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Pathways for CO₂ regulation in NRMM

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CUSTOMER REPORT

VTT-CR-0032-24

Pathways for CO₂ regulation in NRMM

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beyond the obvious

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<p>Summary</p> <p>Information on energy use and emissions from non-road mobile machinery (NRMM) is scattered. Based on available information from 2010, it can be estimated that the NRMM sector represents about 2% of GHG emissions in Europe. Agriculture machinery covers around 50% and construction machinery around 25% of NRMM total CO₂ emissions. The remaining 25% is covered by the various machinery in other categories. This clearly indicates that the highest potential in CO₂ reduction is in agriculture and construction machinery. The remainder of the machinery covers machine types, for example mining and cargo handling, where market driven electrification has developed furthest.</p> <p>Currently, NRMM is the only vehicle/machinery category which is not subjected to CO₂ emission standard regulations. Only regulations for air pollutant emissions are in place. Therefore, one can anticipate that there will be a growing interest to extend CO₂ emission standard regulations also to the NRMM sector. For example, California Air Resources Board (CARB) has started discussions on updating NRMM emission standards and at the same time introducing CO₂ standards. However, the wide variety in types of NRMM and their use patters pose challenges in setting possible CO₂ emission standards to NRMM based on current engine only type-approval process. Current NRMM engines type approval process will enable only a very limited reduction potential for CO₂ emissions. By estimation, a 15% efficiency improvement in engine level could be achievable in the long term. For greater CO₂ reduction, new measures are needed to take into an account the unique nature of the NRMM sector.</p> <p>Tank-to-wheel based approach only will not provide the required toolbox for NRMM Original Equipment Manufacturer (OEM) to develop products that achieve emission reductions and fulfil the requirements of the end-users. The necessary approach should be holistic and technology neutral, combining multiple measures and recognizing also upstream energy carrier emissions. Speeding up RDI investments (e.g. more prominent role in EU RDI funding schemes and regulations) on energy efficient NRMMs, renewable and sustainable energy carriers and powertrains for NRMM use would contribute to market driven approach for CO₂ reduction. Public procurement is another effective way for establishing market demand for low carbon NRMM solutions. Clean vehicle directive (CVD) could be used as exemplary framework for setting up a "Clean Machinery Directive". A variety of energy carriers is needed in the NRMM sector due to complex use cases. Thus, investigation of possible methodologies how to include all renewable and sustainable energy carriers in NRMM regulation would be highly important. At the same time, alternative energy sources require new infrastructure that should be investigated. Finally, introduction of on-road HDV's CO₂ regulation-based approach for defining CO₂ emissions in machine level would provide a comprehensive measure to improve energy efficiency and reduce CO₂ emissions in machine level.</p>	
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1. Description and objectives

This paper is written within a project ordered by the Ministry of Environment Finland. The content is the responsibility of the authors and does not necessarily represent the view of the Ministry of the Environment.

The purpose of this paper is to provide information for discussions on possible regulatory measures at EU-level to reduce the emissions of the non-road mobile machinery (NRMM) – sector. Assignment included four main items to be covered: Significance of NRMM sector on European GHG emissions, current NRMM regulatory scheme, possible methodologies for reducing CO₂ emissions in NRMM and suggestions for the most feasible measures to reduce CO₂ emissions.

Paper constitutes from four main chapters. Chapter 2 provides an overview on NRMM sector CO₂ emissions and how those are divided between different machinery types. It also briefly explains the significance of NRMM sector in EU level and current situation with market driven development of alternative powertrain machinery. Chapter 3 focuses on the current emission regulation for NRMM and on-road HDV's. In chapter 4, possible regulatory measures for CO₂ emission regulation on NRMM level are presented. Chapter 5 presents possible soft measures for CO₂ reduction.

Chapter 6 presents synthesis from the presented possible measures for CO₂ emission reduction in the NRMM sector.

2. A review of NRMM sector emissions in European level considering the development trends

In total, NRMM sector GHG emissions represent around 2% of total GHG emissions in Europe. Agriculture machinery is responsible for approx. 50% and construction machinery approx. 25% of total NRMM sector GHG emissions in EU-27. The rest 25% is caused by for example forestry and mining machinery, municipal maintenance machinery, cargo handling and machinery operating at ports.

Currently, greenhouse gas (GHG) equivalent emissions from NRMM are not regulated in the EU. The NRMM engine emission type approval regulation today covers only air pollutant emissions. Typically, direct CO₂ emissions from fuels combustion have been a major part of engine derived GHG emissions. To comply with the latest regulation, NRMM engines are equipped with Selective Catalytic Reduction (SCR) systems. High efficiency SCR systems can reduce NO_x emissions in tailpipe even below 1% of engine-out emissions. However, some catalytic materials may produce N₂O emissions as a side product of NO_x reduction. N₂O has high GHG factor varying from 280 (20 years) to 310 (100 years) depending on time horizon¹. Depending on system, GHG equivalent emissions of N₂O from a diesel engine may correspond up to some percentage of CO₂ emissions².

In total, NRMM sector GHG emissions represent around 2% of total GHG emissions in Europe based on the values from 2010³. More fresh estimation was not found. This figure might have changed during the past 13 years somewhat. However, it is well anticipated that the change has not been dramatic. The total NRMM sector emission can be divided into three main sub-groups. Largest single source of GHG emissions is agriculture machinery covering approx. 1% of EU-27 emissions based on the 2021 inventory⁴. Construction machinery is the second-largest contributor in total NRMM GHG emissions with around 0.5% share of total EU-27 emissions⁵. The third group, representing the remaining 0.5% of total GHG emissions in EU-27 level, covers rest of the non-road mobile machinery.

The main NRMM sector GHG emissions at EU level can be estimated as follow:

1. Agriculture machinery: 50% of NRMM sector GHG emissions. Representing around 1% of total EU-27 emissions.
2. Construction machinery: Around 25% of total NRMM sector GHG emissions. Representing around 0.5% of total EU-27 emissions.

¹ United Nations Climate Change: <https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials>

² https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_57.pdf

³ <https://doi.org/10.1016/j.eti.2023.103187>

⁴ https://www.cema-agri.org/images/publications/position-papers/CEMA_decarbonising_agriculture_27-04-22.pdf

⁵

<https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwikp5fLpoyDAX7ExAIHZQGAtAQFnoECA4QAw&url=https%3A%2F%2Fwww.cece.eu%2Fcms%2Fstreambin.aspx%3Fdocumentid%3D2900&usg=AOvVaw2VzfEkuLz47nZYeWy1XFEG&opi=89978449>

3. Rest of the NRMM: Around 25% of total NRMM sector GHG emissions. Representing around 0.5% of total EU-27 emissions.

Group three (rest of the NRMM) comprises for example forestry and mining machinery, municipal maintenance machinery, cargo handling and machinery operating at ports. Summarising, groups one (agriculture) and two (construction) machinery cover together around 75% of the NRMM CO₂ emissions at EU-27 level.

It is worth of mentioning that the figures presented above should be considered as indicative only as there was not found single European level inventory for NRMM sector GHG emissions, but estimations are gathered from different sources.

2.1 NRMM industry in European perspective

The overall non-road mobile machinery (NRMM) EU production value comprising agriculture, forestry, mining, quarrying and construction machines can be estimated at around €76 billion per year and is manufactured by both large and small companies⁶. Germany's share of total production value is the largest with approx. €29 billion (38%), following with Italy approx. €12,4 billion and France with approx. €7,5 billion. In Finland the production value is approx. €4.3 billion.

By comparing the country specific NRMM production values against the Gross Domestic Production (GDP) in 2021⁷ makes the listing look different. Industrial significance of the NRMM sector in Finland is clearly the highest in Europe when compared to GDP. Production value compared to GDP is around 1,72 % in Finland and 0.80% in Austria and Germany, following with Czechia with approx. 0.71% and Italy with approx. 0.70%.

In general, the non-road mobile machinery sector in EU is a significant producer and strong exporter globally. Based on European Commission press release out of the annual production value, 42% is exported to non-EU countries and 54% is traded intra-EU, and only 4% is sold in the EU country where production takes place⁸. This highlights that the handprint of European NRMM OEM's is significant in global level. However, it is worth to note that the total production value of non-road machinery in Europe differs significantly between the values informed by Eurostat (around €76 billion in 2020) and European Commission (€12.5 billion).

2.2 Market-driven development

There is already fast-growing demand for zero-emission mobile machinery especially in mining and cargo handling sector. To answer this demand, leading OEM's have already introduced battery electric versions in their product portfolio. For example, Kalmar, Konecranes, SANY and Taylor provide already battery electric container handling machinery. Similarly in mining sector many OEM's, such as Epiroc, Metso and Sandvik, have already available battery electric machines in their product portfolio.

In construction machine sector, some OEM's also offer battery electric machines. Volvo has a rather wide product portfolio starting of around 2 tonnes excavator ranging up to 26 tonnes excavators. Similarly, there is battery electric products available for wheel loaders in around 5

⁶ https://ec.europa.eu/eurostat/databrowser/view/sbs_na_ind_r2__custom_8486606/default/bar?lang=en

⁷ <https://www.statista.com/statistics/613071/gdp-by-country-in-europe/>

⁸ https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2046

tonnes segment. Caterpillar⁹ and Komatsu¹⁰ have announced an introduction of battery electric machines.

On the agri-machinery side, some OEM's have already introduced alternative powertrain solutions. New Holland offers a methane powered tractor, which in the agriculture sector allows usage of bio methane. In addition, New Holland is working on battery electric and LNG fuelled tractors¹¹. Fendt and Case IH are already offering small battery electric tractors^{12,13}.

Most of the NRMM engine OEM's have allowed already for some years the use of HVO diesels.

Concluding, there are clear signals of market-driven development as currently there is no clear regulatory direction requiring OEM's to produce alternative powertrain machines with low or zero tailpipe emissions. It also highlights that market-driven (i.e. users of machines, or end users ordering services provided by the machine operators) approach brings alternative powertrain machines in the first place to two kinds of settings. The first one as in those applications where the OEM and users foresee a competitive and viable total cost of ownership (TCO) and process productivity of the machine compared to traditional diesel-powertrains. Secondly, low or zero-emission NRMM will be favoured in public and private procurement bids where the end user buyer prefers or requires low/zero-emission powertrains due to e.g. environmental reasons. These machine segments where market-driven approach almost or already pull zero and low-emission (CO₂) machinery on the market can be seen as low-hanging fruits for wider deployment of such technologies. As described above, mining and cargo handling sectors are one example of such development.

2.3 The most significant NRMM segments with the greatest CO₂ reduction potential

As presented in previous chapter 2, agriculture machinery is responsible for 50% of the total NRMM GHG emissions in EU-27 and 25% is caused by the construction machinery. Altogether, these two machine segments cover 75% of the total NRMM GHG emissions in EU. The last 25% of the GHG emissions is caused by the rest of the non-road machinery. This group also includes cargo handling and mining machinery where market driven development towards battery electric solutions has evolved furthest. Thus, in case CO₂ regulation measures are considered for the NRMM sector, agriculture and construction machinery segments need to be included in those to achieve significant reduction on CO₂ emissions within the NRMM sector. However, the latest update on both the on-road HDV CO₂ regulation and ETS 2 exclude vehicles and fuels in agriculture and forestry, and this could cause inconsistency.

⁹ <https://www.caterpillar.com/en/news/corporate-press-releases/h/Caterpillar-expands-construction-industries-portfolio.html>

¹⁰ <https://www.komatsu.jp/en/newsroom/2023/20230721>

¹¹ <https://agriculture.newholland.com/de-de/europe/unsere-vision/besondere-projekte>

¹² <https://www.fendt.com/de/landmaschinen/traktoren/fendt-e100-v-vario>

¹³ <https://www.caseih.com/en-us/unitedstates/products/tractors/farmall-series/farmall-electric-tractor>

3. Current regulatory framework for pollutant and CO₂ emissions – On-road and off-road

NRMM is currently the only vehicle/machinery category which is not subjected to CO₂ regulations. Only regulations for pollutant emissions are in place. Therefore, one can anticipate that there will be a growing interest to extend CO₂ regulations also to the NRMM sector. However, the wide variety in types of NRMM and their use patterns pose challenges in setting possible CO₂ limits to NRMM.

3.1 General

Currently, only regulations regarding pollutant emissions (e.g., carbon monoxide CO, hydrocarbons HC, nitrogen oxides NO_x and particulate matter PM) are in place for NRMM. However, California Air Resources Board (CARB) has started discussions on updating NRMM emission standards and at the same time introducing CO₂ (carbon dioxide) standards¹⁴. In the case of on-road vehicles, regulations for pollutant emissions as well as for fuel economy/carbon dioxide (CO₂) emissions are in place.

The methodologies for regulating CO₂ emissions from heavy road vehicles are analysed closer, to make it possible to draw parallels to the NRMM sector.

3.2 Pollutant emissions

The US Environmental Protection Agency (EPA) first set federal emission standards for new nonroad diesel engines in 1994 (Tier 1), thus with a significant delay compared to on-road vehicles, for which regulations were introduced already in 1970¹⁵. Europe lagged behind the US, as the first Euro standards for light- and heavy-duty on-road vehicles were introduced as late as in 1992, and regulations for non-road diesel engines (Stage 1) in 1999¹⁶.

Testing for light-duty vehicles is done with complete vehicles, whereas emission certification for heavy-duty road as well as for NRMM is carried out with standalone engines in engine test benches.

Fortunately, current US (Tier 4)¹⁷ and EU (Stage V)¹⁸ regulations for NRMM are relatively well aligned. As of Tier 4/Stage V, both steady-state and transient testing is required. The dynamic (transient) test cycle used is the Non-Road Transient Cycle (NRTC), developed in cooperation between US EPA and the authorities in the European Union. The steady-state cycle, Non-Road Steady Cycle (NRSC) is basically ISO 8178. Carbon dioxide (CO₂) emissions are measured in testing but not reported or regulated.

Table 1 presents a comparison of Stage V and Tier IV limit values for engines in the power range between 130 and 560 kW. The biggest difference is that EU regulates particulate numbers (PN) and EPA does not. Tier IV can be met without an actual particulate filter, Stage V

¹⁴ <https://ww2.arb.ca.gov/our-work/programs/tier5>

¹⁵ <https://www.epa.gov/transportation-air-pollution-and-climate-change/history-reducing-air-pollution-transportation>

¹⁶ <https://dieselnet.com/standards/eu/index.php>

¹⁷ <https://dieselnet.com/standards/us/nonroad.php>

¹⁸ <https://dieselnet.com/standards/eu/nonroad.php>

cannot. A tightening of the US EPA regulation, Tier V with reduced NO_x and PM values, is anticipated in the timeframe 2028 – 2030.

Table 1: Comparison of EU Stage V and US EPA Tier IV pollutant emission limits for NRMM engines (example for the power band of 130 ≤ kW ≤ 560). From ^{17,18}.

Parameter	EU Stage V	US EPA Tier IV
Year	2019	2011-2014
Test cycle	NRTC, NRSC	NRTC, NRSC
CO (g/kWh)	3.50	3.50
HC (g/kWh)	0.19	0.19
NO _x (g/kWh)	0.40	0.40
PM (g/kWh)	0.015	0.02
PN (#/kWh)	1x10 ¹²	-

3.3 CO₂ emissions

3.3.1 General discussion

Vehicle CO₂ regulations are based on tailpipe (tank-to-wheels) emissions. This stems from the fact that using conventional fossil fuels (petrol and diesel), CO₂ emissions and the amount of fuel used (efficiency) correlate. When comparing conventional vehicles using conventional fuels this approach is valid. However, the tailpipe approach does not in any way take into account the use of renewable fuels. A fair way to assess new energy carriers and new vehicles would be to use well-to-wheel (WTW) methodology (Figure 1) or even better life cycle analysis (LCA) to evaluate overall greenhouse gas emissions and energy use.

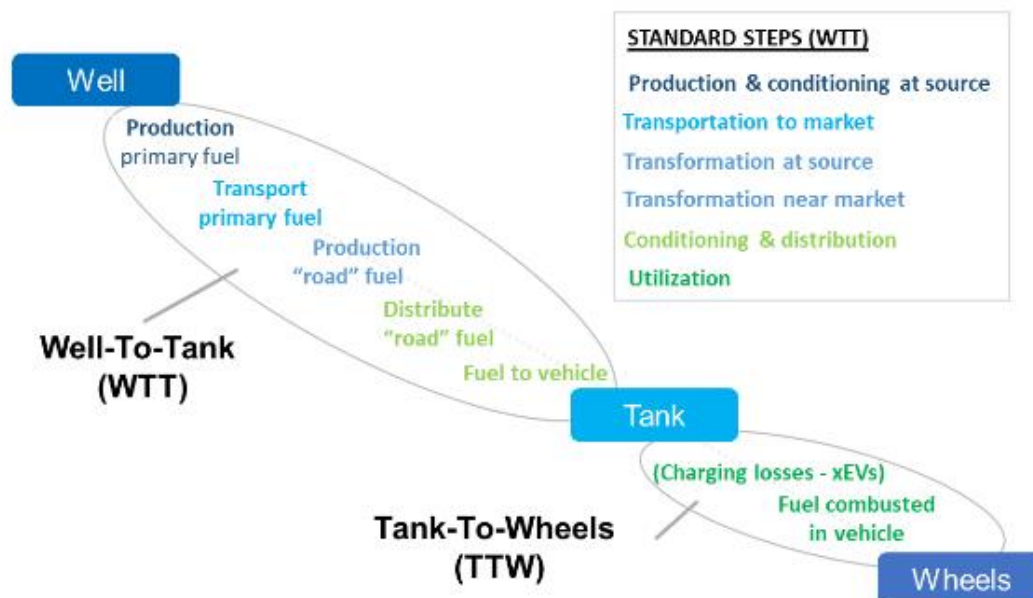


Figure 1: Well-to-wheel versus tank-to-wheels¹⁹.

¹⁹ file:///C:/Users/pronon/Downloads/jec_wtw_v5_121213_final.pdf

Anyway, emission inventories and emission trading schemes report fuel volumes used and the carbon intensity of the fuels, and thus take into account the use of renewable fuels. The recently adopted revision of the Renewable Energy Directive (RED III) sets targets for the use of renewable in transport, expressed either as a 14.5% GHG intensity reduction or a binding 29% target for renewable energy in transport²⁰.

In the US, regulations for CO₂ emissions from heavy-duty vehicles (HDV) are in place as of 2014. EU introduced CO₂ regulations for heavy-duty vehicles in 2019, in the first step setting targets for 2025 and 2030²¹.

3.3.2 Testing for CO₂ emissions and factors affecting tailpipe CO₂ emissions

In the case of light-duty vehicles, CO₂ testing is done with complete vehicles on a chassis dynamometer. Basically, each and every car or van model has a specific CO₂ value, even taking into account the impact of accessories.

However, due to much higher unit costs of testing and lower production numbers in combination with a high number of vehicle configurations (with variations in engine, transmission, chassis, tyres and bodywork) and applications compared to passenger cars, chassis dynamometer testing has not been deemed feasible for HDV CO₂ certification purposes. Therefore, the predominant methodology in heavy-duty vehicle CO₂ regulations is actually measuring and testing the engine and other key components, and form performance data for the complete vehicle by combining measured engine data with simulation of the vehicle. The same kind of methodology could in principle be applied to NRMM.

Typically, only the most common vehicle types and/or vehicles which consume the largest fuel volumes are subjected to CO₂ regulations. In the case of a long-haul truck, the manufacturer of a vehicle equipped with an internal combustion engine (ICE) can take several measures to reduce fuel consumption and thus tailpipe CO₂ emissions, e.g., increase the efficiency of the engine, apply hybridisation to recuperate kinetic energy, improve vehicle aerodynamics to reduce drag and bring down vehicle curb weight to reduce weight related resistance forces.

Electrification delivers zero end-use tailpipe CO₂ emissions, in the same way as hydrogen, either used in an ICE or in a fuel cell. All above-mentioned features can be taken into account in modelling CO₂ emissions.

VECTO is the European simulation tool developed by the European Commission (Figure 2). It is used for determining CO₂ emissions and fuel consumption from HDV (trucks, buses and coaches) with a gross vehicle weight above 3500 kg.

²⁰ <https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/renewable-energy-council-adopts-new-rules/>

²¹ <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1242>

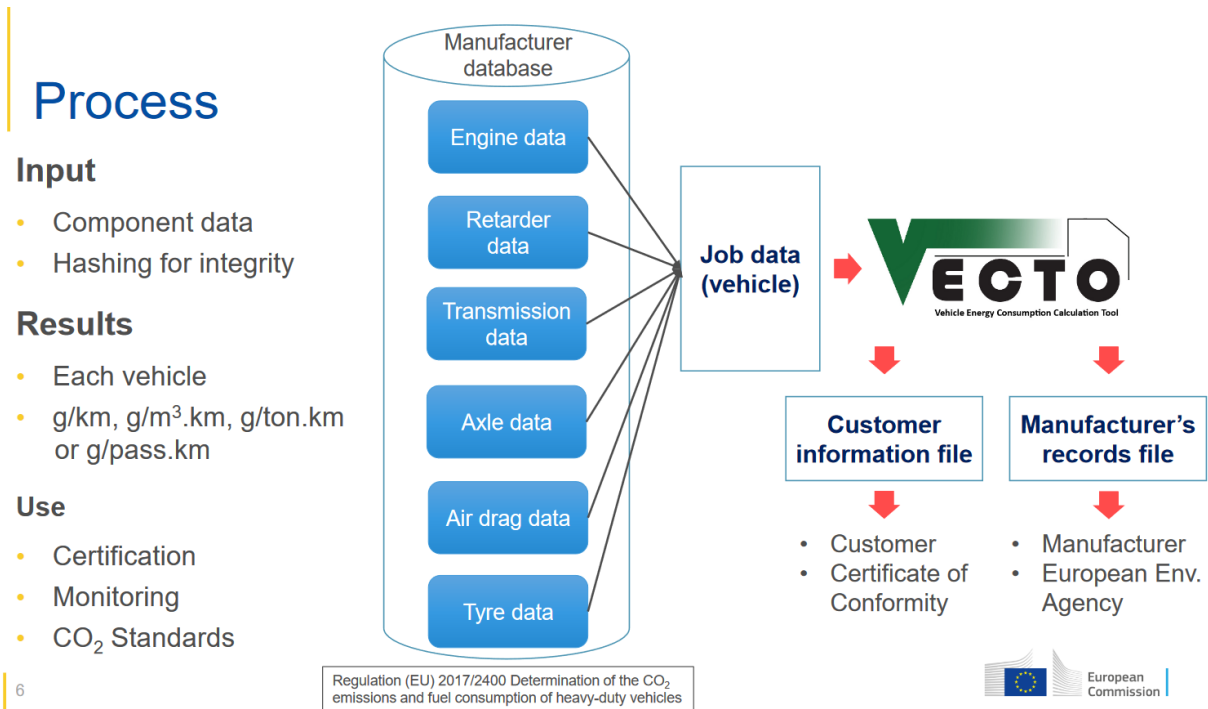


Figure 2: The VECTO process²².

To provide engine data, the engine is tested using the two emission test cycles, World Harmonised Transient Cycle (WHTC) and the World Harmonised Steady Cycle (WHSC), and in addition, using the fuel consumption mapping cycle (FCMC), which consists of some 100 speed/load points²³. In addition to the engine itself, VECTO covers several components and parameters²⁴:

In the case of NRMM, testing of complete machines for CO₂ emissions is in most cases not feasible, as it would be even more challenging than testing heavy-duty trucks. Even finding ways to reduce CO₂ emissions is more challenging than in the case of trucks. Aerodynamics has no effect in slow moving NRMM, machines are often heavy to provide sufficient traction and tyres are chosen for traction, not low friction. For practical reasons some machines utilize hydrostatic drivelines which have much lower efficiency than mechanical ones. Many machines have hydraulic actuators, e.g., elevators, that require significant amounts of energy to perform the work cycle. Improving the efficiency of the ICE, hybridising and partly or totally electrifying the drivetrain and actuators will improve efficiency and lower CO₂ emissions.

For conventional tractors, one recognised testing method exists, that is the German DLG-PowerMix test for measuring tractor output, efficiency and fuel consumption²⁵. Fuel consumption figures could easily be translated into CO₂ emissions. Testing is carried out in a chassis dynamometer, complemented with putting load on the power-take-out (PTO) unit.

The PowerMix test consists of 14 test cycles that simulate various loads on the tractor and measure its fuel and AdBlue consumption, its output and efficiency as the machine goes through the test cycle. The individual test cycles replicate typical field and transport applications at various loads. These applications include pure draught work (e.g., ploughing or cultivating)

²² https://climate.ec.europa.eu/system/files/2023-04/policy_transport_vecto_20230309_workshop_bus_en.pdf

²³ https://climate.ec.europa.eu/system/files/2018-12/201811_engine_en.pdf

²⁴ https://climate.ec.europa.eu/system/files/2018-12/201811_simulation_tool_en.pdf

²⁵ <https://www.dlg.org/en/agriculture/tests/dlg-powermix>

but also mixed work that applies load on the transmission, the PTO and the hydraulic system (Figure 3).

A data base is formed for each and every machine tested. In the DLG app, the user defines a mix of use cases, and the app then calculates overall fuel consumption for the chosen work profile. The DLG-Powermix system is first and foremost aimed at making it possible for end-users to compare machines and to optimise choice of machinery.

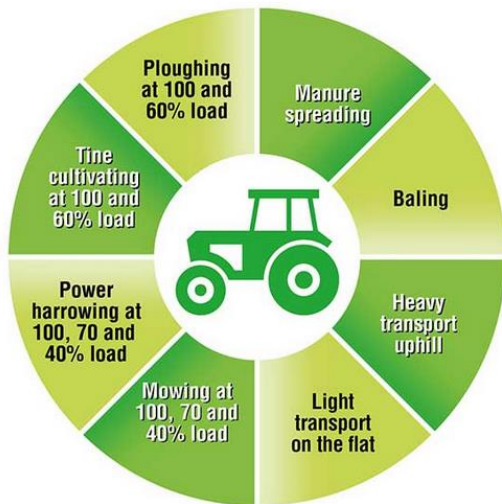


Figure 3: Elements of the DLG-Powermix test²⁵.

3.3.3 CO₂ regulations

In the following, vehicle CO₂ regulations will be presented, with emphasis on HDV, as NRMM and HDV have more in common than NRMM and LDV.

Japan was the first country to enact fuel efficiency standards for HDV in 2005. Since then, several countries and regions have followed: China in 2012, Canada and the US in 2014 and Europe in 2019²⁶. The way to report fuel economy or CO₂ emissions vary; km/litre (Japan), litres/100 km (China), g CO₂/ton-mile, g CO₂/bhp-hr and gallons/1,000 ton-mile (Canada and the US), g CO₂/ton-km (EU).

The original regulation European regulation ((EU) 2019/1242)²¹ calls for a 15% reduction in tailpipe CO₂ emissions by 2025 and a 30% reduction by 2030, compared to the reference period 2019 - 2020. The European system differs from the other systems as it defines fleet average reference levels for the individual manufacturers which require them all to reach the same relative CO₂ reductions. The system originally covered only certain heavy-duty trucks of more than 16 tons.

In February 2023, the Commission presented a proposal for a revision of the regulation²⁷. In January 2024, the Council and the European Parliament's negotiators reached a provisional

²⁶ https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_57.pdf

²⁷ https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_763

political agreement on the regulation²⁸. The ambition level is higher and the coverage broader. The proposed new reduction targets are:

- 45% from 1 January 2030
- 65% from 1 January 2035
- 90% from 1 January 2040 onwards

According to the proposal the regulation will be expanded to cover smaller trucks, city buses, long-distance buses and trailers. To stimulate faster deployment of zero-emission buses in cities, the proposed amendment introduces a 100% zero-emission target for urban buses by 2035, while setting an intermediate target of 90% for this category by 2030.

The Commission states that in 2040, the 90% emissions reduction target ensures that heavy-duty vehicles intended for driving in difficult conditions (e.g., very steep mountains) can still be non-zero emission vehicles.

It is noteworthy that the proposal explicitly says that vehicles used for mining, forestry and agricultural purposes are not subjected to CO₂ emission reduction targets.

The Commission's original proposal also took a stand on renewable fuels. Renewable fuels were not to be a part of the proposal, and the motivation for this was that a mechanism on renewable and low carbon fuels would create an incentive to redirect fuels needed to decarbonise sectors with fewer alternatives, like aviation and maritime, to road transport.

In the political agreement, however, the Commission is given the task to evaluate the possibility of developing a common methodology for the assessment and reporting of the full lifecycle CO₂ emissions of new HDVs and produce an assessment of the role of a carbon correction factor (CCF) in the transition towards zero-emission mobility in the HDV sector. The role of a methodology for registering HDVs exclusively running on CO₂-neutral fuels will also be assessed in the review.

Anyhow, including renewable fuels in vehicle CO₂ regulations will require some kind of system to ensure that vehicles getting a CO₂ credit actually are operated on renewable fuels only (Figure 4).

²⁸ <https://www.consilium.europa.eu/en/press/press-releases/2024/01/18/heavy-duty-vehicles-council-and-parliament-reach-a-deal-to-lower-co2-emissions-from-trucks-buses-and-trailers/>

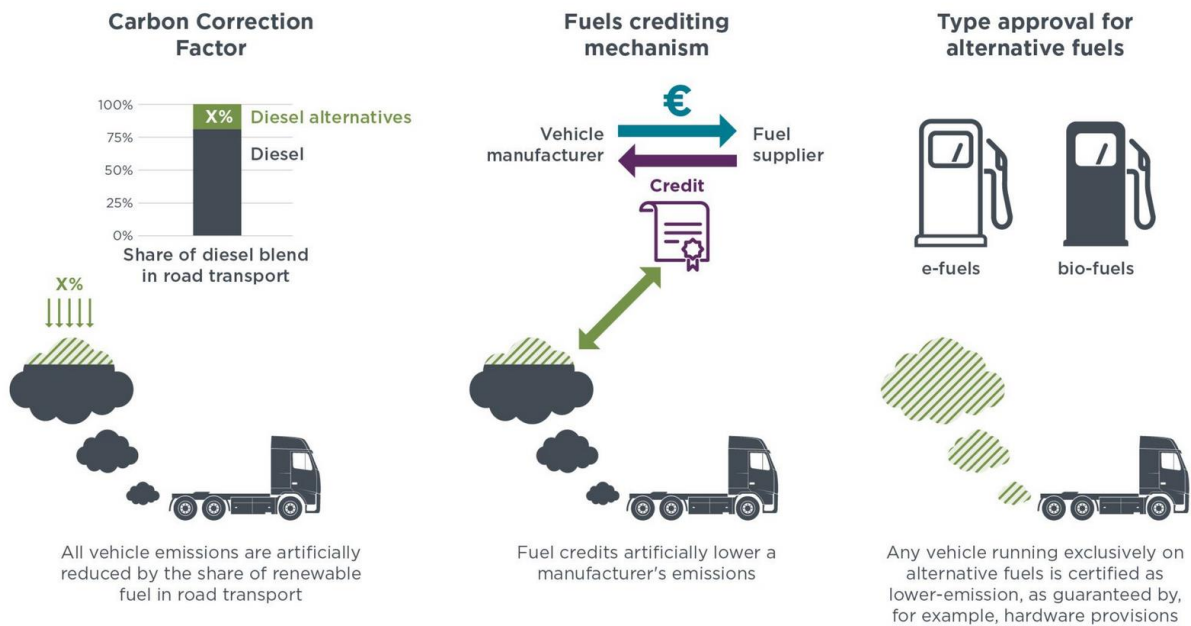


Figure 4: Alternative fuels crediting mechanisms²⁹.

In North America, the United States and Canada, heavy-duty vehicle regulations are substantially aligned, with the introduction of heavy-duty CO₂ and fuel efficiency regulations in 2014^{30,31}. One notable difference, however, is that the US regulates both fuel efficiency and CO₂ while Canada regulates CO₂ only. The methodology for determining fuel consumption and CO₂ emissions is, as in the case of Europe, based on measuring the engine and simulating the vehicle. In addition, in the US, also regulations for engine level CO₂ emissions and fuel efficiency are in place.

Phase 1 of the US regulation, adopted in August, 2011 covers model years 2014 - 2018, and Phase II covers the years 2021 – 2027 (DieselNet, 2020).

Phase 1 required CO₂ and fuel consumption reductions vary by vehicle type and range from 6 – 23% compared to a model year 2010 baseline³². Compared to Phase I, Phase II will reduce CO₂ emissions and fuel consumption by 3 - 17%, depending on the vehicle category.

Table 2 presents standards for engines installed in tractors. The 2017 heavy-heavy-duty engine values translate into 625 g CO₂/kWh and some 198 g fuel/kWh (engine efficiency 42%). The 2027 values correspond to 587 g CO₂/kWh and some 186 g fuel/kWh (engine efficiency 45%), respectively.

In the case of NRMM, California basically follows rule-setting by EPA, but California Air Resources Board (CARB) can still influence NRMM regulations to a certain extent. CARB has started discussions on Tier 5 requirements, which also would cover CO₂ emissions. Decisions on tailpipe CO₂ emissions for NRMM diesel engines could possibly be taken in 2027. CO₂ levels

²⁹ <https://theicct.org/publication/crediting-alternative-fuels-europe-co2-standards-trucks-buses-oct23/>

³⁰ https://dieselnet.com/standards/us/fe_hd.php

³¹ <http://gazette.gc.ca/rp-pr/p2/2018/2018-05-30/html/sor-dors98-eng.html>

³² <https://www.transportpolicy.net/standard/us-heavy-duty-fuel-consumption-and-ghg/>

under discussion are 773 – 724 g CO₂/kWh for the powerband 56 ≤ kW < 130 and 724 – 691 g CO₂/kWh for the power band 130 ≤ kW ≤ 560³³.

Table 2: US engine standards for engines installed in tractors³⁰. Tractors in this case means vehicles interned to pull trailers. Grey columns calculated assuming a carbon intensity of 73.2 g CO₂/MJ and a heating value of 43.1 MJ/kg for diesel fuel.

Category	Year	Fuel consumption	CO ₂ Emissions	Fuel consumption	CO ₂ Emissions	Efficiency
		gallon/100 bhp-hr	g/bhp-hr	g/kWh	g/kWh	η
MHD Engines	2014	4.93	502	216	683	38.6
	2017	4.78	487	210	662	39.8
	2021	4.65	473	204	643	41.0
	2024	4.53	461	199	627	42.0
	2027	4.49	457	197	621	42.4
HHD Engines	2014	4.67	475	205	646	40.8
	2017	4.52	460	198	625	42.1
	2021	4.39	447	193	608	43.4
	2024	4.28	436	188	593	44.5
	2027	4.28	432	186	587	44.9

4. Possibilities to regulate CO₂ emissions from NRMM

4.1 General discussion

As stated, NRMM is a very diverse group of machinery, with huge variations in size and weight, power level, autonomy and duty cycles, much more diverse than, e.g., on-road heavy-duty trucks. Figure 5 demonstrates differences in power, autonomy and dynamism.

³³ <https://ww2.arb.ca.gov/sites/default/files/2023-10/%232%20Proposed%20Emission%20Standards-ADA-10232023-revised.pdf>

Characterisation of services

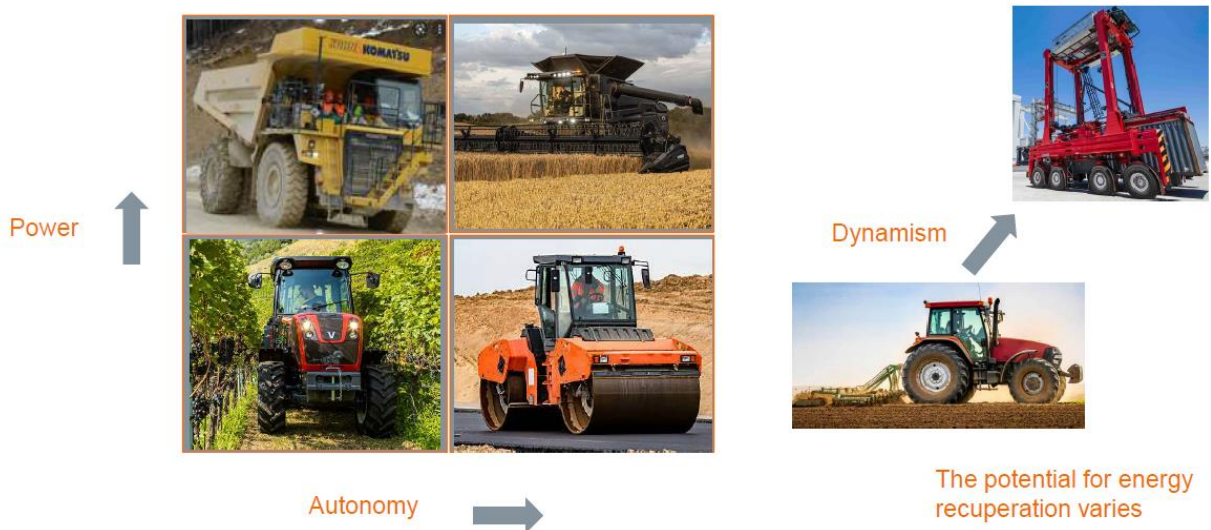


Figure 5: Characterisation of services of NRMM.

In the case of on-road vehicles, CO₂ emissions are proportioned to transport work, g/km for light-duty vehicles and g/tonne-km for heavy-duty vehicles. If CO₂ emission regulations were to be introduced for NRMM, other than requirements just for the engine, ideally the limit values should be related to useful work. For agri-sector tractors this can be done, as demonstrated by the DLR-Powermix test methodology, considering work at the driving wheels as well as at the PTO device, delivering a universal g fuel/kWh value for certain mixes of services, a value that can be converted into g CO₂/kWh.

CARB proposes to regulate tailpipe CO₂ emissions in the upcoming Tier 5 regulation, but the reduction potential when focusing on tailpipe CO₂ emissions only is rather limited.

If NRMM regulations were to concern complete machines, defining duty cycles and useful work might prove difficult for certain types of machinery, e.g., for cargo handling equipment, excavators and forestry machinery. Due to high energy losses, machines with hydrostatic transmissions and hydraulic actuators will be less efficient than machines with mechanical or electrical drives. Development towards next generation NRMM with e.g., zonal electrically driven hydraulics, direct electric drives and actuators requires comprehensive redesign of the machines. Besides new machines construction, retrofit modernisations of existing machines can provide alternatives for NRMM fleet renewal and CO₂ reductions. The potential for energy savings and thereby CO₂ reductions through hybridisation and electrification varies by service. Less can be gained for, e.g., combine harvesters and farm tractors used for ploughing, whereas there are significant amounts of energy to be recouped for cargo handling equipment.

Table 3 presents characteristics of heavy-duty on-road vehicles (with CO₂ regulations in place) and NRMM, pointing out differences between the two segments and listing items to be considered when contemplating eventual CO₂ regulations for NRMM.

Table 3: Characteristics of heavy-duty on-road vehicles versus NRMM.

	Heavy-duty on-road	NRMM
Types of services	Relatively consistent for the highest consuming categories	Highly various

Manufacturers	Engine and vehicle from the same manufacturer	Often separate equipment and engine manufacturers
Production numbers by manufacturer	Usually rather high	Usually rather low
Unit capital cost on purchase	Important across vehicle classes	Critical for small machines, important for larger machines
Basic engine technology	Same for on-road and NRMM	Same for NRMM and on-road
Driveline	Mechanical + increasing contribution from electricity	Mechanical + hydrostatic, contribution from electricity expected
Hydraulic actuators	Minor importance	High importance
Potential for hybridisation	Moderate	Low to high
Potential for electrification	Medium to high	Low to high
Alternative fuel infrastructure (electricity, methane)	Defined by AFID ³⁴ and AFIR ³⁵ , main roads	No requirements
CO ₂ emission standard regulations in place	Yes	No
Test methodology	VECTO for all vehicle categories	Only DLG for tractors (fuel efficiency)
Vehicle CO ₂ emission standard regulations taking into account renewable fuels ²⁷	No	n/a
Motivation and potential to use locally produced fuels	No particular	E.g., biomethane in agriculture
Vehicles exempted from CO ₂ emission standard regulations ²⁷	Mining, forestry, agricultural, civil protection, military	n/a

Table 3 demonstrates that although the basic engine technology is the same for on-road and NRMM, there are significant differences between these two sectors, differences which have to be taken into account when setting possible CO₂ emission standard regulations for NRMM.

Some machines in agriculture and forestry are difficult to electrify, e.g., due to high requirements for power and autonomy while the grid connection for charging is harder to arrange. In addition, creating distributed fast charging facilities and distributed hydrogen refuelling (if aiming at zero tailpipe CO₂ emissions) require additional measures such as mobile buffer and conversion units, whereas local production and refuelling of biomethane has been demonstrated successfully. In the road sector, the Alternative Fuel Infrastructure Directive (AFID)³⁴ and the AFIR³⁵ regulation adopted in 2023 secure charging on electric vehicles and refuelling of hydrogen and methane along the main transport corridors.

In the following, possible ways to regulate CO₂ emissions and how they might or may not suit the NRMM sector are discussed.

As stated, the conditions and potential for CO₂ emission reductions vary from one category of machinery to another, and it will be impossible to use one single metric for all NRMM.

³⁴ Directive 2014/94/EU on the deployment of alternative fuels infrastructure, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094>

³⁵ The alternative fuels infrastructure regulation (AFIR), <https://data.consilium.europa.eu/doc/document/PE-25-2023-INIT/en/pdf>

Thus, it might be necessary to differentiate requirements depending on the vehicle category. In the case of on-road vehicles, vehicles for agriculture, forestry and mining are likely to be excluded from HDV CO₂ regulations, this might provide some guidance for the regulations being discussed for the NRMM sector as well.

For road vehicles, “small volume” and “niche vehicle” manufacturers can apply for a derogation from their specific CO₂ emission target. Compared to road vehicles, manufacturers of NRMM machine have in general significantly smaller production numbers, and also this should be taken into account.

4.2 Emission trading and fuel taxation

- **Emissions trading and elevated fuel tax fossil CO₂ fraction could promote alternative energies for NRMM**

Emission trading has been in place for aviation since 2012 and will be implemented for shipping as of 1.1.2024. The emission trading for shipping will cover ships of more than 5 000 gross tonnage and above. An emissions trading system is under development for buildings and the road transport sector through a separate Emissions Trading System 2 (ETS 2) covering fuel combustion in buildings, road transport and additional sectors (mainly small industry not covered by the existing EU ETS)³⁶. The ETS 2 is an upstream system that regulates fuel suppliers rather than households and car drivers. The fuel suppliers and retailers for the NRMM sector are often the same as for the on-road vehicles and therefore NRMM is partly covered in ETS 2. However, it is specifically stated that ETS 2 does not apply to fuels used in agriculture and forestry, and this could result in a need for differentiated fuels for different categories of NRMM.

Setting a substantial price for fossil CO₂ emissions in the form of fuel taxes is in a way related to emission trading. A high price for fossil CO₂ would drive improvements in energy efficiency as well as promote the use of renewable fuels as well as electrification. Currently, the minimum levels of fuel tax are set by the Energy Tax Directive, but several countries have set a higher excise duty on energy. Therefore, fuel taxation is not harmonised in Europe.

4.3 Setting requirements for the engine itself, CO₂ emissions or alternatively engine efficiency

- **Relatively easy measure with limited potential (up to 15% in engine efficiency)**

In the US, heavy-duty vehicle CO₂ emissions are regulated both on the engine and on the complete vehicle level, so there are examples of engine level CO₂ regulations. With a given fuel, engine efficiency correlates to CO₂ emissions. A relatively easy and straight forward way to regulate CO₂ emissions from NRMM would be to regulate engine performance only, meaning setting requirements either on engine efficiency or CO₂ emissions. CO₂ emissions are already measured in the type approval process. Like in the US on-road regulation, the requirements should be graduated by engine power or size, the bigger the engine, the more stringent the requirement. This is also the case for pollutant emissions (Stage V, Tier 4). Such an approach is reasonable, as the need to limit costs is most pronounced for small engines.

³⁶ https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets-2-buildings-road-transport-and-additional-sectors_en

In practice, regulatory target levels could be set for either engine efficiency or engine CO₂ emissions. The engine efficiency-based approach will reduce energy consumption independent of fuel used in the engine. Actual CO₂ emissions will then depend on the carbon intensity of the fuel used. The CO₂ based approach reduces the CO₂ emissions to the set level taking into account the combination of engine efficiency and fuel carbon intensity.

The expected impacts of engine CO₂ limits are, however, rather limited, and will not lead to deep decarbonisation. Through improvements on the engine efficiency, CO₂ emissions could ultimately be lowered with traditional fossil diesel-like fuels some 15% compared to status quo.

As stated, CARB is now contemplating to include CO₂ limits in the upcoming Tier V regulation³³.

Although CO₂ is already measured in the type approval processes, it would still take years of work to include CO₂ in the regulatory framework.

4.4 Setting CO₂ requirements for complete machines

- **Would take into account driveline and auxiliaries and cater for electrification, but would be technically complex**

If regulations were to be set for complete machines, this would give a holistic picture of the performance of the machine, taking into account, e.g., the power unit (ICE, electric motor, fuel cell), the driveline (mechanical, hydrostatic, electric) and possible hybridisation, auxiliaries of various kinds (mechanical, hydraulic, electric) and possible recouping of energy.

There are two possible ways of generating performance data, the first one being actual measurements on the machine, like in the DLG-Powermix testing for tractors. DLG-Powermix requires a chassis dynamometer for measuring traction power and a dynamometer for measuring PTO power. Measuring a wide variety of machines this way would be arduous, impractical and expensive. The scarcity of suitable testing laboratories also forms an obstacle.

The second alternative would be a VECTO type approach, a combination of measured engine and key component data and simulation of the vehicle or machine. As this methodology has been chosen for on-road vehicles, most probably this would be the preferred option for NRMM as well.

Independent of approach, key questions include, at least:

1. Which types of machines should be regulated?
2. What would be representative load cycles for various categories of machinery?
3. How to set the CO₂ limit values?

As for question one, as it most probably will be impossible to regulate each category of machines, the obvious answer would be that machines making the greatest contribution to CO₂ emissions should be regulated. Additional points that should be considered is the exclusion of certain applications, like in the proposed update of the HDV CO₂ regulation excluding vehicles for mining, forestry and agriculture. As for production numbers, in the on-road sector “small” and “niche” manufacturers are exempted from CO₂ regulations.

As CO₂ regulations preferably should be linked to useful work, typical load cycles need to be defined. Figure 6 shows the forces acting on a wheel loader, forces stemming from moving the machine, climbing uphill as well as from operating the bucket.

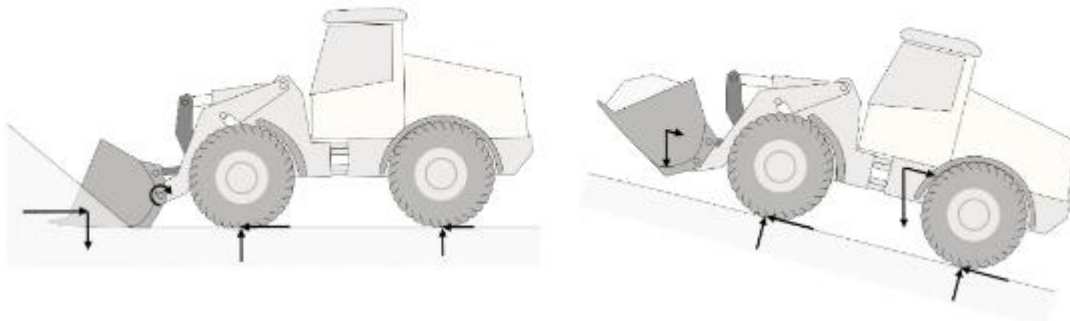


Figure 6: Forces acting on the wheel loader during bucket filling and driving in a slope³⁷.

As work cycles vary from one machine category to another, CO₂ limits would need to be set by machine category. Hydrostatic powertrains and hydraulic actuators impair overall efficiency compared to mechanical and electrical systems. This must be taken into account, as many machines still rely on hydraulic system.

If a VECTO type approach would be introduced for NRMM, this would mean significant efforts in developing the methodology and adequate simulation tools. The HDV CO₂ emission regulation defines CO₂ reduction targets relative to the reference year of 2019. If a corresponding system were to be introduced for NRMM, also CO₂ reference levels would have to be established.

4.5 Requiring certain shares of alternative fuel or zero emission machinery

- **Copying the principles of the Clean Vehicles Directive to NRMM, straight forward approach? Can we have a Clean Machines Directive?**

The Clean Vehicles Directive (CVD) (EU) 2019/1161³⁸ promotes clean mobility solutions in public procurement tenders and sets national targets for their public procurement. It applies to different means of public procurement, including purchase, lease, rent and relevant services contracts for road vehicles. The CVD requires the Member States to ensure that minimum percentages of “clean” and “zero-emission” road vehicles will be procured.

As for heavy-duty road vehicles, clean vehicles are defined as follows:

“A vehicle running on electricity (including plug-in hybrid vehicles), hydrogen, natural gas including biomethane, in gaseous form (compressed natural gas (CNG)) and liquefied form (liquefied natural gas (LNG), synthetic and paraffinic fuels and sustainable biofuels when not blended with conventional fuels.”

In addition, a definition for a zero-emission heavy-duty vehicle is in place:

“A “zero-emission heavy-duty vehicle” means a clean vehicle without an internal combustion engine, or with an internal combustion engine that emits less than 1 g CO₂/kWh.”

³⁷ https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_50.pdf

³⁸ <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L1161>

The public sector is required to procure certain minimum shares of these vehicles or services produced by these. The targets vary from country to country. In the case of Finland, the targets are:

Period 8/2021 to 12/2025:

- buses 41%
- trucks 9%

Period 1/2026 to 12/2030:

- buses 59%
- trucks 15%

For buses, half of the target shall be met with zero-emission vehicles.

A similar kind of thinking could be applied to NRMM. Primarily it could be applied to public procurement as in the case of the CVD. Target setting would depend on machine category. The mechanism would probably be rather simple compared to the HDV CO₂ regulation, which calls for establishment of reference values and determining CO₂ values for certain vehicle categories and presents the reduction targets relative to the reference values. This measure would be most applicable to NRMM's operating in the built environment performing tasks commissioned through public procurement.

In principle, the thinking could be extended to equipment manufacturers as well. For on-road vehicles, the manufacturers must meet individual CO₂ targets. If the CVD thinking were to be extended to NRMM equipment manufacturers, the manufacturers would be obliged to deliver certain shares of machinery categorised as clean, instead of meeting specific CO₂ emission levels, which in the case of NRMM would be very difficult to establish.

4.6 Taking into account renewable fuels

- **Alternative and renewable fuels should be taken into account in possible NRMM CO₂ regulations (can deliver up to 90% reduction in well-to-wheel emissions)**

Current vehicle CO₂ regulations do not include any provisions for the use of renewable fuels. However, discussions on possibilities to account for renewable fuels are ongoing.

Especially agricultural machinery could in principle run on locally produced fuels or even fuels produced on the farm. That stream of renewable energy should not be disregarded in possible NRMM sector CO₂ emission considerations.

A simple approach would be to consider engines and machines running exclusively on alternative or renewable fuels as zero CO₂ emission machinery. Fuels or engines falling into this category would be, e.g., methane, di-methyl ether (DME), ethanol and methanol, all of these requiring dedicated engines. Guidance could be taken from the Clean Vehicle Directive. This would provide the actors with an incentive to bring forwards, e.g., methane fuelled farm tractors.

Taking into account renewable diesel-type fuels would require some kind of crediting mechanism, as discussed in 3.3.3.

5. “Soft” measures for CO₂ reductions

5.1 General

In addition to limiting CO₂ emissions from NRMM by regulatory measures, there are also other types of measures for emission reductions, ranging from incentives and voluntary agreements all the way to more efficient use of machines.

5.2 Promoting alternative fuel infrastructures for NRMM

- **Synergies between public and semi-public charging infrastructures for on-road vehicles and NRMM towards multi-user hubs should be explored and promoted**

The new Regulation for the deployment of alternative fuels infrastructure (AFIR) sets mandatory deployment targets for electric recharging and hydrogen refuelling infrastructure for the road sector, for shore-side electricity supply in maritime and inland waterway ports, and for electricity supply to stationary aircraft. Although the regulation is not presenting measures or targets specifically to the NRMM sector, some parts of the infrastructures to be deployed can also benefit mobile machinery running on alternative energies. This synergy is most likely in urban areas and the built environment as well as transport nodes such as ports and airports where multiple types of NRMM operate in tasks of service, maintenance and construction. The infrastructure regulation framework should be reviewed to assess and promote actions to speed up creation of alternative fuel infrastructures for NRMM.

However, many charging hubs are not suitable for catering for multiple user groups and vehicle types unless this is taken into account already in the planning phase in the layout of the hubs, positioning of the charging points and securing suitable interfaces and power levels. Ways and measures to promote shared use and multiple user group public and semi-public charging should be assessed together with regional authorities and cities, also including planning of municipal land use.

5.3 Voluntary measures by cities towards zero-emission zones including NRMM

- **Cities need to recognise their role in driving the emission reduction targets through voluntary measures and also securing smooth permits and processes for alternative energy infrastructures**

Progressive cities across the world have made voluntary commitments towards green actions to make their urban space cleaner and cut emissions. In 2020, four leading mayors (Oslo, Los Angeles, Mexico City and Budapest) are initial signatories to the C40 Clean Construction Declaration, pledging to work with industry to halve emissions from construction projects in their cities by 2030³⁹. The Declaration sets bold, ambitious targets to develop the net-zero emission buildings and infrastructure. Regarding construction machinery, the target is to procure and when possible, use only zero emission construction machinery from 2025.

Norway is the leading country in electrification of road transport, waterborne applications as well as off-road sector. Norwegian cities lead the way in reaching zero-emissions in construction

³⁹ <https://www.c40.org/news/clean-construction-declaration-launch/>

sites; at least Oslo, Bergen, Trondheim, Stavanger, Drammen, Tromsø and Kristiansand are aiming at zero-emission construction sites by 2030. ENOVA in Norway also offers subsidies for the extra costs in purchases of zero-emission equipment. Some of the sites have also taken measures to support a weaker grid connection by battery-buffered charging stations, which can also be mobile and move from site to site.

Beyond construction sites, cities can and should have a big role overall in the CO₂ reduction and green shift in urban areas. If low or zero-emission zones are implemented for certain categories of road vehicles, e.g. deliveries and taxis, there is potential to include some measures also to drive low-emission NRMM operating in these areas, provided that there are possibilities and infrastructure to support such operations. This points back to coordinated land use planning, reserving the urban spaces for charging hubs and facilitating the approval and permit process.

Additionally, there is a lot of unused potential in the electrical grid infrastructures in the built environment in the form of medium voltage grid transformers and services towards local neighbourhoods and energy communities.

Besides cities, this type of action will be of relevance to private actors procuring transportation or machine services who aim at reducing the CO₂ footprint of the value chain of their intermediate or final products. The future may bring a growing number of customers who are aware of the environmental footprint of the products and services they use and ask for sustainable value chains. There may also be customers who are ready to pay a surplus for clean products and services.

5.4 Speeding up research, development and innovation on NRMM

- **Research, development and innovation on next generation of NRMM needs to be sped up by lifting it as a cross-cutting RDI theme at EU level**

There are a lot of synergies between on-road vehicles and next generation of NRMM: developments in batteries, fuel cells, next generation engines and charging technologies can all benefit both on-road and off-road applications. At the same time, NRMM are more complex and diverse than road vehicles due to their various auxiliary systems, actuators, work cycle implements and use of hydrostatic transmission and hydraulics.

Besides necessary national actions, RDI at European level is of key importance. The Horizon Europe framework programme is currently not properly addressing mobile off-road and industrial applications. This is especially true in Cluster 5 work programme, which addresses the green and digital transition in climate, energy and mobility.

Most of these non-road mobile machinery systems are key factors in materials, logistics and freight transportation chains for industry and commerce. Significance of NRMM sector CO₂ emissions will increase as other sectors CO₂ emissions will be reduced. Thus, there is need as well for decarbonisation. The RDI topics of main transportation modes in the green deal framework are covered by specific co-programmed partnerships (2Zero for road transport, Waterborne for maritime and shipping, Clean aviation for airborne), and cross-cutting topics other relevant partnerships (Batteries European Partnership, Green hydrogen, CCAM, CET). The NRMM domain falls outside of these main activities and is mainly not eligible for RDI. This area should be sufficiently covered and taken into account in when planning the last years of Horizon Europe, to speed up the green shift in NRMM. The following areas should be included in a group of funding calls to tackle this area:

- Hybrid, low and zero emission powertrains including renewable and sustainable fuels, NRMM configurations and energy infrastructures for open-pit and underground mines

beyond the obvious

- Zero-emission powertrains, NRMM configurations and energy infrastructures for materials and cargo handling in ports and at industrial sites
- Hybrid, low and zero-emission powertrains including renewable and sustainable fuels, NRMM configurations and energy infrastructures for agriculture and forestry
- Hybrid and zero-emission powertrains including renewable and sustainable fuels, NRMM configurations and energy infrastructures for urban and built environment, including construction and maintenance

These RDI actions should be matched with measures speeding up pilots and deployments of next generation NRMM in various end use segment and applications.

6. Summary for potential regulatory measures for reducing NRMM CO₂ emissions

Previous chapters covered the significance of different NRMM segments on total NRMM sector CO₂ emissions, current emission regulatory scheme and potential measures and regulations for CO₂ reduction. Considering the variety of use cases and machine types it is rather clear that an approach combining multiple measures set timewise reasonably would lead to the best outcome. In Table 4 summarises the suggested measures presented in the previous chapters with expected CO₂ reduction potential and estimation of timeline for adaption. The listing is arranged based on the estimated time for adaption and includes regulatory as well as “soft” measures.

Agriculture and construction machinery represent together around 75% of all NRMM sector CO₂ emissions among the EU-27 countries. Thus, those machines need to be prioritized in actions taken for CO₂ emission reduction. At the same time, that group is highly heterogeneous containing machinery operated in different environment and use cases. This leads to a fact that the most realistic (considering costs, operability, productivity, user acceptance etc.) and effective way for reducing CO₂ emissions is a simultaneous adaption of multiple measures in a holistic and technology neutral manner.

Measures summarized in Table 4 includes multiple means, which all promote CO₂ emission reduction in NRMM. They vary both in time horizon and significance, and could be advanced simultaneously strengthen the overall impact. For example, by adapting NRMM sector more strongly in EU level RDI funding schemes with introducing simultaneously EU level regulation, “Clean Machinery Directive”, for public services procurement would at the same time promote supply and generate market demand for clean machinery. Those measures could even be adapted within short timeframe. Simultaneously, methodologies could be investigated on how to include all renewable and sustainable energy carries in NRMM and alternative fuels infrastructure regulation.

Adaption of CO₂ emissions or engine efficiency targets in NRMM engine type-approval regulation could be divided in timewise set steps allowing NRMM engine OEM’s realistic time for developing new solutions meeting the targets. The longest time horizon would be in adaption of on-road HDV like CO₂ regulation in NRMM sector. This would require development of completely new regulatory framework and methodology in NRMM regulation with suitable simulation tool capable of modelling defined machinery energy consumption in targeted manner. In addition, all the necessary components related to powertrain and power consumption would be required to be included in the model component library.

Finally, the latest update on both the on-road HDV CO₂ regulation and ETS 2 exclude vehicles and fuels in agriculture and forestry. When contemplating CO₂ regulations for NRMM aligning with current on-road HDV regulation, a consistent approach would mean excluding of machines for agriculture and forestry from CO₂ regulations. This is not a suggestion by the authors, but rather an observation based on the current formulation of on-road HDV CO₂ and ETS 2 regulations.

Table 4: Potential measures for CO₂ emissions reduction within NRMM.

Measure	Estimated CO ₂ reduction potential	Estimated timeframe for adaption
Investigate feasibility of EU regulation for alternative fuels infrastructure for NRMM use. Possibility to align with Alternative Fuels Infrastructure Regulation (AFIR).	Indirect impact by supporting of deployment of alternative energy infrastructures for NRMM.	1 – 2 years.
Speeding up EU level RDI investments on energy efficient NRMMs, renewable and sustainable energy carriers and powertrains for NRMM use.	Indirect impact by increasing technology readiness level (TRL) and market introduction of new energy efficient NRMM's.	1 – 3 years.
Clarify and strengthen the role of cities to require low and zero emission zones and NRMM sites and secure availability of their energy infrastructure to create demand for next generation NRMM.	Faster deployment of low and zero emission NRMM creating end-user demand.	2 – 3 years.
Investigate possible methodologies how to include all renewable and sustainable energy carriers in NRMM regulation, i.e. include Well-to-wheel approach in NRMM regulation.	Significant and enables CO ₂ reduction among the hard to electrify machinery like agriculture machinery, other high energy consumption machinery and rural area operated machinery	2 – 3 years.
Investigate possibility to develop and take in use “Clean Machine Directive” for public procurements following the framework of Clean Vehicles Directive (CVD).	Significant in public NRMM use and develops market demand for low carbon emission solutions.	3 – 4 years.
Include CO ₂ emission targets in European NRMM engines type-approval regulation.	5 – 15 % depending on engine power category.	Could be adapted in steps for example within 5 – 10 years.
Investigate possibility for introducing on-road HDV's CO ₂ regulation-based approach, i.e., testing of engine for fuel consumption and simulation of machine energy consumption and finally defining CO ₂ emissions in machine level.	Significant as whole vehicle can be taken in consideration: Whole powertrain (energy converter and power transfer), hydraulic actuators, cooling systems.	6 – 10 years: Methodology and simulation tool development. Integration of OEM's sub-systems and components. Development of regulatory framework.

