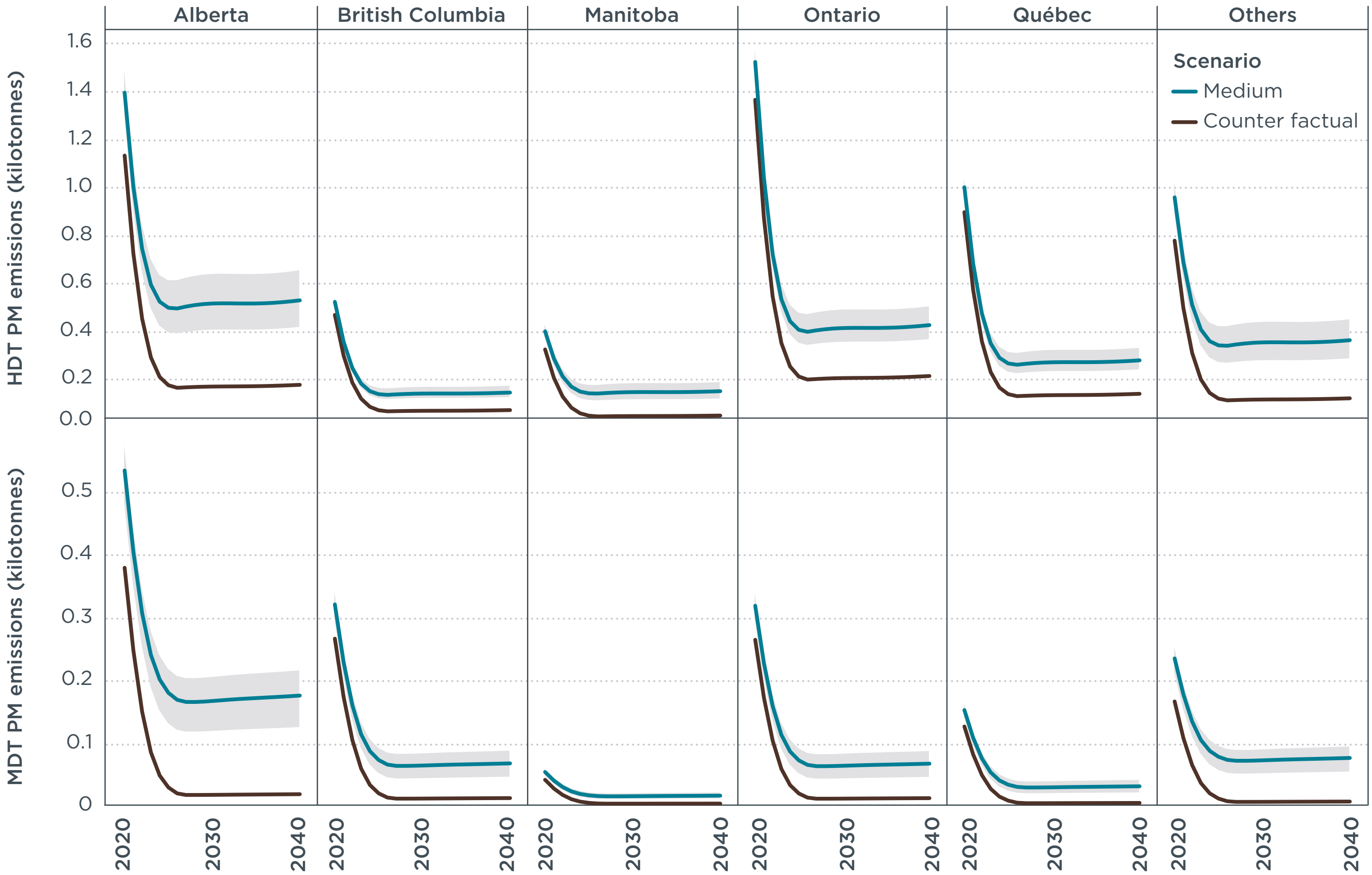


**Figure 18.** PM emissions by vehicle type, scenario, and province, 2020-2040. Uncertainty bounds show the range given by the Low and High scenarios.

Because the emissions impact of tampering grows over time relative to an untampered fleet, any reduction to the tampering incidence would result in increasingly significant emissions benefits. To consider tampering incidences outside the ranges defined in the scenarios above, we estimated the relative change in emissions associated with a single percent increase in tampering incidence. Figure 19 shows the estimated increase in emissions associated with a 1% tampering incidence (across all emission control levels) in 2020, 2030, and 2040. We project that by 2040 each 1% increase in the tampering incidence will increase emissions of $NO_x$ and PM by approximately 57% (6,400 tonnes) and 15% (130 tonnes) respectively.


**Figure 19.** $NO_x$ and PM emissions (kilotonnes) by province in 2020, 2030, and 2040. Dark segments show baseline emissions from untampered vehicles. Light segments indicate the increase in emissions associated with a 1% increase in the number of tampered vehicles on the road.

The public health benefits from reducing emissions from diesel trucks are substantial. We estimate that fleet-wide adoption next-generation standards has the potential to reduce annual premature deaths by 85% in just two decades, as shown by the Counterfactual scenario in Figure 20. This figure shows the annual health burden due to emissions from MDTs and HDTs without tampering and under the Medium scenario. Similar to the emissions figures above, the grey uncertainty band represents the range defined by the Low and High scenarios. In the worst-case scenario, high tampering incidences may completely offset any emissions reductions provided by stronger controls in the untampered fleet. The projected health impacts shown here use the mean exposure response and do not include additional uncertainties.[8]

8 FATE reports a range of results due to uncertainties in ozone formation as well as uncertainties in the relative risk estimates.

While the total annual health burden is projected to decrease over the next 20 years, the excess health burden incurred by pollution from tampered vehicles is expected to increase. For example, in the Medium scenario we estimate tampering results in an additional 122 premature deaths in 2020 but more than three times that in 2040. Cumulatively over the next 20 years, pollution from diesel trucks is estimated to cause a total of 4,670 premature deaths and 84,200 disability-adjusted life years before considering excess emissions from tampering. Each 1% increase in the fraction of the fleet that has been tampered results in 690 additional premature deaths and 11,800 disability-adjusted life years in the same timeframe. The cumulative excess health burden in the Medium scenario is projected to total 5,700 premature deaths and 96,700 disability-adjusted life years by 2040. For context, it is estimated that 181,000 premature deaths globally were from on-road diesel vehicle tailpipe emissions in 2015 (Anenberg et al., 2019).

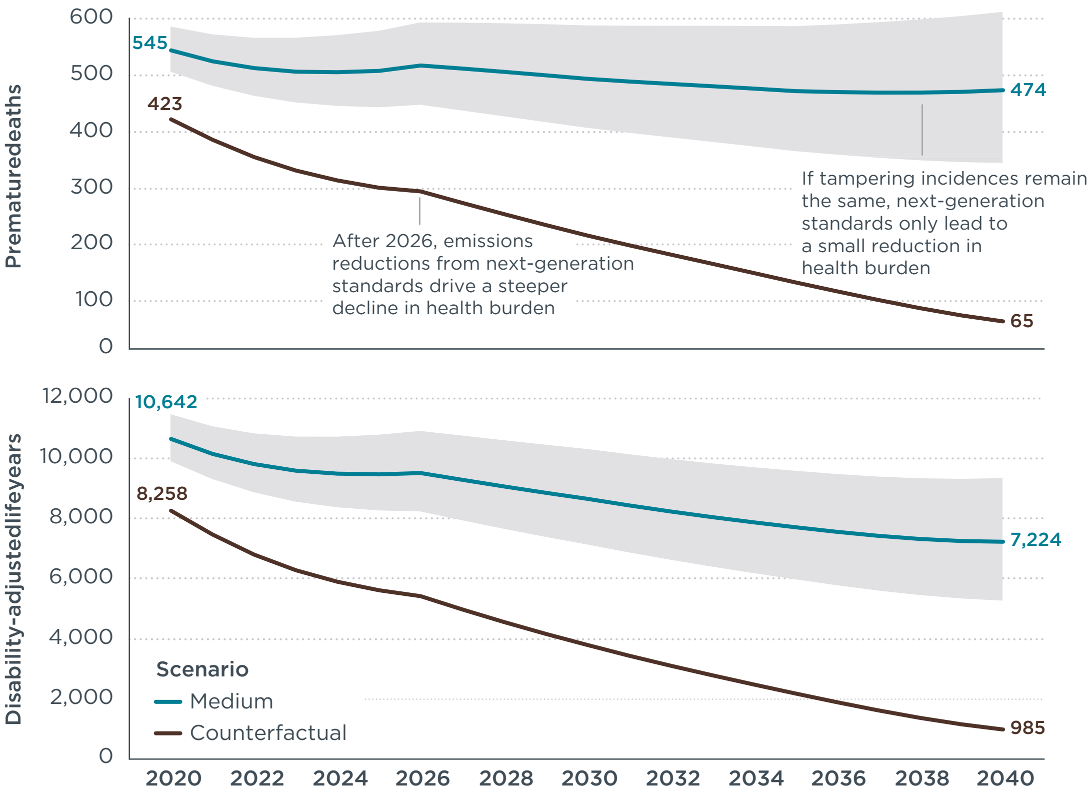


**Figure 20.** Annual national health burden from diesel MDT and HDTs by scenario, 2020-2040. Uncertainty bounds show the range given by the Low and High scenarios.

# CONCLUSIONS AND POLICY RECOMMENDATIONS

This study assesses the prevalence of tampering of the emission control systems in heavy-duty vehicles, the environmental and health impacts of such activities, and the solutions to prevent them. The key findings of our analysis are summarized below.

» **Anti-tampering legislation in Canada is insufficient.** Regulatory provisions prohibiting tampering and enabling its detection are decentralized and within the jurisdiction of provinces and territories. While many provincial statutes explicitly prohibit the tampering of emission control systems (see Table 1), only few provinces have adopted provisions that enable the enforcement of such tampering prohibitions. Currently, the most important regulatory lever available with the potential to deter tampering in Canada is limited to inspection and maintenance programs. Only British Columbia, Ontario, and Québec have emissions testing for HDVs as part of inspection and maintenance programs.

» **While the prevalence of tampering in heavy-duty vehicles operating in Canada remains unknown, the findings in the United States—with a similar vehicle market and stronger anti-tampering regulations—present a bleak reality.** Tampering, largely due to its illegal nature, is not a well-documented phenomenon. Thus, no studies have attempted to quantify the extent of tampered vehicles. In Canada, a number of remote sensing studies have identified that high emitting vehicles account for a large fraction of $NO_x$ and PM emissions of the HDV fleet. However, it is not possible to tell whether those high emitting vehicles were tampered with or had legitimate reasons (e.g., the regeneration of aftertreatment system) for exhibiting high emission values. Respondents to the survey conducted as part of this study provided a wide range of estimates for the prevalence of tampering in fleets operating in Canada. Around 30% of respondents estimated the prevalence of tampering above 2%, and 50% estimated it below 2%. In the United States, which shares pollutant emission standards with Canada, EPA estimates that 15% of U.S. Class 2b and 3 diesel trucks have tampered emission control systems but this study did not provide any insight into the tampering incidence of heavier trucks.

» **Tampering devices are readily available from well-established providers.** Several key components of emission control systems, such as the EGR, SCR, and DPF, are vulnerable to tampering through both hardware and software modifications. Our evaluation reveals that a combination of hardware removal and reflashing of the control units is one of the more popular approaches in the North American market. Although the use of emulators for SCR tampering, which does not require hardware modifications, was also identified in our analysis, the tampering approach appears to be more prevalent in the European market than North America.

» **Tampering leads to substantial increases in pollutant emissions.** Compared to the counterfactual case where no tampering occurs, especially in provinces without inspection and maintenance programs**,** we project that each percentage increase in the tampering incidence will result in an increase in emissions of PM and $NO_x$ of approximately 57% and 15%, respectively, in 2040. Historically, the effects of tampering are overshadowed by the improvements due to the implementation of US 2007 and US 2010+ standards, demonstrating the success of those policies. In recent years, however, tampering has increasingly set back potential reductions in emissions. As the on-road fleet continues to be dominated by US 2010 vehicles and new technologies are deployed to meet future emission standards, the contribution of emissions from tampered trucks increases significantly.

» **The increase in emissions from tampering leads to severe health impacts.** Soot and $NO_x$ emissions from diesel engines are primary causes of ambient air pollution of $PM_{2.5}$ and ozone, both of which have been shown to result in significant health impacts such as ischemic heart disease, COPD, lower respiratory infection, lung cancer, and diabetes mellitus type 2. We estimate that an increase in tampering incidence of 1% leads to 690 excess premature deaths over the next 20 years. The health burden was disproportionately felt by elderly people from ages 70 to 90 years old, with the main causes being heart disease, chronic obstructive pulmonary disease, and cancer. It is also expected that the health impact will be disproportionately borne by disadvantaged communities living near high traffic freight corridors.

The motivation to tamper with emission control systems is multifaceted. While some might seek to reduce the operating cost of their vehicles through the elimination of DEF dosing or the improvement of fuel consumption through the deactivation of the EGR system, others might be motivated by avoiding maintenance related downtime and costs. In any case, public policy can have a crucial role in raising the technology barrier for tampering, increasing the likelihood of being discovered, and in balancing incentives with appropriate penalties. Based on our findings, we offer the following policy recommendations for effectively deterring the tampering of emission control systems.

» **Canada should explicitly prohibit tampering at the federal level.** While several Canadian provinces and territories have made it illegal to tamper with emission control systems, the prohibition does not apply across the complete Canadian territory. Four provinces do not prohibit tampering, the most notable example being Alberta, Canada's fourth most populous province.

  In the United States, the Clean Air Act Civil Prohibitions outlaw, at the federal level, removing or rendering inoperative any emission control component on a certified motor vehicle or engine. Given the disproportionate impact of tampering on emissions of criteria pollutants, the explicit prohibition of tampering could be a subject for discussions under the joint committee on transboundary air pollution between Canada and the United States.

» **Steep penalties should be set for the providers and users of tampering devices and services.** Adequate penalties for tampering, and for those offering such services or products, can be a strong deterrent. Canada can seek to set penalties aligned with those of the United States. For instance, the Clean Air Act in the United States sets penalties of up to $4,527 per tampering event or sale of the defeat device. In 2019, the civil penalties amounted to approximately $1 million dollars.

» **Inspection and maintenance programs must be redesigned to address tampering.** Inspection and maintenance programs can be an effective policy to deter tampering. The programs mandate the regular testing of emissions performance and aims to identify high emitters while providing owners and operators with a chance to repair the vehicle and reduce emissions. While these programs are not failsafe, as components can be replaced or remounted just for passing the test, they are easy to implement and can provide an additional barrier against tampering. A successful inspection and maintenance program requires a comprehensive institutional infrastructure and a technical design coherent with modern emission control systems. As a first step, smoke opacimeters can be substituted by particulate number counting instruments which are able to detect particulate filter removal/tampering or other DPF malfunctions.

Many Canadian jurisdictions have the institutional infrastructure to implement such programs as they are actively in place in Ontario, British Columbia, and Québec. However, Alberta nor Manitoba have an inspection and maintenance program, despite having close to 33% of MDTs and HDTs in the Canadian fleet inventory. A modern program with unified provisions between all Canadian provinces would avoid inter-provincial discrepancies. The establishment of a multi-jurisdictional federal and provincial government task force can define guidelines for such integrated legislation.

» **Remote sensing and roadside emission inspection should be used in tandem as a market surveillance tool against tampering.** Remote sensing is a very effective technology for identifying high emitting vehicles, enabling robust and targeted market surveillance, particularly if the remote sensing records are shared across market surveillance authorities. Remote sensing instruments temporarily deployed in targeted locations—such as known routes of diesel trucks, ports, terminals, or transportation hubs—or installed in plume chasing vehicles can provide valuable information on the incidence of high emitters.

  However, it is not possible to determine the cause of the elevated emissions measurements without further inspection of the vehicle. Therefore, a combination of remote sensing measurement and roadside inspection is a successful market surveillance approach. An effective roadside inspection program would enable inspectors, or law enforcement, to pull over suspicious vehicles for tampering inspection.

» **Future pollutant emission standards should drive the adoption of anti-tampering technologies.** Several technologies can be used to harden emission control systems against tampering. Such technologies have the potential to prevent, detect, and deter future tampering attempts by making them significantly resource intensive, and increasing the likelihood of downtime or derating as a consequence of a tampering attempt. In modern vehicles, tampering attempts invariably require the manipulation of electronic signals to deceive the control units of the vehicle, or the reprogramming of the control units themselves to ignore the tampering. Anti-tampering regulations can set clear requirements to HDV manufacturers for data authentication and anomaly detection, forcing the development and application of modern secure communications protocols in emission control systems. Such regulatory requirements can build upon the current OBD legislation or be introduced as part of new pollutant emission standards. Of particular relevance is the use of on-board monitoring, requiring vehicles to collect and store the pollutant emission measurements and estimates from the vehicle's own sensors and models, as already adopted in California and China.

» **Active measures must be taken to close the knowledge gap around the prevalence of tampering in Canada.** There are knowledge gaps and research areas that need to be addressed to better understand the emissions and health impacts of tampering, and to reduce its prevalence. Roadside measurement campaigns, remote-sensing, in-use measurement of tampered vehicles, and controlled laboratory chassis dynamometer testing are instrumental in understanding the emissions impact of the diverse tampering practices, in conditions specific to Canada, such as driving cycles, cold temperature, and idling practices. Furthermore, there is a need to better quantify the prevalence of tampering in different vehicle classes and provinces, to improve the accuracy of emission inventories and health impact studies.

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# APPENDIX A

This appendix contains the detailed description of the five key metrics defined to model the emissions impacts of tampered vehicles in Canada:

» Untampered vehicle emission factors

» Cold temperature multipliers

» Tampered vehicle emission multipliers

» Tampered vehicle share (TVS)

» Tampered age

## UNTAMPERED VEHICLE EMISSION FACTORS

Emission factors developed in a recent ICCT study were used with adjusted emission control levels in Canada (Jin et al., 2021). We defined Canadian HDV emission control groups and emission factors based on their U.S. equivalents, since Canada's progression of HDV emissions standards has been aligned with the U.S. timeline. We did not consider tampering among vehicles certified under pre-2004 emission standards, since these vehicles were not equipped with aftertreatment emission controls. Utilization of EGR and aftertreatment systems in Canada only became widespread in response to the implementation of MY 2004 and later standards. We included six emission control levels: 1998, 2004, 2007, 2010, 2016, and next-generation. These emission control levels are defined as the technologies needed to comply with the respective pollutant emission standard. While no new emission standards were implemented in 2016, that year represent a change in compliance strategy by manufacturers to comply with US 2010 standards, warranting the introduction of the 2016 emission control level in our modeling. The next-generation emissions control level represents the technologies required to meet standards equivalent with California's heavy-duty engine and vehicle omnibus regulation, assumed to be implemented in Canada in 2027.

Vehicles certified to US 2004 standards are expected to have EGR systems in conjunction with diesel oxidation catalysts to reduce $NO_x$ emissions. Likewise, the 2007 and higher control groups have a DPF to reduce PM emissions, and the 2010 and higher control group have an SCR system to comply with reduced $NO_x$ emission limits. Due to evidence from recent studies that indicate a gradual decrease in real-world $NO_x$ emissions as a function of vehicle MY from 2010 to 2016, we introduced a 2016 control level (Badshah et al., 2019). This control level does not coincide with any regulatory framework but is representative of real-world conditions. The emission factor for $NO_x$ for this control level was derived as a conservative estimate based on the results Badshah et al. (2019) and Bernard et al. (2020). Beyond the 2016 control level, we also include a next-generation control level that comes into effect in the year 2027 and represents a 90% reduction in the $NO_x$ emission factor from the 2016 control level. For PM, we keep the same emission factor for control level 2010–2027 since the application of the DPF has already reduced real-world PM emissions in most cases beyond the regulatory limit. $NO_x$ and PM emission factors for vehicles with functioning emission controls, as a function of the respective emission control level, can be found in Figure A1. It is important to note that instead of using engine certification level values, we use $NO_x$ and PM emission factors that were previously derived by the ICCT (Jin et al., 2021). These emission factors are more representative of the real-world emissions as it uses a combined approach of implementing remote sensing and PEMS data in its derivation.

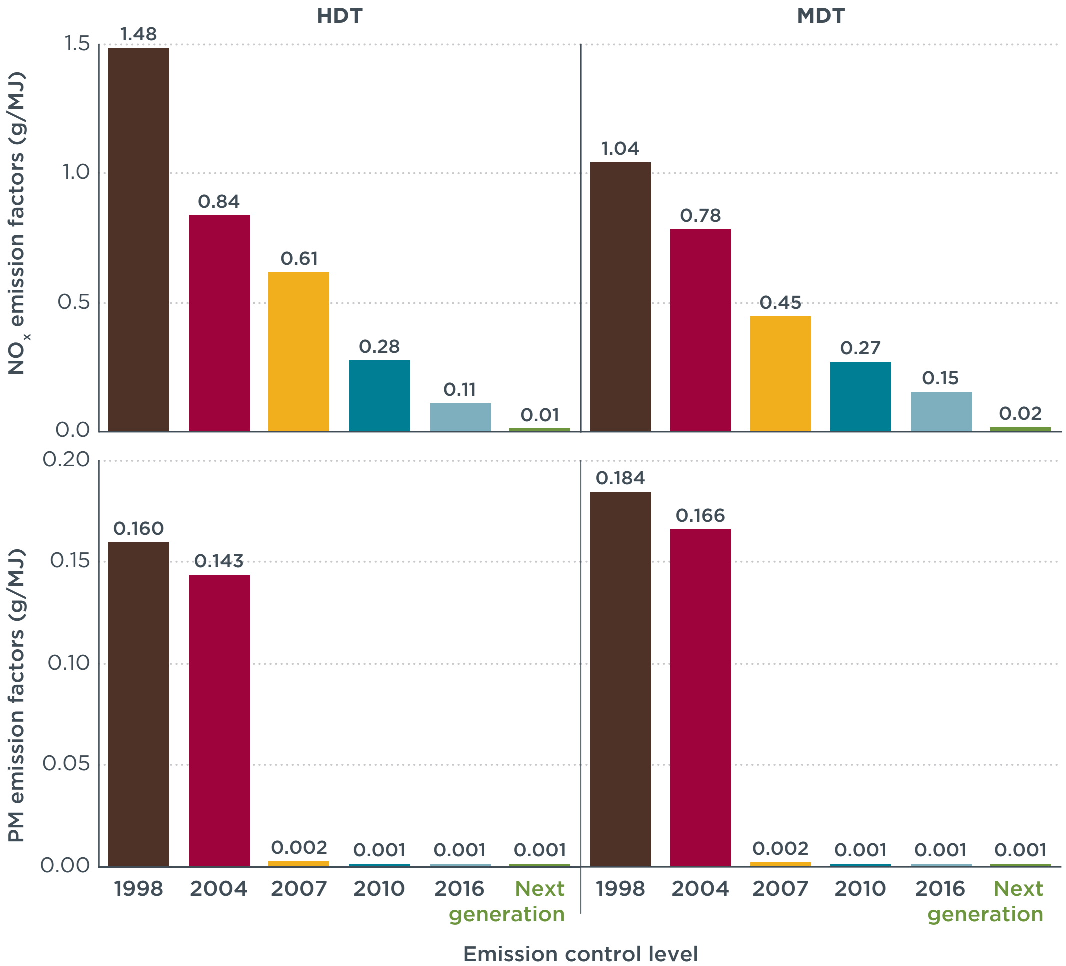


**Figure A1.** $NO_x$ and PM emission factors in grams pollutant per MJ fuel consumed by emission control level for MDTs and HDTs, including cold temperature multipliers.

## COLD TEMPERATURE MULTIPLIERS

The real-world emission factors described above represent the U.S. MDT and HDT fleet. Emissions are known to vary with ambient temperature, especially during the cold-start period after engine start. Colder temperatures can delay the aftertreatment system from reaching its operational temperature, called light-off, and accelerate the cooling of the aftertreatment system in certain situations, such as prolonged idling and sustained low-speed operation. While there are numerous readily available technologies to address these limitations, the testing provisions set by pollutant emission standards do not require them.

To account for the effects of such colder operating conditions in Canada, we developed and applied cold temperature multipliers to the emission factors available from the United States.

There are limited studies that have attempted to evaluate emissions under very low temperatures—between -20°C and -7ºC—for heavy-duty vehicles. However, as the regulation does not include any emission testing under -7°C, it is expected that engine calibration is geared towards improved drivability at those temperatures and operation conditions outside of the regulatory provisions. These regulatory limitations to drive robust emission control technologies that function in a wider range of operations, can have the following consequences:

» The emissions control system does not reach the needed operating temperatures during short trips, frequent vehicle start/stop, or low-load operation.
» The rate of heat transfer increases due to the surrounding cold environment, which in turn can bring the temperature of the emissions control system outside of its operating range.
» The calibration of the engine and emission control system might differ in cold environments, as there is no type-approval emission testing below -7°C. As a result, limited or no EGR is implemented at extreme cold climate conditions, the urea injection in SCR is avoided due to crystallization at cold conditions, among others.

Given the lack of published literature on HDV emission factors temperatures below the regulatory requirements, we surveyed the literature on diesel vehicles deployed in other regions to estimate the cold climate multipliers used in this study. While the information available pertains to light-duty diesel vehicles, we consider that their extrapolation to HDVs is appropriate due to the similarities in the architecture of the aftertreatment systems. The literature is summarized in Table A1.

**Table A1.** Summary of literature surveyed in the development of cold-temperature multipliers

| Region | Notes | Source |
|---|---|---|
| **China** | At -7°C, the $NO_x$ certification limit for China 6 vehicles is 250 mg/km. That corresponds to a multiplier of 4.2 compared to the normal type-approval conditions. | MEE (2016) |
| **Europe** | At -7°C, the test vehicles showed increases in $NO_x$ between 2.8 and 3.4, compared to the normal type-approval conditions on a WLTC. | Adamiak et al. (2020) |
| **Europe** | Cold ambient increases $NO_x$ emissions significantly from 20 mg/km up to of 900 mg/km, a factor of 45. | Söderena et al. (2020) |
| **Europe** | An increase of ambient temperature from 5°C to 25°C decreased roadside $NO_x$ emissions by 50% which was attributed to diesel vehicles | Hall et al. (2020) |
| **Europe** | Euro 6 diesel vehicles in Nordic ambient conditions reported $NO_x$ emissions of 20-70 times higher than the value reported in type approval | Weber et al. (2019) |
| **Europe** | Remote sensing study. Between ambient temperature of 25°C and 0°C, the fuel specific $NO_x$ emissions (g/kg fuel) were increased by a factor of 2.5 | Grange et al. (2019) |
| **Europe** | A standard emission test at -7°C of diesel vehicles reported higher $NO_x$ emissions between 2.3 to 6 times than Euro 6 level | Suarez-Bertoa & Astorga (2018) |

### Cold Multiplier for NOx

The cold multiplier for NOx emissions is justified by many studies in Table A1 showing the impact of ambient temperature on NOx emissions. Ranges are varied between 1.5 times to more than 50 times and higher NOx emissions depending on the testing procedure, ambient temperature, and vehicle emission control technology. We selected a conservative estimate of 1.75 and 1.5 for vehicles with emission control levels before and after 2007 respectively. It is important to note however that there is no test data below -7°C despite most Canadian winter climates experiencing much colder temperatures.

For SCR equipped engines of control level 2010 and newer, increased $NO_x$ emissions are well-studied for cold climate, and a conservative estimate of 1.5 times is considered. The primary mechanism is less NO to $NO_2$ conversion in the DOC and less urea injection at cold exhaust temperature, increasing $NO_x$ emissions. For non-SCR engines of 2007 control level and older, EGR is the only $NO_x$ control mechanism. When there is no regulatory requirement at low ambient temperature, EGR is considerably reduced or completely removed for better cold start and cold climate performance of the engine. Lower intake air temperature results in increased air density in the combustion chamber, but the fuel is also less vaporized, thereby promoting rich and lean combustion regions. This in turn increases the chances of $NO_x$ formation in the lean regions. A reduced EGR rate and increased $NO_x$ emissions are the leading causes of the cold multiplier for non-SCR engines. Compared to SCR engines, a slightly higher cold temperature multiplier of 1.75 was chosen as a conservative estimate.

### Cold Multiplier for PM

The filtration mechanism of a DPF is physical and does not rely on temperature-dependent chemical reactions. However, DPF regeneration is temperature-dependent due to a few mechanisms. At low ambient temperature, the NO to $NO_2$ conversion in the DOC is reduced, more idling time is often required for cabin heating, and overall exhaust temperature is reduced. All three mechanisms cause reduced regeneration functionality under cold ambient temperatures, which may increase PM. The cold emission multiplier was conservatively estimated at 1.5 for DPF-equipped vehicles.

For non-DPF vehicles, limited studies are available under cold ambient temperatures. A tenfold increase in diesel engine raw emissions between cold start and normal idling is showed in (Sakunthalai et al., 2014). Non-DPF diesel engines emitted relatively the same number of particles; however, the particle size of the cold ambient testing was larger, which increased the mass of total particles significantly. (Ramadhas et al., 2017) also showed similar findings, where induced intake heating lowered particle emissions in cold ambient temperatures. Accordingly, we used a five-fold emission multiplier as an estimate of PM emission increase in a cold climate for non-DPF engines.

The summary of all the emission factors, with the cold temperature multipliers are shown in Table A 2 and Table A 3 for $NO_x$ and PM, respectively.

**Table A2.** $NO_x$ emission factors

| Vehicle | Emissioncontrol level | Original $NO_x$ (g/MJ) | $NO_x$ cold temp multiplier | $NO_x$ EF with cold temp multiplier | | |
|---|---|---|---|---|---|---|
| | | | | $NO_x$ (g/MJ) | Fuel-specific $NO_x$ (g/kg) | $NO_x$ (g/bhp-hr) |
| MDT | 1998 | 0.59 | 1.75 | 1.04 | 44.78 | 6.72 |
| | 2004 | 0.45 | 1.75 | 0.78 | 33.63 | 5.04 |
| | 2007 | 0.25 | 1.75 | 0.45 | 19.20 | 2.88 |
| | 2010 | 0.18 | 1.50 | 0.27 | 11.49 | 1.72 |
| | 2016 | 0.10 | 1.50 | 0.15 | 6.57 | 0.99 |
| | Next-gen | 0.01 | 1.50 | 0.02 | 0.66 | 0.10 |
| HDT | 1998 | 0.85 | 1.75 | 1.48 | 63.95 | 9.59 |
| | 2004 | 0.48 | 1.75 | 0.84 | 36.00 | 5.40 |
| | 2007 | 0.35 | 1.75 | 0.61 | 26.47 | 3.97 |
| | 2010 | 0.18 | 1.50 | 0.28 | 11.88 | 1.78 |
| | 2016 | 0.07 | 1.50 | 0.11 | 4.64 | 0.70 |
| | Next-gen | 0.01 | 1.50 | 0.01 | 0.46 | 0.07 |

**Table A3.** PM emission factors

| Vehicle | Emissioncontrol level | Original PM (g/MJ) | PM cold temp multiplier | PM EF with cold temp multiplier | | |
|---|---|---|---|---|---|---|
| | | | | PM (g/MJ) | Fuel-specific PM (g/kg) | PM (g/bhp-hr) |
| MDT | 1998 | 0.0369 | 5.00 | 0.184 | 1.590 | 0.238 |
| | 2004 | 0.0332 | 5.00 | 0.166 | 1.430 | 0.214 |
| | 2007 | 0.0014 | 1.50 | 0.002 | 0.061 | 0.009 |
| | 2010 | 0.0006 | 1.50 | 0.001 | 0.028 | 0.004 |
| | 2016 | 0.0006 | 1.50 | 0.001 | 0.028 | 0.004 |
| | Next-gen | 0.0006 | 1.50 | 0.001 | 0.028 | 0.004 |
| HDT | 1998 | 0.0319 | 5.00 | 0.160 | 1.376 | 0.206 |
| | 2004 | 0.0287 | 5.00 | 0.143 | 1.236 | 0.185 |
| | 2007 | 0.0016 | 1.50 | 0.002 | 0.068 | 0.010 |
| | 2010 | 0.0010 | 1.50 | 0.001 | 0.041 | 0.006 |
| | 2016 | 0.0010 | 1.50 | 0.001 | 0.041 | 0.006 |
| | Next-gen | 0.0010 | 1.50 | 0.001 | 0.041 | 0.006 |

## TAMPERED VEHICLE EMISSION MULTIPLIERS

The U.S. EPA conducted chassis dynamometer testing of a "full-delete" vehicle[9] with the use of a replacement straight pipe and software tuning products (Brooks, 2019). This led to the significant finding that a Class 2b or 3 truck certified under the latest 2010 EPA regulations with complete emission control removal (EGR, DOC, DPF, or SCR) can emit 30 to 300 times higher $NO_x$ and 15 to 40 times higher PM over the

9 2011 Ford F-250 with a 6.7 L Powerstroke engine

Federal Test Procedure (FTP) drive cycle. This is roughly equivalent to emission levels observed from MY 1980 trucks.

In cases where emissions test data was not available, the EPA's TDPT study conservatively used the levels of each pollutant that the vehicle/engine was certified against. Since, in our case, we do not have any available data for tampered versus untampered vehicles, we chose to adopt a similar approach for estimating excess emissions from tampered vehicles. For example, MDT vehicles certified to 2010 standards have a real-world $NO_x$ emission value of 0.267 (g/MJ) (with cold start multiplier) for untampered vehicles. We assumed that for tampered vehicles in this same certification level, $NO_x$ emissions would be equivalent to those that are operating under the 1998 level. The real-world $NO_x$ emission rate for vehicles certified under the 1998 standard is 1.039 g/MJ; therefore, a tampered 2010 MY vehicle will emit about 3.9 times its untampered value. Vehicles with engines certified under the 1998 emission control level were the last engines to be certified without an emission control system. Therefore, we make the reasonable assumption that tampered vehicles with "full deletes" are equivalent to emissions from a 1998 MY truck. This is a significantly conservative estimate, as a factors of 30 to 300 have been observed during chassis dynamometer tests of certain tampered vehicles (U.S. Environmental Protection Agency, 2020).

For vehicles with engines certified under the 2004 and 2007 emission control level, tampered vehicles are assigned the same $NO_x$ emissions as that of a 1998 certified engine. For PM, the same is the case for engines certified under the 2007 standard. Engines certified under the 2007 standard have a DPF as part of its aftertreatment system to comply with low PM limits. Although real-world PM has been lowered with modern/newer post 2010 engines and accompanying emission control systems, they continue to employ a DPF as its principal mechanism to lower PM. We adopt a more conservative approach and assign tampered vehicles certified under the 2010 standards the same multiplier as that of 2007, such that any tampered vehicle certified under the 2007 or 2010 standard will emit about 26 times its real-world PM from untampered vehicles. Compared to the 1998 level, real-world PM emissions under the 2010 emission control level would otherwise be 56 times greater for untampered vehicles, which is higher than that found during testing.

For the 2004 control level, tampered vehicles are assigned a default multiplier of 1 for PM. Engines certified under the 2004 emission control level likely implemented the use of EGR systems to lower $NO_x$, thereby increasing PM emissions. Therefore, a tampered 2004MY to 2006MY vehicle likely only involves the removal of the EGR. Instead of an increase in PM emissions, the removal of EGR may lead to a decrease in PM. Hence, we employ a factor of 1 for PM emissions for tampered engines certified under the 2004 standards. The above principles are replicated for the HDT category. All tampered vehicle multipliers can be referenced in Table A4.

**Table A4.** Tampered vehicle multiplier for NOx and PM

| Vehicle | Emission control level | Tampered vehicle multiplier | |
|---|---|---|---|
| | | $NO_x$ | PM |
| MDT | **1998** | 1.00 | 1.00 |
| | **2004** | 1.33 | 1.00 |
| | **2007** | 2.33 | 26.00 |
| | **2010** | 3.90 | 26.00 |
| | **2016** | 6.82 | 26.00 |
| | **Next-gen** | 68.19 | 26.00 |
| HDT | **1998** | 1.00 | 1.00 |
| | **2004** | 1.78 | 1.00 |
| | **2007** | 2.42 | 20.37 |
| | **2010** | 5.38 | 20.37 |
| | **2016** | 13.78 | 20.37 |
| | **Next-gen** | 137.83 | 20.37 |

## TAMPERED AGE

The age at which a vehicle is tampered with can substantially affect the vehicle's lifetime emissions. To account for this, our modeling approach includes an age-based adjustment to the number of vehicles that are tampered with of a particular vintage. EMFAC and MOVES use a linearly increasing emission rate to model emission deterioration as a function of vehicle age (United States Environmental Protection Agency, 2020) and a similar approach is taken in this analysis, but in the application of modeling tampering incidences. As shown in Figure A2, the emission rate in the MOVES model is constant until the end of the warranty period and then increases linearly up to the useful life. In our case of modeling tampering incidence, however, we assume that tampering can be prevalent from the first year of ownership. Data from the EPA TDPT study found that over 90% of tampered vehicles are tampered within the first seven years of service life. Therefore, we use seven years as our useful life age, after which no tampering is expected to occur. Between the ages of zero and seven, we assume that the percentage of tampered vehicles of a given model year increases linearly as a function of vehicle age. Once those vehicles reach seven years old, the maximum share of tampered vehicles has been reached. The methods for determining the maximum share of tampered vehicles are discussed further in the following section.

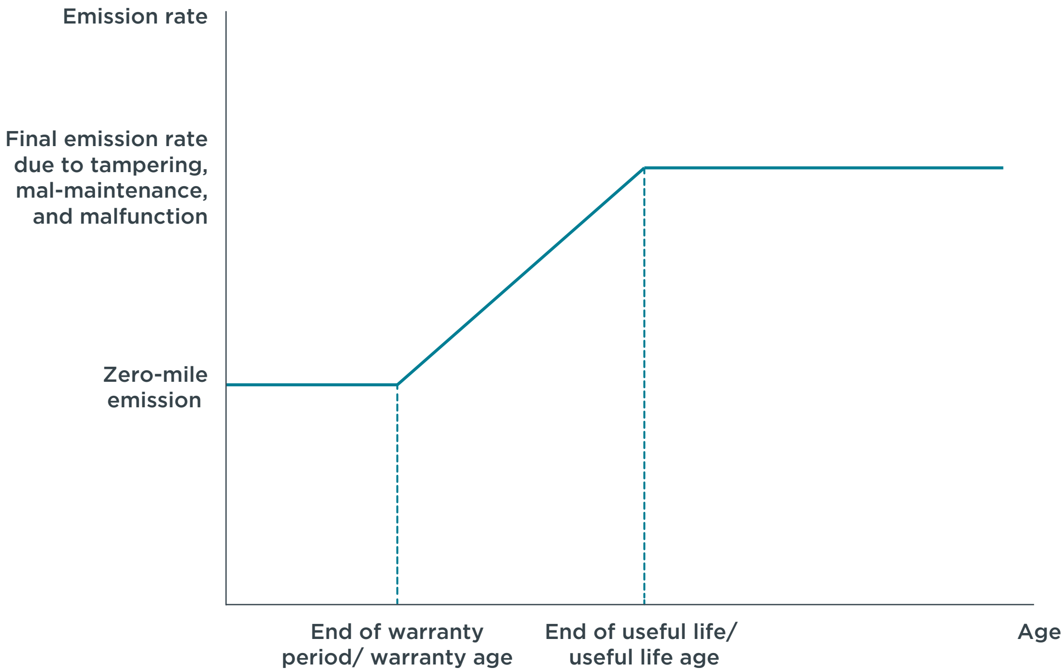


**Figure A2.** Depiction of the implementation of age effects according to MOVES3 technical report

## TAMPERED VEHICLE SHARE

Because the tampering incidence has not been comprehensively studied in Canada, this analysis builds upon the findings in the United States by EPA's TDPT study, considers the differences in the presence of provincial inspection and maintenance programs (see section Legislative background in Canada), and discriminates between MDTs and HDTs.

The tampering incidences used in the analysis below were developed based on an extrapolation from the US MDT fleet and must be considered with the understanding that there is a large degree of uncertainty in the quantification of the situation in Canada. Regardless of the selection of the tampered vehicle share described in the paragraphs below, the analysis enables us to quantify the response function of the emissions and health impacts per percentage point increase in tampering.

### Tampering prevalence modeled from U.S. EPA's findings for diesel pickup trucks

EPA's TDPT study breaks down the number of tampered trucks according to the emissions level under which the vehicles were certified. In comparison, we consider three emission control levels between 2004 and 2010, in line with the major policy steps in the United States, the EPA study uses a fourth additional level in the 2007 MY– 2012 MY category. During the phase-in approach after 2007 to comply with the lower $NO_x$ limits mandated by the standards, vehicles were certified with different types of aftertreatment systems. The most common ones were either with no $NO_x$ aftertreatment system or the inclusion of a passive $NO_x$ adsorbing (PNA) catalyst. The TDPT study identifies the additional emission control level (2007–2012) as that associated with vehicles equipped with PNA. However, ICCT's Roadmap model does not distinguish vehicles separately based on whether or not they had $NO_x$ aftertreatment. To accommodate this, we chose to combine the two overlap levels from the EPA's TDPT study (2008–2010 and 2007–2012), evenly splitting the number of tampered vehicles in the 2007 and 2010 emission control level as defined in the Roadmap model.

The TDPT study uses 2016 vehicle registration data to derive vehicle tampering shares according to the defined emission control levels. Similarly, we used the 2016 U.S. MDT stock totals from the Roadmap model and the number of tampered trucks from the EPA TDPT study to derive the average U.S. TVS for emission control levels 2004, 2007, and 2010+. The TVS that we derive is not to be confused with tampering incidence (because in actuality, the TVS will never be equal to the tampering incidence), rather it is a modeling metric used to arrive at the linear rate of increase needed to reach a target value at the end of the tampered age. As outlined above, an additional 2016 emission control level was added to modify the emission factors for 2016 and later MY vehicles; however, the tampering vehicle shares remain the same. For the purposes of this section, the 2010 and 2016 emission control levels will be referred to as the 2010+ control level.

Combining the data from the EPA TDPT study on the number of tampered trucks (Table A5) with vehicle inventory data from ICCT's Roadmap model, the prevalence of tampering for MDTs can be derived according to emission control levels (Table A6).

**Table A5.** Tampering prevalence for MDTs in the United States, 2016

| Emission control level | Number of tampered trucks |
|---|---|
| **2003-2006** | 72,904 |
| **2008-2010** | 129,555 |
| **2007-2012** | 150,954 |
| **2010+** | 204,066 |
| **Total Tampered** | **557,479** |

**Table A6.** Tampering prevalence for MDTs in United States, 2016 and 2020

| Emission control level | Number of tampered trucks | U.S. inventory | % Share in year 2016 | % Share in year 2020 |
|---|---|---|---|---|
| **2004** | 72,904 | 1,037,952 | 7.0% | 7.0% |
| **2007** | 205,032 | 697,478 | 29.4% | 29.4% |
| **2010+** | 279,543 | 2,132,740 | 13.1% | 18.6% |
| **Total** | **557,479** | **3,868,170** | **14.5%** | **21.5%** |

Vehicle MYs belonging to the 2004 and 2007–2009 control levels are above the age at which the TVS is reached (at 7 years), and thus we define the percent share of tampered vehicles as the target TVS metric for the respective control levels. In other words, 7% of the 2004 control level and 29% of the 2007 control level vehicles are expected to have been tampered by the year 2016. However, this is not the case for vehicles in the 2010+ emission level. Based on our linear assumption that the tampering incidence increases as a result of vehicle age until it reaches the defined tampered age of 7 years, we can deduce that the tampering incidence will be the lowest for MY 2016 vehicles and the highest for MY 2010 vehicles. For example, MY 2015 vehicles are only one year old in 2016, and thus the tampering prevalence among MY2015 vehicles is only a fraction, in this case one seventh, of the target TVS. Therefore, the 13.1% tampering incidence in 2016 from the 2010+ control level will not yield the predicted total tampering incidence of approximately 14.5% in the EPA TDPT study.

We adjusted the yearly TVS in the 2010+ control level to achieve consistency with the tampering prevalence reported in the EPA TDPT study. Based on this extrapolation, we found that the target TVS for MY 2010+ vehicles must be 31.5% to yield a total tampering incidence (weighted according to all vehicles in all emission control levels) to be about 14.5% in the year 2016. In this regard, we set a target TVS of 31.5% for vehicles in the 2010+ emission control level (Table A7). Although the tampering incidence in 2016 is only 13.1%, it is composed of varying tampering incidence (due to the linear increase assumption for modeling purposes) as a function of vehicle MY for vehicles in the 2010+ control level (as seen in Figure A3).

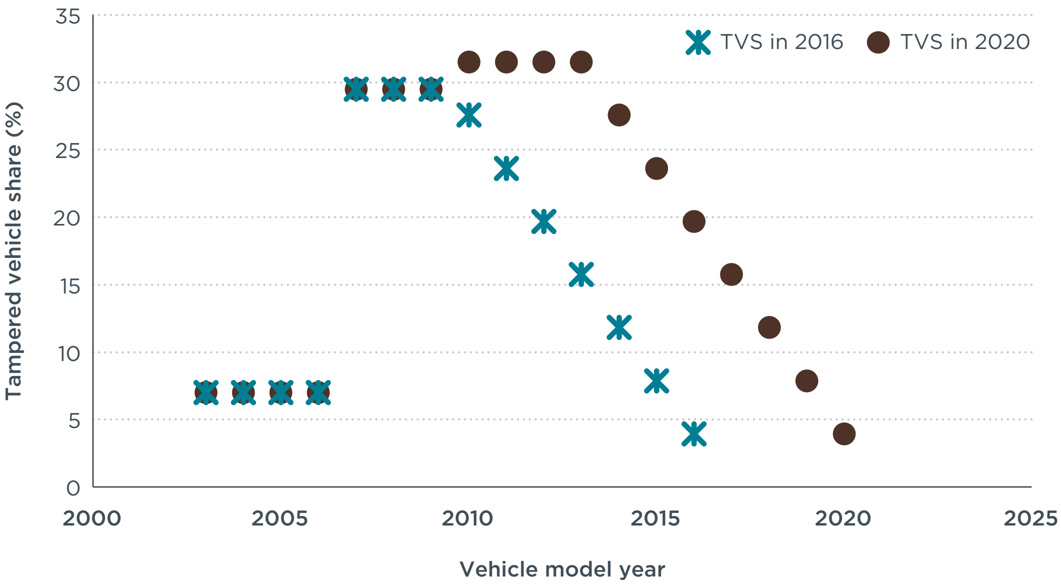


**Figure A3.** Tampering vehicle share in 2016 and 2020 as a function of vehicle model year

**Table A7.** Tampering vehicle share according to emission control levels

| Emission control level | Tampering vehicle share |
|---|---|
| **2004** | 7.0% |
| **2007** | 29.4% |
| **2010+** | 31.5% |

By the year 2020, there was a higher fraction of vehicles with 2010+ emission control level due to fleet turnover and, accordingly, a higher percentage of vehicles with the same level have been tampered with relative to 2016. As seen in Figure A 3, a higher share of vehicles MY 2013 and prior have reached the target TVS of 31.5%. Consequently, this results in a 21.1% tampering incidence for the 2010+ control level for Canadian MDTs and translates to 23.3% tampering incidence for all MDTs (Table A8). This is on par with the extrapolated 2020 tampering incidence for US MDTs of 21.5% as shown in Table A6.

**Table A8.** Tampering prevalence for MDTs in Canada, 2016 and 2020

| Emission control level | % Share in year 2016 | % Share in tear 2020 |
|---|---|---|
| **2004** | 7.0% | 7.0% |
| **2007** | 29.4% | 29.4% |
| **2010+** | 16.2% | 21.2% |
| **Total tampering incidence** | **16.8%** | **23.3%** |

For each province, the tampering incidence are further divided among the three different emission control levels: 2004, 2007 and 2010+. For example, for the MDT Medium scenario, we defined a 15% tampering incidence for provinces with an inspection and maintenance program, however, the targeted TVS (needed for modeling purposes) had to be adjusted according to individual emission control levels (2004, 2007, and 2010+) which yield a weighted tampering incidence of 15%. To evaluate this, we extrapolate in reverse using the 2020 inventory data. We know that the 2004 and 2007 control levels do not vary as a function of vehicle age since all vehicles certified to those levels are older than 7 years (our defined tampering age threshold). For the 2010+ control level, we input a linear function and increase the targeted TVS until the weighted tampering incidence yields 15%. We do this methodologically for all the individually defined incidences,to result in a breakdown of the target TVS' needed as inputs for modeling purposes as a function of the emission control level. The target tampering incidence of 15% for example is achieved by implementing a TVS of 4.7% for 2004, 19.7% for 2007, and 21.0% for the 2010+ emission levels. These targeted TVS' are not representative of the tampering incidence for each emission control level, rather they are just a modeling metric used to achieve the desired tampering incidence targets due to our assumption of a linearly increasing incidence over 7 years.

# APPENDIX B

**Table B1**. Examples of businesses offering tampering or tuning services in North America

| Company | Vehicle type | Vehicle make/ model | Size (liters) | Years | Type | Hardware software | ECM | DPF | EGR | SCR | Hardware price ($) | Software price ($) | Distribution | Place | Country | Year caught or settled | EPA settlement | Additional notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rawtek Inc** | LHD | Daimler Sprinter | 3 | 2010–2019 | Delete & Tune | H+S | 1 | 1 | 0 | 0 | 695 | 689 | Online | Ontario | Canada | | | |
| **Diesel Spec Inc** | MHD-HHD | Cummins, Daimler, Detroit Diesel, Isuzu, Paccar | all | | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | Online and Dealers | Québec | Canada | | | |
| **defdeletekits.com** | LHD | GM Duramax, Dodge Cummins, Ford Powerstroke | 6.4–6.7 | 2007–2015 | Delete & Tune | H+S | 1 | 1 | 0 | 0 | | | Online | | | | | Sold exclusively on Amazon and Ebay |
| **Diesel PowerUP** | LHD | GM Duramax, Dodge Cummins, Ford Powerstroke | 6.4–6.7 | 2007–2015 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | Online | | | | | Sold exclusively on Amazon and Ebay |
| **J-Ball Electronics** | All | Cummins, Detroit Diesel, Daimler, Volvo | | | Delete & Tune | H+S | | | | | | | Online, Regional Dealers | Vernon, British Columbia | Canada | | | Advertised as Tuning only |
| **EGRDELETEKIT.com** | LHD | Dodge Cummins, Ford Powerstroke | 6–6.7 | Ford 2003–2007, Cummins 2010–2016 | | H | 0 | 0 | 1 | 0 | 129 | 0 | Online | Tennessee? | United States | | | Claims to have over 8000 "happy diesel owners" From area code, could be located in Tennesse, US |
| **IMS Industrial Matrix Solutions** | All | Cummins, Isuzu, Daimler/ Mercedes, Paccar,Volvo/ Mack | Range | | | H+S | 1 | 1 | 1 | 1 | 1500 | | Online | Vancouver BC and Montreal Québec | Canada | | | |
| **ECM TUNEUP** | mainly HHD | Cummins, Detroit Diesel, Volvo, Paccar, Volvo-Mack | | | | H+S | 1 | 1 | 1 | 1 | | | Online | Orlando? | United States | | | |
| **Performance Diesel** | | Caterpillar, Cummins, Detroit Diesel, International, Paccar | all | 1993–2020 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | | Utah/ Pennsylvania | United States | 2019 | Y | Sold at least 5549 defeat devices |
| **Derive Systems (Bully Dog and SCT)** | | Ford-Powerstroke and GM | 6.7 | | Tuners | S | 1 | 0 | 0 | 0 | | | | Multiple | United States | 2019 | Y | Over 360,000 tuners/ devices sold |
| **Klenz Brothers Diesel** | LHD | Mainly Ford | 6.4–6.7 | | | | 1 | 1 | 1 | 0 | | | | Philadelphia | United States | 2019 | Y | |
| **Spartan Diesel** | LHD | Ford Diesel F250-550 | 6.4–6.7 | 2008–2012 | | S | 1 | 0 | 0 | 0 | | | Online | | United States | 2019 | Y | |
| **PSP Diesel** | LHD | GM Duramax,Ford Powerstroke | 6–6.7 | | | H+S | 1 | 1 | 1 | 1 | | | | Houston | United States | 2019 | Y | SCT Performance 7015 X4 Flash Programmer - custom tunes |
| **Innovative Diesel** | LHD | Ford-Powerstroke | 6 | 2003–2007 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | | Philadelphia | United States | 2020 | Y | SCT Tuners and Delete Pipes |
| **Freedom Performance** | LHD | Ford, Chevy/ GMC, Dodge-Cummins engines | 5.9–6.7 | 2003–2017 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | | Florida | United States | 2020 | Y | Multiple violations - pg 17-31 -14000 deletes |
| **PowerProductSunLimited** | | Cummins, FCA, GM, Ford | | | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | | Spokane Washington | United States | 2020 | Y | Crankcase emission control removal, electrinic tuning and remove pipes/bypass |
| **Hardway Solutions** | LHD | Dodge Ram/ Cummins, GM/Chevy Duramax | | | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | | Florida | United States | 2020 | Y | SCT, H&S Mini Maxx, BullyDog, and XRT Tuners, EFILive Tunes - specifically alter fuel timing maps and calibrations. Also sells delte pipes |
| **Revolution Motors** | LHD | Ford, GM, Dodge, Chevy | | | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | Online - book appointment | Edmonton | Canada | | | advertised as "Enhance Your Diesel's Performance & Efficiency with a DPF, DEF, or EGR Delete Service" |
| **Pusher** | LHD | Dodge Ram/ Cummins, GM/Chevy Duramax, Ford Powerstroke | | 2000–2017 | Delete | H | | | 1 | | | | Online | | US and Canada | | | Dieselarmy Blog post shows EGR delete capability via straight pipe |
| **Tune My Trucks** | HHD | Cummins, Maxxforce-Navistar, Detroit Diesel, Mack-Volvo, Paccar | | | Delete & Tune | H+S | 1 | 1 | 1 | 1 | 1300-5000 | 1700 | Online | Houston | United States | | | Wide range of available options, ECM tune to complete deletes |
| **Big Rig Power** | HHD | Caterpillar, Cummins, Detroit Diesel, Maxxforce-Navistart-International, Paccar, Mercedes, Volvo | | 2003–2018 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | | | Online | Edmonton | Canada | | | |
| **DTP Diesel Truck Products** | LHD | Dodge Ram/ Cummins, GM/Chevy Duramax, Ford Powerstroke | | 2007–2019 | Delete & Tune | H+S | 1 | 1 | 1 | 1 | all prices shown online | 1500 | Online | | | | | EZ LYNK Tune |
| **Anarchy Diesel Tuning** | LHD | Dodge Ram/ Cummins, GM/Chevy Duramax, Ford Powerstroke | | 2004–2019 | Tune | S | 1 | 0 | 0 | 0 | | all prices shown online | Online & Store | Tennesse | United States | | | EZ LYNK and MM3 Tune |
| **Starlite Diesel** | LHD | Dodge Ram/ Cummins, GM/Chevy Duramax, Ford Powerstroke | | | Tune | S | 1 | 0 | 0 | 0 | | | Online | | United States | | | Reseller of EFILive, EZLYnk, MM3 and HPTuners tuning software/device |
| **Diesel Performance of Montana** | | Cummins, Detroit Diesel, CAT | | | Delete & Tune | H + S | 1 | 1 | 1 | 1 | | | Online & Store | Montana | United States | | | |

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communications@theicct.org

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