Economic and environmental performances of natural gas for heavy trucks: A case study on the French automotive industry supply chain

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Abstract

Road transport is a major CO2 emitter that can be reduced by using alternative fuels. This paper offers a micro-simulation of the adoption of compressed natural gas in heavy-duty vehicles based on real French data on industrial flows in 2018 from the automotive manufacturer Renault. Our purpose is to assess the potential of natural gas as a transition fuel for the supply chain by determining the economic conditions under which natural gas is both economically and environmentally beneficial.

We consider two types of natural gas: bio-sourced and fossil. Both types of gas trucks prove cost-effective for long-distance flows within a short 5-year time period. However, fossil-fuel natural gas trucks emit from 3 up to 13% more CO_{2eq} than diesel trucks on the same trip, due to the extra kilometres required to reach refuelling stations (+6.21% of distance covered on average). Conversely, compared to diesel trucks, bio-sourced gas reduces the carbon footprint of transportation up to -76%. Thus, only bio-sourced gas proves to be favourable. We also investigate other types of externalities, such as air pollution and noise. We finally find that carbon taxes should be based on life-cycle emissions in order to boost wider adoption of biogas.

Highlights

- Bio-sourced natural gas can be cost-effective for heavy-duty trucks
- Fossil natural gas trucks emit more than diesel trucks in real conditions due to low-density of refuelling network
- Detours to reach refuelling stations are key parameters for emissions
- Life-cycle based carbon taxes could support biogas trucks in supply chain

Keywords: Compressed Natural Gas ; Energy Transition ; Heavy-Duty Vehicles ; Externalities ; Transport Policy ; Carbon Tax

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1 Introduction

Global energy consumption and greenhouse gas (GHG) emissions are now peaking at around 13.7Mtoe and 32GtCO_2 (IEA, 2018). The transport sector is regularly singled out as a major energy consumer, as it accounts for 29% of final energy consumption and 25% of global GHG emissions. Emissions from transport have risen by 71% since 1990, and the trend is likely to continue increasing in the coming years.

At the same time, the Paris Agreement set the goal of remaining below a 2°C rise in temperatures, and governments have set targets for each sector of their economies. The French transport sector is to reduce its carbon footprint by more than 6% between 2019 and 2023 (SNBC, 2018) while compensating for its insufficient efforts over the 2015–2018 period (Le Quéré, 2019). Heavy-duty vehicles (HDVs) are a strategic focus for reducing net transport-sector emissions in France as the small fleet is a big carbon emitter, and so the focus is on carriers to intensify their efforts. Indeed, HDVs emit as much as half of the private vehicles fleet with 60-times-fewer vehicles (CGDD, 2019); HDVs account for 6.3% of the national carbon footprint whereas private cars stand for 15.7%.

The trend in efforts to reduce road transport emissions has long been based on reducing fuel vehicle consumption (Yeh, 2007), but despite undeniable progress, attention is now moving towards alternative fuels such as natural gas for vehicles (NGV) (Bicer & Dincer, 2018; Sangeeta *et al.*, 2014). NGV is now a mature and readily available option that has developed since the 1930s for private cars (Yeh, 2007). NGV is used by internal combustion vehicles that operate relatively close to diesel combustion vehicles, which means production and deployment only require incremental innovation (Wang-Helmreich & Lochner, 2012). Plant-based biodiesel is available as an option to reduce GHG emissions, but its environmental impacts are complex to assess, and still unknown (Hosseinzadeh-Bandbafha *et al.*, 2018). Hybrid, hydrogen, or electric heavy trucks will not become widely available in the short term, and they are also widely criticised as environmentally unsustainable as they are dependent on manufactured batteries and the electricity power mix (Bicer & Dincer, 2018; Doucette & McCulloch, 2011).

The purpose of this paper is to investigate what political and economic conditions would be needed for natural gas trucks to succeed in reducing GHG emissions while ensuring their economic profitability. Our core contribution is that we study the penetration of this technology during the adoption and transition period and then look at designing appropriate policies to support environmental-friendly use of NGV. We find that NGV requires significant average detours (+6.21%) to reach refuelling stations, thus increasing the GHG emissions of compressed natural gas (CNG) over diesel. A well-to-wheel (WtW) carbon tax based on the life-cycle emissions of the gas proves to be the best tool to incentivise the use of bioCNG. In all the scenarios developed here, the fuel needs to blend in 30% of biosourced gas to reduce CO_{2eq} emissions by at least 6% to reach emissions reductions objectives.

The originality of this article is that it is based on spatial data for both flows and the current refuelling stations network, within the framework of the French supply chain of the automotive manufacturer Renault. This automotive industry has oligopolistic characteristics, but rivalry is fierce. Automotive firms have to operate under intense price competition, and the industry is notoriously tight-margined. Cost issues are therefore likely to play a critical role in the sector's decision to opt for a greener supply chain. Consumers' willingness to pay for a more sustainable supply chain is low, hence an increase in costs will not be reflected in selling prices (Lane & Potter, 2007). Any adoption of technologies to reduce carbon emissions is hence conditional on the economic profitability of the allied investment.

The paper is organised as follows. Section 2 outlines the state of the art in both economic and environmental benefits of NGV. Section 3 presents simulations of replacing diesel trucks by natural gas trucks on a company's real freight flows in France and details the assumptions, methodology and scenarios framework employed. Section 4 presents and analyses the results, we also discuss the levels of taxes and subsidies needed to ensure profitability. Section 5 concludes the work and draws the policy implications of this study.

2 Literature review

There are three main gaps in the current models of NGV trucks highlighted in this literature review. Our study is designed to address all three of these gaps.

First, we show that few studies focus on CNG trucks and even fewer assessing CNG for HDVs on long-distance trips in real-world conditions. However, other applications of CNG, such as refuse trucks or city buses, have been studied in various countries. Laboratory research and real-world studies have highlighted lower GHG emissions from CNG compared to liquified natural gas (LNG) (Khan *et al.*, 2015; Meyer *et al.*, 2011). Section 2.1 details these results and reviews additional articles in the literature, and concludes that the use of CNG for long-distance HDVs proves a promising avenue for research.

Second, both on-site studies (Schnetzler & Baouche, 2019) and numerical simulations (Lajevardi *et al.*, 2018) conclude that fuel consumption, emissions and profitability are dependent on real-word conditions, i.e. factors such as road profile, detours to reach refuelling stations, engine efficiency, type of driving, etc. We call these factors 'hidden costs', as they do not appear in a theoretical framework. Section 2.2 details the relevant studies and their conclusions. We conclude that to assess the real performances of CNG and design appropriate support policies, we need to use real-world data and reveal some of these hidden costs. Here we explicitly model two hidden costs: real engine consumption, and lack of refuelling infrastructure leading to detours.

Third, section 2.3 reviews the impact of support policies on the investment decision-making process. Few studies have computed the effect of carbon taxes (Morrison *et al.*, 2018) or subsidies (Heimer *et al.*, 2017) on CNG truck purchases. The deployment of a larger NGV refuelling network appears to be the key condition for making CNG attractive at national level. To our knowledge, the quantitative impact of refuelling-network density on CNG investment decisions and profitability has never been investigated.

The rest of the paper therefore addresses these three gaps by focusing on CNG HDV for long-distance applications and by explicitly accounting for detours and fuel consumption. Finally, we compute the impact of different support policies and the level of subsidy required to trigger investment.

2.1 Compressed and liquified natural gas for vehicles

NGV is the same natural gas used for domestic purposes. To increase its energy density (and thus the range of vehicles), natural gas can be either compressed at 200 bars (CNG) or liquified at -162°C (LNG). We do not consider hybrid configurations such as CNG-LNG trucks or LNG-diesel trucks. The objective would be to combine the greater range of LNG and the availability of CNG from the domestic networks, but the expenditure involved in building a dual-fuel truck makes HDVs purchase too costly (Gao *et al.*, 2013).

Gas storage mode, i.e. liquified or compressed, is one of the key drivers of the uncertainty in emissions. Liquefaction is an energy-intensive process which, once completed, requires transport of the gas by purpose-adapted tanker trucks or by ship, and no longer through a pipeline network: these two stages are both local and global sources of pollution (Hagos & Ahlgren, 2018b; Khan *et al.*, 2015).

There is no consensus on how CNG and LNG CO_2 emissions levels compare. However, methane leaks must be considered on top of CO_2 emissions as they could generate more environmental damage than diesel (Cooper & Balcombe, 2019; Camuzeaux *et al.*, 2015; Cai *et al.*, 2017). LNG emits three times as much methane as CNG, and so the CO_2 equivalent emission indicators (CO_{2eq}) argue for CNG against LNG (Ventura *et al.*, 2017). Indeed, Meyer *et al.* (2011) find that for CO_2 emissions only, CNG is to be preferred over LNG (-8.3% and -4.2% CO_2 emissions, respectively, versus diesel), and when considering all GHG (CO_{2eq}), LNG emits even more than diesel (+0.6%) while CNG loses environmental benefit (-3%).

As the on-road stage is very GHG-intensive, some studies have focused exclusively on this phase without integrating the upstream emissions, whereas the liquefaction and road transportation of LNG is very energy-intensive and increases the upstream emissions of LNG compared to CNG (Ademe, 2014). Most empirical HDV studies have focused on LNG, as it offers greater range thanks to its higher energy density (Meier *et al.*, 2013).

Despite uncertainty regarding GHG emissions, CNG appears to have lower GHG emissions on a WtW life-cycle basis than Diesel and LNG. There is consensus that using CNG brings local-level gains in air pollutants such as NOx and fine particles, or even noise, at least for the original equipment manufacturers (Reynolds *et al.*, 2011; Yeh, 2007). However, hydrocarbon and carbonyl (in particular formaldehyde HCHO) emissions are higher for CNG than diesel (Anderson, 2015). CNG buses emit more carbon monoxide (CO) than diesel buses (Hesterberg *et al.*, 2008), while CO emissions are not found significantly different for trucks (Anderson, 2015). Fitting CNG trucks with an exhaust catalyst—oxidation catalysts or three-way catalyst—can significantly reduce HCHO, NOX and CO emissions (Thiruvengadam *et al.*, 2015; Yoon *et al.*, 2014), and unburnt methane emissions (Khan *et al.*, 2015). Bicer & Dincer (2018) find that CNG has a low toxicity index at a level close to 10 times below electric vehicles and only bettered by hydrogen vehicles.

Local pollution is now a major environmental issue in large cities (Chan & Yao, 2008). NGV is seen as part of the solution in the city of Delhi (India), where all public transport has been running exclusively on CNG since 2001 (Pal *et al.*, 2009). CNG is a common solution for urban applications such as refuse trucks (Shahraeeni *et al.*, 2015; López *et al.*, 2009) or bus networks, with up to 34% less GHG emissions compared to diesel in the US and Brazil (Galbieri *et al.*, 2018; Shahraeeni *et al.*, 2015; Chandler *et al.*, 2006). However, there is still no large-scale empirical study focused on HDV running on CNG.

In this article, we focus on CNG as an alternative fuel for HDVs, which unlike LNG is already biosourced and is produced by the methanisation of waste or biomass, (NGVA, 2017). The International Energy Agency (IEA, 2010) warns that while natural gas can play a role in reducing CO_2 emissions, in the long term the transition to clean sources of natural gas still requires ambitious support policy.

2.2 Empirical conditions and determinants of ecofriendliness and profitability for NGV

Measuring the environmental performance of a vehicle is a notoriously tricky task as the results can be affected by a variety of factors. Empirical studies and full-scale tests are essential to resolve emissions uncertainty. Discrepancies in CO_2 and GHG emissions can be partly explained by a difference between the theoretical and actual efficiency of fuels and engines (Shahraeeni *et al.*, 2015).

Both the profitability and emissions results of any model are extremely sensitive to the modelling choices made to detail certain parameters and the variables considered. For instance, travel speed and the particular road chosen for the trip appear to influence transport ecofriendliness (Kirschstein & Meisel, 2015), and it is also important to consider truck type, load weight, road profile (flat, hilly, mountainous), and road type (motorway, urban road, etc.) as part of the emission factors (Hausberger *et al.*, 2009). Taken together, the interplay of these factors is such that they influence the comparative environmental performances of two competing technologies. For instance, real consumption is 33.7% lower for diesel trucks than CNG trucks on urban high-speed roads (22.2kg CNG/100km *vs* 16.6kg diesel/100km) but only 3.8% lower in dense urban areas (36.1kg CNG/100km *vs* 34.8kg diesel/100km) (Schnetzler & Baouche, 2019). Neglecting road grade can lead to underestimate CO_2 emissions by as much as 24% for Lajevardi *et al.* (2018), compared to 18% for Quiros *et al.* (2016). Thus, on-road efficiency is part of the hidden costs and emissions factors that play a huge part in the investment decision.

It is crucial for any new technology to be profitable independently its emission reduction potential, since profitability critically shapes the technology adoption decisions taken by private firms, especially in cost-pressured sectors such as car manufacturing. For CNG vehicles, the economic impact outweighs the GHG reduction objectives (Sharma & Strezov, 2017). Over the same distance travelled, the difference in price between gas and diesel will allow more profit in the case of large volume consumption, as in the case of heavy-duty vehicles (HDVs), than in the case of light-duty vehicles that consume less (Cai *et al.*, 2017). We show in the rest of the study that other parameters affect the profitability of HDVs, such as the lack of stations and the detours needed.

Based on payback period alone, non-hybrid natural gas vehicles appear to be the most economical option (Krupnick, 2010). Given a sufficiently long travelled distance, LNG trucks could even be profitable within one year (Hao *et al.*, 2016).

Lack of refuelling infrastructure cause drivers to divert their route to reach a gas station. In the US, natural gas vehicle owners declare an average detour of +46.7% from their regular route, whereas regular car owners only declare a detour accounting for 19.1% of their trips. CNG car owners estimate an added 29%–64% travel time (Kuby *et al.*, 2013). In Los Angeles (USA), this additional time is not only inconvenient but costs from \$22 up to \$39 on refuelling days including fuel cost and time lost in congestion (Kang & Recker, 2014). This extra detour influences purchase decision, but its effect decreases with the development of alternative fuels and more refuelling stations (Morrison *et al.*, 2018). However, most papers do not take detours into account in their cost breakdown. Here we consider the extra cost of detours to challenge the scholarship's conclusions on the profitability and emissions of CNG trucks. We express each flow's real distance including refuelling deviation, which is more precise than interviews (Kuby *et al.*, 2013).

Next, the empirical CNG research appears to have under-addressed the influence of oil price trends. Oil prices will likely increase as oil reserves become scarcer, but geopolitical tensions in oil-producing regions can also cause significant fluctuations in the price of oil. Most studies model the cost breakdown of CNG investment as an extra cost on the purchase and a gap in fuel prices multiplied by a given annual distance (Mouette *et al.*, 2019; Hagos & Ahlgren, 2018b; Hao *et al.*, 2016; Krupnick, 2010). Galbieri *et al.* (2018) studied projected fuel prices by 2035 in Brazil but ignored the tricky transition period, which is key to technology entrenchment, and hence the most likely outcome would be an abandon of natural gas projects, as was the case in Germany (von Rosenstiel *et al.*, 2015), Canada (Flynn, 2002) and New Zealand (Yeh, 2007).

To our knowledge, no study has considered the impact of fuel price trajectories in NGV market growth. Since the breakeven use/duration of a fleet is unlikely to be less than a year, it is necessary to factor fuel and gas price changes over the years as a key input to the investment decision. The contribution of this study is to reveal the hidden cost of implementing NGV based on evolving cost factors such as fuel or the growing refuelling network, as well as the detours and maintenance needed in real-world-flow practice.

2.3 Supporting natural gas: policies and barriers

Governments are pushing for rapid development of the NGV market, and incentives have a crucial role to play in helping to develop a steady market for natural gas as an alternative fuel (Flynn, 2002). The 2017 French Mobility conference set the objective of 30% of the national trucks, buses and coaches fleet run on gas by 2030. Policies praise natural gas due to its high energy-to-carbon ratio, which offers great potential to reduce GHG emissions (Khan *et al.*, 2015; Rose *et al.*, 2013). However, no scientific consensus has been reached yet on the net environmental benefits of natural gas for transportation nor its profitability compared to diesel (Hao *et al.*, 2016; Krupnick, 2010). And even if the environmental goal could be achieved, the decisive factor remains economic (Sharma & Strezov, 2017).

The challenge for expanding the use of an alternative fuel such as natural gas is to make it both economically and ecologically attractive to diverse users and producers. Hence government policy in favour of NGV uptake needs to establish the natural gas ecosystem (Flynn, 2002; Yeh, 2007). A clear and steady path of government support should then offset the uncertainty of fuel prices.

By incentivising the production of natural gas, governments make it viable to develop the refuelling stations network (Engerer & Horn, 2010). A carbon tax also increases the profitability of refuelling stations as can be used to make a larger number of NGV segments competitive comparatively to conventional fuels (Morrison *et al.*, 2018). The bottlenecks to development of gas-powered vehicles include the small network of gas stations, the technical standards that vehicle-makers need to meet, the limited choice in available offers, and the financing and profitability conditions of the investment (Jaffe *et al.*, 2016).

Note that even if effective, the effects of policies may be long to emerge, due to the long delays between measured indicators (sales and infrastructure expansion) and current policies (Janssen *et al.*, 2006). This long-term approach makes it unclear whether subsidies will have a significative influence on the market (Heimer *et al.*, 2017).

3 Methodology: cost breakdown applied to real-world-flow data

3.1 Scope and real-world-flow data

Renault's Traffic database records all Renault-Nissan flows in Europe in the period 2015–2017, detailing flow characteristics including volume and distance. We use cost assumptions to determine the microeconomic profitability of each flow using CNG instead of diesel. The major asset of this database is its level of disaggregation which allows us to go beyond an average mileage. We reproduce the effective route of each truck, which serves for example to identify the deviation from the shortest path to reach a natural gas station.

We focus on intra-France routes to deal with the French legislation and refuelling network. We choose to focus on CNG rather than LNG due to ecological reasons discussed in section 2.1 and the already large number of CNG stations. From the 240,000 transport units delivered on a France-to-France route in 2017 (2598 axis), we only consider 42 flows corresponding to 39,000 transport units between major plants in Renault's chain of production (Fig. 1). Pre-selection was composed of steady flows that can sustain daily back-and-forth (round trip) activity. When number of flows from B to A is inferior (due to empty packaging optimisation) than the A to B volume, we retain the smallest number. We consider only flows that could feasibly be handled in gas using the current CNG refuelling stations map, i.e. the distance between to refuelling points had to be less than 340 km, including a safety margin drawn from Renault expertise (based on manufacturer claims of more than 500 km range for CNG HDV). This pre-selection offers carriers an insurance that their investment in a CNG truck will generate enough activity to be profitable without further need to look for other customers than Renault.

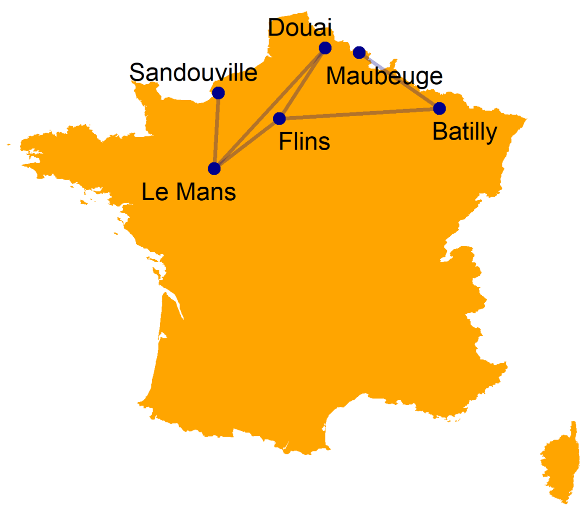

FIGURE 1: Flows eligible for conversion to natural gas related to core Renault plants in France

The profitability of investing in CNG is assessed by the net present value (NPV) of the investment I in year 2018 (base year), plus the discounted gains (R_i), with the years i from 2018 to 2022, before the truck is sold back at 10% of its value (in accordance with generally accepted market conditions):

$$NPV = -I + \sum_{i=2018}^{2022} \frac{R_i}{(1+\delta)^{i-2017}} \tag{1}$$

Discounting factor was set at $\delta = 20\%$ to account for the 5-years depreciation of a HDV. A profitable flow, with a strictly positive NPV over 5 years, is automatically considered as switching from diesel to CNG.

3.2 Cost assumptions

Costs can be separated between fixed costs (independent of distance travelled) and variable costs (that depend primarily on the truck's activity). Fixed costs are further subdivided into material investment and human resources. Variable costs include fuel and maintenance[1]. Details can be found in Table 1 (data on other steps are available as supplementary material).

Most of the cost assumptions come from the French National road committee (CNR, 2018). The extra investment in a CNG truck is profitable compared to an equivalent diesel truck as it is offset by a reduction in fuel cost. As price is widely available data common to most studies, the real fuel consumption of trucks is the key parameter to assess the economic value of switching to CNG (Schnetzler & Baouche, 2019). The difference in fuel consumption (kg/100km) is 8% in favour of CNG on primary roads (most often used by trucks). According to Renault experience and carrier-reported consumption figures, we assume a fuel consumption of 29.7 L/100km (or 25.1 kg diesel/100km) for diesel HDV and 27kg/100km for CNG HDV.

This study explicitly models two hidden costs: detours and real consumption. Detours are a hidden cost because they are not an explicit line on the cost breakdown, but we model them explicitly by computing the extra variable cost due to additional distances travelled to reach refuelling points. We also consider that real fuel consumption is also a hidden cost in that it is partly due to human behaviour and environmental conditions. We address this by using real consumption based on Renault field expertise, instead of the theoretical fuel consumption of the trucks.

3.3 Scenarios structure: integrating uncertainties

Precise flow data allows us to anticipate the truck's journey for each flow and plan out the refuelling stations where each truck will have to stop, according to the current stations map, and the real range of CNG trucks. For each flow, we possess data on the actual distance driven in diesel and natural gas, including detours made to refuel with gas at the beginning, middle and end of the route.

Firm's commitment to CNG. The increase in refuelling network density would limit the costly detours for carriers. We split the firm's commitment into three steps. A first step (Step 1) is a low commitment from the company: less than 10 flows are converted to natural gas. We can consider this step as an introductory trial that has to be conclusive for the company to commit to a massive en-bloc purchase. The second step (Step 2) is a massive commitment to a cleaner technology, allowing a discount on quantities purchased. The last

[1]Let us point out that we have not explicitly taken into account the difference between CNG and Diesel trucks in terms of the cost of exhaust clean-up systems to reduce pollutant emissions. Indeed, the three-way catalyst technology for CNG HDV exhausts reduces NOX emissions at a lower price than diesel technology and with less complexity and thus greater durability (Thiruvengadam *et al.*, 2018). This new cost item is in line with the greater profitability of CNG compared to diesel, and supports our results.

TABLE 1: Comparative cost breakdown of diesel, CNG and bioCNG

	Material investment			
	Diesel	CNG	mixCNG	bioCNG
Commitment duration	5 years	5 years	5 years	5 years
Biogas percentage	0%	0%	30%	100%
Investment	€85153	€109000	€109000	€109000
Truck price after negotiation	€85153	€109000	€109000	€109000
License and registration	€850	€5	€5	€5
Truck buyback price after 5Y	€20000	€10900	€10900	€10900
Financing rate	1%	1%	1%	1%
Monthly cost of material	€1145	€1 686	€1686	€1686
Total cost of material (5Y)	€68694	€101164	€101164	€101164
	Human resources			
Monthly hours	220 h	220 h	220 h	220 h
Manpower (full-time equivalent)	1.00 FTE	1.07 FTE	1.07 FTE	1.07 FTE
Hourly wages	€18.32	€18.32	€18.32	€18.32
Total monthly cost	€4029/mo.	€4311/mo.	€4311/mo.	€4311/mo.
Total 5Y cost	€241766.12	€258689.75	€258689.75	€258689.75
	Variable cost			
Average fuel price over 5Y	€1.2703/L	€0.8631/kg	€0.8931/kg	€0.9631/kg
Consumption	29.7kg/100km	27.0kg/100km	27.0kg/100km	27.0kg/100km
Average fuel price/km	€0.340/km	€0.233/km	€0.241/km	€0.260/km
Maintenance	€0.074/km	€0.089/km	€0.089/km	€0.089/km
Tyres	€0.039/km	€0.039/km	€0.039/km	€0.039/km
€/km average	€0.490/km	€0.361/km	€0.369/km	€0.388/km

step (Step 3) requires a massive supply chain-wide conversion and significant investment to purchase a new fleet. If there are enough flows serving a plant, it is possible to install a CNG station directly next to the plant. No investment is needed from the company, given that the daily truck traffic is high enough to ensure the profitability of a gas operator installing a station near a company's plant. Note that a scale effect is at work, as the logistics mobilises an entire fleet of trucks. Carriers therefore usually make bulk purchases to secure a discount price. We estimate based on Renault expertise that the bargaining power of carriers against truck manufacturers is 5% for steps 2 and 3.

This three-step procedure allows the scenario to remain profitable for refuelling station operators. As the first two steps require no additional stations, we based our calculations on existing stations in France (as of November 2018). The French NGV advocacy platform (AFGNV) issues periodic updates on newly-created stations.

Diesel price uncertainties. As there is uncertainty over changes in diesel prices, we study two price evolution scenarios: a ‘Central’ scenario which is the more likely according to Renault’s in-house research, and a ‘Black’ scenario where the price per barrel soars. We anticipate that the price of natural gas for vehicles will be more stable by 2022, and so we consider only one scenario. Prices are given in Supplementary material.

CNG Composition. Nonetheless, the gas price scenario may vary depending on whether it is fossil or bio-based or a mix of the two. The paper refers to these different fuels as CNG, bioCNG, and mixCNG[2].

Table 2: Scenarios and assumptions

Diesel price evolution	
Central Scenario	Diesel from €1.054/L (2017) to €1.426/L (2022)
Black diesl scenario	Diesel from €1.054/L (2017) to €1.426/L (2022)
(Carbon Tax)	Carbon tax from €30.5/tonCO_2 (2017) to €86.2/tonCO_2 (2022)
Firm’s commitment	
Step 1	≤ 10 flows converted to NGV
Step 2	All profitable flows converted to CNG at 5% purchase discount
Step 3	Step 2 & refuelling station near to the plants
CNG composition	
CNG	Fossil Natural Gas
mixCNG	30% biosourced gas & 70% fossil natural gas
bioCNG	100% biosourced natural gas

3.4 Greenhouse gas emissions

GHG emissions for fuel are expressed as a quantity of carbon released for a certain quantity of fuel (kg or L). Tank-to-wheel (TtW) emissions are the emissions due to combustion of

[2]It is possible to imagine a ramp-up scenario, starting with Step 1 as a test phase, then through Step 2 until the construction of stations in Step 3. A company may gradually increase the share of biogas in its energy mix to compensate for the increase in relative price of diesel compared to CNG. Only typical cases are presented here, so both the ecological and economic performance results of such ramp-up scenarios would be an approximately linear combination of the results presented.

one litre of diesel or one kilogram of gas. WtW analysis includes the upstream emissions related to extraction, refining and transport of the fuel (Well-to-Wheel). Table 3 summarises the emissions corresponding to both WtW and TtW per kg of fuel and per km. The TtW CNG emission coefficient (regardless of source) is 2.78 kgCO_2/kg gas, while the respective coefficients of CNG and bioCNG are 3.48 and 0.82 kgCO_2/kg gas. Indeed, methanisation is considered as 'capture' of CO_2 (which makes the WtW coefficient negative), which makes it doubly attractive. The source used for the emissions coefficient is the French Environment Agency (ADEME[3]) 'Base Carbone', version 11 (Ademe, 2014).

TABLE 3: Emissions coefficients for diesel, CNG, bioCNG and mixCNG
Reading: At equal mileage, CNG emits 0.2% less than diesel. CNG has higher on-road emissions (TtW) but 4% lower sourcing emissions (WtT – Well-to-Tank). The WtT step is negative for bioCNG, strongly reducing its WtW carbon footprint

	Diesel	**CNG**	**mixCNG (30% biosourced)**	**bioCNG**
WtT (kgCO_{2eq}/kg)	0.78	0.7	-0.10	-1.96
TtW (kgCO_{2eq}/kg)	2.97	2.78	2.78	2.78
WtW (kgCO_{2eq}/kg)	**3.75**	**3.48**	**2.68**	**0.82**
Consumption	29.7 L / 100 km 25.1 kg / 100 km	27.0 kg / 100 km 27.0 kg / 100 km	27.0 kg / 100 km 27.0 kg / 100 km	27.0 kg / 100 km 27.0 kg / 100 km
WtT (kgCO_{2eq}/km)	0.196	0.189	-0.026	-0.529
TtW (kgCO_{2eq}/km)	0.745	0.751	0.751	0.751
WtW (kgCO_{2eq}/km)	**0.941**	**0.940**	**0.724**	**0.221**
% WtW *vs* Diesel	**0%**	**-0.20%**	**-23.09%**	**-76.48%**

3.5 Other externalities

Negative *externalities* are the collateral damage of an economic activity whose costs are not directly paid through production or consumption by the economic agents who cause them—the costs are instead borne uniformly by society (including the environment). The externalities of transportation can be collapsed into seven categories: congestion, acci-

[3]Agence de Maitrise de l'Energie et de l'Environnement

dents, noise, pollution, climate change, infrastructures, and others (Delft, 2016a,b, 2015; RICARDO, 2014; Delft, 2011; Vickrey, 1963).

CNG reduces the externalities of diesel on three fronts: i) GHG emissions, ii) air pollution, iii) noise levels. These three externalities can be measured relatively accurately and monetised in order to balance them against the cost of the policies to reduce them.

CNG can reduce pollutants by nearly 80% (which is the official figure given by the manufacturers for NOx and PM (NaturalGas.org, 2019) compared to Euro VI-standard diesel[4], which is far less than the 88-fold coefficient given by Pietikäinen *et al.* (2009) and reasonable compared to the literature (Lyford-Pike, 2003). Hagos & Ahlgren (2018a) claims “almost zero particulate matter (PM) emissions, 87 to 90% reduced NOx emissions, and 67 to 76% reduced hydrocarbon emissions at comparable fuel economy”. There is also a consensus that natural gas vehicles are 50% quieter than diesel-powered vehicles (Hagos & Ahlgren, 2018a; Maji *et al.*, 2008).

GHG reductions are very much related to the composition and source of the gas in question, which is not the case for noise or local pollution where only combustion matters.

There is a plethora of methods for assessing damage caused by GHGs, air pollutants and noise. In this study, we follow the methodology and figures given in Delft (2011), which provides a monetary estimate of externalities expressed in tonne-kilometres[5] for diesel trucks depending on type of road and age of the vehicles. The noise and emissions reductions translate into an equivalent reduction in externalities per kilometre.

4 Results

4.1 Scenarios analysis: Biogas is the key to emissions reduction

The main assumptions are subdivided into several scenarios: the company’s level of commitment ranges from step 1 to step 3, and fuel prices can follow a steady ‘Central’ scenario or a ‘Black diesel’ scenario in which the barrel price soars. Source of the natural gas considered can be of fossil origin or biosourced at 30% (mixCNG) or 100% (bioCNG). For each scenario and their particular assumptions, we select the flows allowing a net benefit compared to diesel (benefit is the reduced cost of fuel net of the extra investment cost of the CNG truck).

Figure 2 details the number of trucks for which CNG enables a net benefit compared to diesel, in real-world conditions. Cost savings and GHG reductions are reported in the lower

[4]Knowing that the Euro IV standard already marks a 92% decrease in acceptable NOx limits compared to the EURO III standard: https://www.ecologique-solidaire.gouv.fr/normes-euros-demissions-polluants-vehicules-lourds-vehicules-propres. Euro III standard is 7 gNOx/kWh against 0.4 gNOx/kWh for Euro VI

[5]A tonne-kilometre (tkm) corresponds to the displacement of a ton of goods over one kilometre. The average load of a heavy vehicle is 10T, so a truck travelling 100 kilometres is considered to weigh 1000 tkm in the calculated externalities.

matrix. Note that the percentage reductions in cost and emissions only encompasses CNG-converted flows. The company could convert 31 trucks to CNG with a medium level of commitment (Step 2) in the Central scenario, and could then save 1.7% of total operational cost on its routes' compared to the same 31 trucks running on diesel.

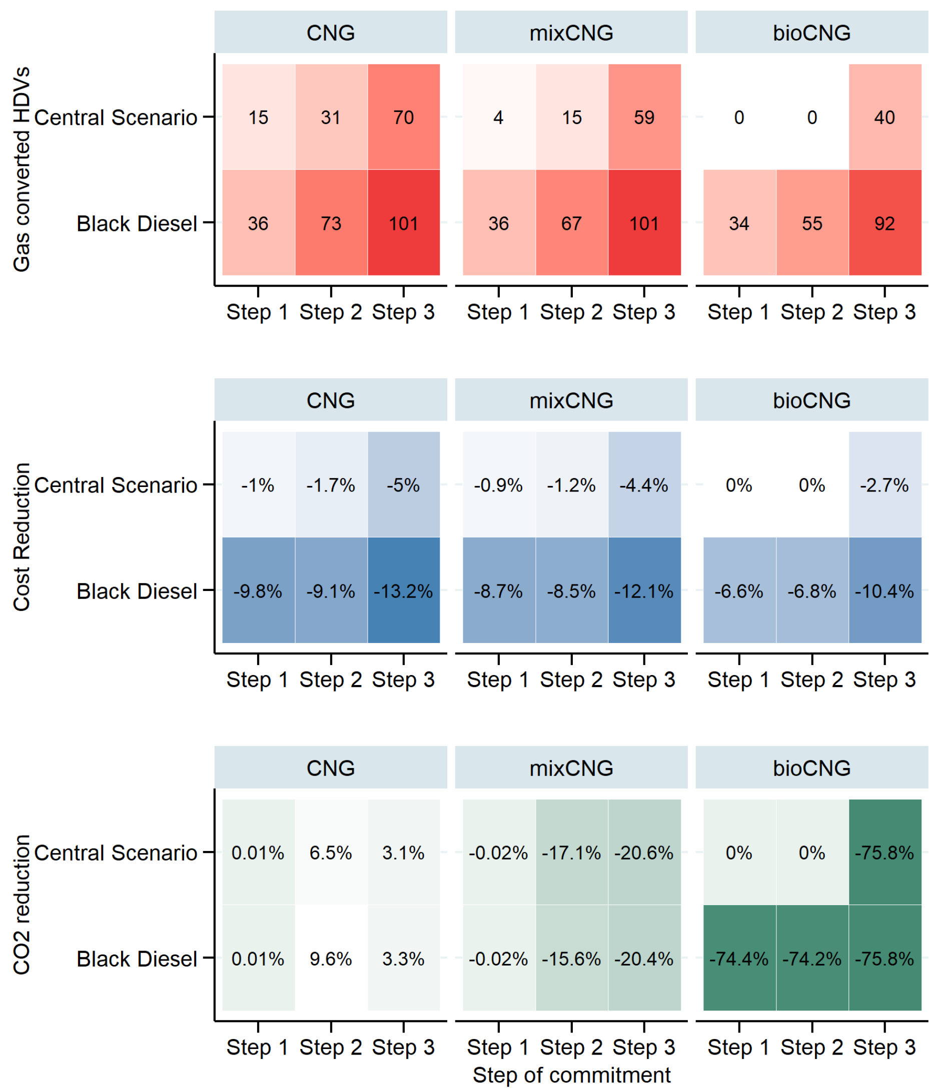

FIGURE 2: Cost and emissions reductions for each scenario
Reading: In the Central scenario, in Step 2, adopting CNG will reduce on-road cost of CNG-converted routes by 1.7% whereas emissions increase by 6.55%.

The Central scenario reaches profitability for at least 9% of the trucks converted to CNG and up to 42% with a higher commitment (step 3). As biogas is more expensive, it becomes barely profitable since the firm needs to make a high commitment (step 3) to make 40 trucks profitable in CNG compared to diesel. In contrast, the Black diesel scenario allows a trial phase with bioCNG where only the 10 best flows, corresponding to 34 HDVs, are converted to CNG, thus cutting costs by 6.6%. Indeed, with increasing commitment from the company, the percentage cost reduction increases while detours to reach refuelling stations decrease and investment is reduced as the carrier gains bargaining power. The most favourable situation is the scenario that widens the gap between gas and diesel prices at minimum cost (Black diesel x Step 3). The company could convert 32 out of the 42 pre-selected flows to bioCNG (>75%) or convert a maximum of 101 HDVs to CNG.

The first conclusion is that the profitability of CNG trucks in real flows depends on the global price of oil. Unsurprisingly, as biosourced gas is more expensive, the number of profitable flows is lower for bioCNG than for CNG and mixCNG, and the expected cost savings are also smaller.

However, the environmental benefits of NGV could become negative, as CNG may emit more GHG gases over a trip than diesel. No CNG scenario is able to cut emissions compared to diesel: the rise in CNG emissions ranges from 3.1% to 9.6%. In contrast, a 100% biogas scenario is able to cut around 75% of GHG emissions, including CO_2 and methane (CO_{2eq}).

Real flow conditions erode the environmental benefits of natural gas beyond the figures cited in section 2. Long-distance flows are the most profitable, as the fuel-price gap between gas and diesel offsets the extra investment cost of CNG trucks. As NGV trucks have limited range, long flows become characterised by numerous stops to refuel and detours to reach CNG stations. These extra distances increase both the price and the emissions of trips.

These results are typical of long interurban trips and are not therefore comparable to urban fleets (e.g. -34% in CO_2 emissions for a refuse truck fleet in Shahraeeni *et al.* (2015) or -12% in López *et al.* (2009)) where refuelling is not a problem, especially without considering the adoption period of the technology.

Figure 3 charts the trade-off between share of biogas and efficiency of conversion to CNG in terms of trucks on the roads, costs and emissions reduction in the particular case of Step 2 in the Central scenario[6]. Increasing biogas share in the fuel mix increases emissions reductions but decreases cost savings until diesel cost is reached. With 8.04% of biogas, the experiment reaches carbon neutrality compared to diesel within the same scope-frame as CNG (31 trucks, over 10 flows), whereas 90% biogas lead to more than 60% reduction in GHG emissions for bioCNG trucks compared to diesel.

The French Government's 2009 Carbon budget sets the transportation sector an objective of cutting GHG emissions by 6% (Quinet *et al.*, 2009). A 21.3% share of biogas would allow the mixCNG flows to reach this objective for all scenarios studied here. For the rest of this study, we consider a mixCNG scenario with a 30% biogas share to ensure a larger CO_2 decrease to offset the remaining diesel flows. A larger share of biogas raises the price of the fuel while reducing its economic attractivity.

[6]NB: For both emissions and costs, the perimeter is variable and expressed as a percentage reduction only for routes that have switched from diesel to CNG (bio-sourced, mixed or fossil), which is why we see peaks in Figure 3 with thresholds where we lose routes that were just-about profitable to keep only the most profitable (i.e. a higher percentage gain).

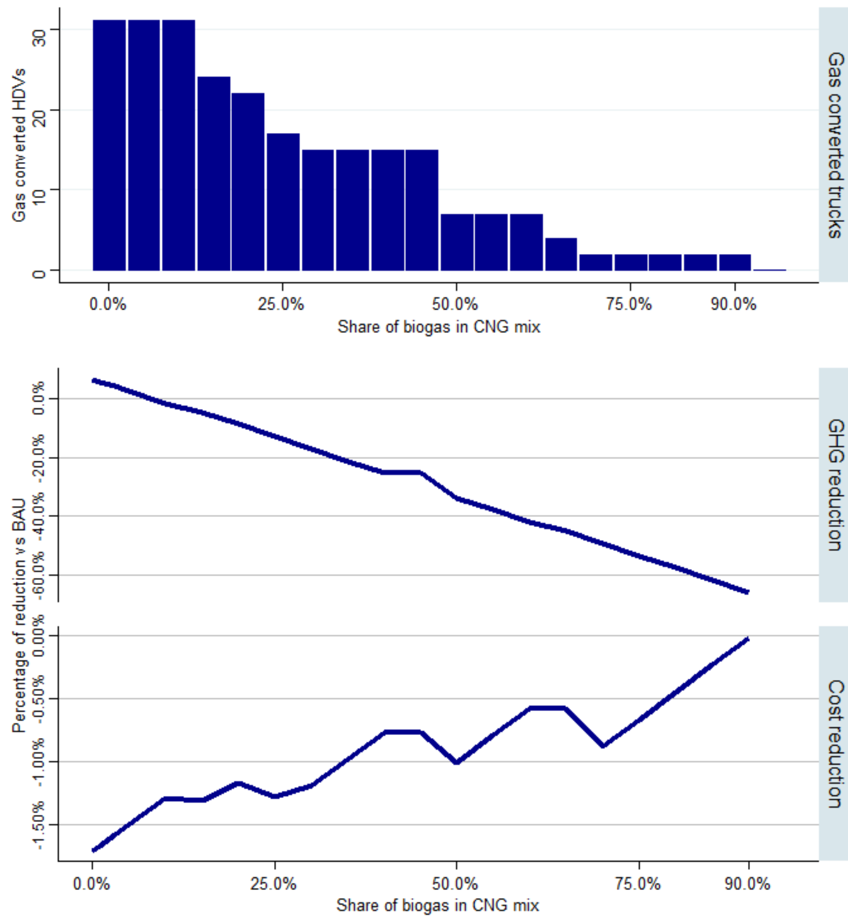

FIGURE 3: Cost and CO_2 savings as a function of biogas share in the mixCNG scenario

The French Multiannual Energy Programme (PPE) aims to produce 14 TWh of biogas domestically in 2023 and 32 TWh in 2028. The same source states a consumption of 192 TWh by road freight transport in 2016. The use of bioCNG could therefore only concern a fraction of the HGVs on domestic roads. The second conclusion is that CNG raises emissions in the real-scale situation compared to diesel due to the low density of the refuelling network, and biogas production capacity will be unable to sustain the entire market, making it difficult for natural gas to play the role of bridge fuel to enable the whole transportation sector to make its energy transition.

4.2 Key parameters and sensitivity analysis

One of the key parameters in our modelling of gas truck penetration is the detour imposed by the low density of the refuelling station network. This detour, which depends on the company's commitment to natural gas, averages between 3.82% and 7.41% for all flows considered (see Table 4). Indeed, Step 3 means a substantial commitment by the company of at least 40 trucks in bioCNG and 101 in CNG, which would be enough to make it profitable for a filling station to locate next to the plant, thereby reducing the detours need to refuel the trucks. Bigger detours lead to a smaller gap between diesel and CNG emissions. In the case of CNG, the detour more than offsets the emissions gains. The level of detail of our dataset allow us to define which routes are profitable for the company and which refuelling stations each truck stops at. Note that the cost of the additional labour required to drive these extra kilometres is not expressed on a flow-by-flow basis but as a 7% increase in full-time equivalents for Steps 1 and 2 and a 3% increase for Step 3. Not accounting for detours leads to overestimating the potential of natural gas, since all scenarios advise converting at least 29 HDVs into biogas[7].

Clearly, it is the detours that kill the environmental performance of natural gas for vehicles, since all scenarios announce a CNG emissions reduction of 0.2%, which is close to the 0.6% calculated by Meyer *et al.* (2011) instead of a rise of 3.1 to 9.6%. If we neglect the position of the refuelling stations, we favour long trips, which is why the cost reduction reaches 9% by CNG for the Central scenario but is only 1% with the detours. Without the detours, our gains over 5 years are at best 18.8% compared to the Diesel scenario, i.e. more than 5 years to achieve payback. However, these estimates are based on price gaps of more than €1.50 whereas we consider gaps that are narrower at the beginning but at least as big at the end. This is why even without detours, our economic results are much less optimistic than Krupnick (2010) who asserted a payback in less than 2 years.

Detours are a hidden cost that dramatically changes the attractivity of NGV. Detours, extra maintenance costs, and a less optimistic gas consumption with a more detailed cost breakdown (see Supplementary material) explain the different conclusions of this study compared to Hao *et al.* (2016) or Krupnick (2010).

TABLE 4: Detours in CNG *vs* diesel trips

CNG	Central Scenario	Black diesel scenario
Step 1	7.98%	7.70%
	(31.3 km)	(27.4 km)
Step 2	7.41%	10.14%
	(26.3 km)	(31.8 km)
Step 3	3.82%	4.01%
	(11.6 km)	(9.6 km)

Conversely, neglecting the evolution of relative fuel prices leads to underestimating the attractiveness of CNG. Even with a diesel/gas price differential set at the 2018 level for the 5-year study period, natural gas for vehicles remains attractive for carriers and loaders. The switch to CNG would reduce operating costs for 5 out of 42 of them. The change would

[7]For control purposes, we performed the calculations reported in Supplementary material without taking detours into account, thus neglecting both the additional distance covered and overtime hours required.

concern 9% of the trucks (15 trucks a day). These 5 flows would generate a €56k net present value (NPV) out of the switch to CNG trucks from 2018 to 2022 which represents 1.00% of the current operating cost for those routes using Diesel trucks (€5.7M over 5 years).

A fixed gap between natural gas and diesel is a very conservative assumption that does not contradict the economic attractivity of natural gas as HDV fuel. Carrier adoption of CNG technology is therefore possible as of now, and our simulation is robust on this parameter. Indeed, the relative price gap between diesel and CNG will only increase during the period (2018—2022). Increasing the carbon component in the fuel taxes will affect diesel more severely than gas. Meanwhile, it is likely—but not certain—that market fluctuations will increase oil prices. The second conclusion of this first simulation is therefore that neglecting the evolution of relative fuel prices leads to underestimate the attractiveness of CNG.

We selected this study's parameters based on input from the French National Roads Council (CNR, 2018), Equilibre report (Equilibre, 2018), the French Environmental Agency 'Base Carbone' database (Ademe, 2014), and supply chain experts at Renault. We tested the influence of a 10% error margin on uncertain parameters (CNG consumption per 100 kilometres, Financing rate, Purchase price, extra cost of maintenance, resale price, and hourly wages) on the number of trucks deployed (Figure 4). CNG consumption per kilometre and purchase price are major cost items and both appear to have a big influence on the attractivity of CNG technology, but the variance is not enough to unsettle the trend we described in the previous section. Consumption is the most volatile parameter as it largely depends on the driving skills of each driver, yet the average is far less uncertain across 40 trucks, each one driving more than 70,000 km a year.

The current state of the refuelling network and the future trend in oil prices appear to be the main drivers of the results. The differences in economic and environmental results with previous studies are therefore due to the integration of new parameters related to the transitional period of technology adoption. The paradox is therefore that the network of stations needs to be developed to reduce costs and emissions while at the same time oil is still too cheap compared to natural gas.

4.3 Public incentives and policies

The previous section highlighted the conditions under which CNG can be a profitable option over diesel while cutting GHG emissions, i.e. long trips with short detours to reach refuelling stations, and big players with large fleet and a high level of commitment. The challenge for the State is therefore to promote NGV through an understanding of the real microeconomic determinants of the investment, while reducing GHG emissions. Public policies should clearly encourage the use of bioCNG: the objective is to make a mixCNG solution attractive compared to diesel and fossil CNG. A rise in carbon tax could make it possible to increase the attractiveness of bioCNG along with its ecological value, provided that the calculation method is changed.

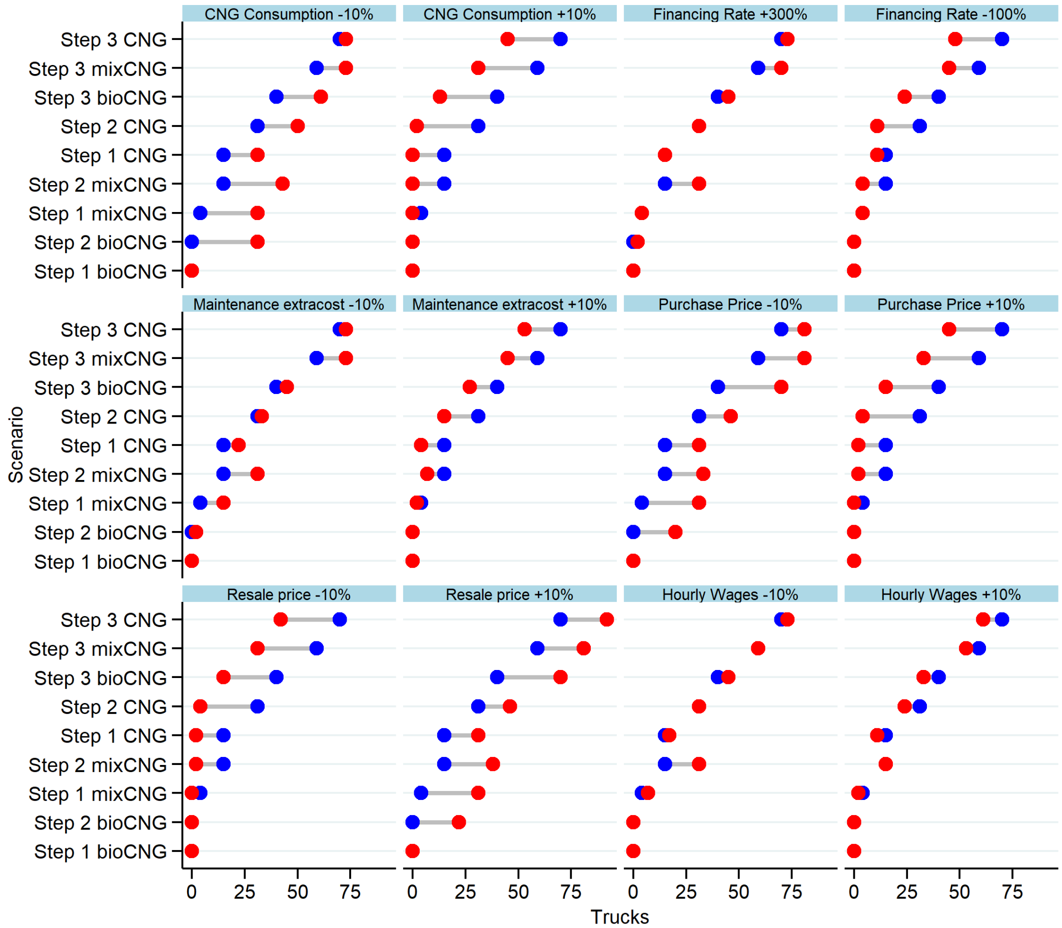

FIGURE 4: Hypotheses and sensitivity analysis on the costs and benefits of converting trucks to CNG
Reading: From blue to red, a +10% uncertainty on purchase investment will reduce converted trucks by 87% for Step 2 in CNG (from 31 to 4)

The carbon trajectory used until now was defined by the French Finance Act 2018[8] and is incorporated into the price of diesel. Quick least-squares interpolation shows that it will reach €174.34/tCO_2 ton by 2030, which is still far below the recommended €250/tCO_2 to reach carbon neutrality by 2050 (Quinet *et al.*, 2009). The drawback of the current carbon tax is that it is based on calculated TtW emissions. The TtW calculation does not consider any emission difference between biosourced and fossil gas, whereas the WtW calculation considers the carbon weight of each fuel. Here we modelled diesel, CNG and bioCNG price trajectories using the TtW and WtW hypotheses given in Figure 5. The WtW calculation increases the price of diesel and CNG while lowering the price of bioCNG. Therefore, emissions calculation methods influence policy design. A WtW carbon tax is a tool that can

[8]https://www.senat.fr/rap/a17-113-1/a17-113-14.html

achieve both economic and environmental objectives by pushing bioCNG and mixCNG.

A steady-state tax of €50 per tonne is sufficient for all bioCNG scenarios to ensure a minimal GHG emissions reduction of 6% and for all scenarios to meet the Carbon Budget goal of limiting global warming to 2°C. More than the double, i.e. €102.31, would be required to achieve the same objective with a 30% bioCNG mix[9]. Note that the €50 tax is not high enough to allow all mixCNG scenarios to deploy gas HDV on the roads. In the long term, carbon price trajectories as planned in the Finance Laws imply a much higher carbon price compared to the steady state. A higher carbon price will make biogas and mixCNG more attractive compared to CNG and diesel, and it is likely than companies' levels of commitment and percentage emissions reduction would also be higher.

There is a huge discrepancy between the steady-state carbon price needed to reach environmental targets and the trajectory with a real and constrained starting point. Here, unlike other studies (Galbieri *et al.*, 2018; Krupnick, 2010), we account for the transition period. Thus, the profitability of projects depends on the specific evolution of fuel prices but also on the carbon component specific to each country. The lack of visibility on this subject could lead agents to under-invest, hence the need for a clear framework for alternative fuels and clear long-term sustainable policies.

In theory, a tax and a subsidy have exactly the same incentive effect if they are at same levels: the rational agent does not differentiate between an increase in the cost of one option through the tax or a decrease in the cost of another through the subsidy. In reality, carbon taxes have repercussions on society as a whole, destroying jobs in polluting sectors such as transport, or having very significant unequal impacts on the most fragile layers of society (Büchs *et al.*, 2011). For a HDV, the additional investment cost between a CNG and a diesel is €23,847. Full compensation of this amount by the State could make practically every route potentially profitable (even though the price per km is still less for bioCNG than for diesel). Full reimbursement of the additional cost of purchasing a gas HDV would imply that the State has to subsidise up to 21.88% of the truck purchase. In the median scenario (Central scenario x Step 1 x bioCNG), the minimum subsidisation required to convert at least one flow is 3.8% of the truck price, or 17.3% of the initial over-investment, i.e. €4,109. To ensure at least 1% of economic profitability for this flow would need a subsidy of 8.25%, i.e. €8,992 per truck. We found a significant influence of taxes and subsidies on company commitment levels and on numbers of CNG-converted HDVs in the model, in line with the conclusions of Morrison *et al.* (2018) and Hao *et al.* (2016) which indicate a 20% purchase subsidy to encourage investment. Similar levels are found in French law: the system put in place by France since 2015 provides a tax deduction equal to 40% of the cost price of the investment. This amount is deducted from the profit on a straight-line basis over the depreciation period chosen by the company to depreciate the asset via a reducing-balance

[9]While it may seem odd that the level of carbon tax required to ensure profitability is higher for mixCNG than for bioCNG, the reason that the difference between emissions per km multiplied by amount of carbon tax more than offsets the small extra cost of 10cts€/kg of biogas compared to CNG and, therefore, the extra cost of 6.67cts€/kg between bioCNG and mixCNG.

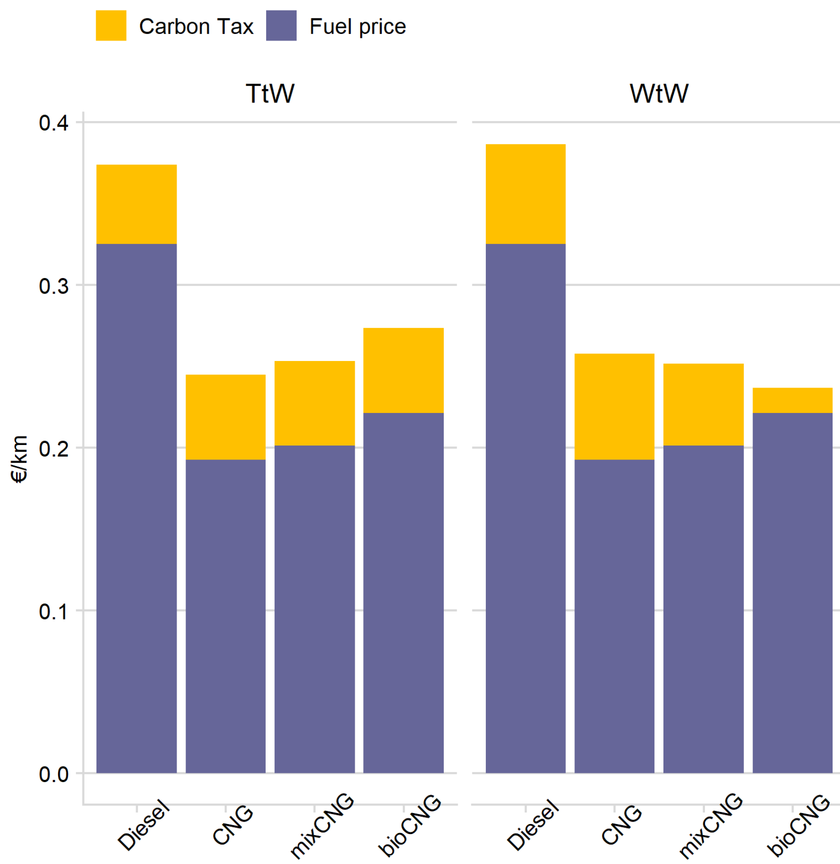

FIGURE 5: 2020 fuel prices for CNG, mixCNG, bioCNG and diesel under TtW and WtW emissions computations
Reading: A kilometre by a bioCNG truck is worth 0.181 of fuel and 0.052 of carbon tax for on-road emissions or 0.015 per km of carbon tax for life-cycle emissions. Prices per kilometre encapsulate the consumption of different types of trucks and their detours.

method. This then comes to an amount of €14,388, i.e. 60% of the initial over-investment and 13.2% of the total purchase amount.

Government should move quickly to support commitment from major players in order to encourage the network to develop and ensure minimum profitability (Imran Khan, 2017). By the time the network is developed, the relative attractiveness of gas compared to diesel will have increased, and smaller players unable to reach Step 2 or Step 3 of commitment would be able to enter this market. Study of the transition period also shows that, counter to Heimer *et al.* (2017), a subsidy policy for the purchase of HDVs could be limited in time as the fuel price gap increases. Subsidies carry a cost burden for public budget, but this cost has to be weighed against all the co-benefits in terms of reduced public external costs. Table 5 summarises the different average gains over the three fronts considered in section 3.5.

A crucial comparison is the ratio of the amounts granted by the State through subsidies collected from households through taxes to the external costs avoided by the change from diesel to CNG. In the case of a 7% subsidy, the avoided costs are more than 300 times higher (0.26%) than the amount of the subsidy granted.

Compared to diesel, bioCNG averages 50% lower external costs when considering only pollution, climate change and noise. For CNG the gain is not automatic as CO_2 emissions are increased by 6.5% in the Central scenario, and in Step 2, unlike other steps, the decreases in noise and local pollution fail to offset this increase.

TABLE 5: Avoided external cost for central scenario over 5 years (2018-2022)

Fuel	Commitment step	Converted trucks	Total subsidisation (€) (8.25% subs.)	Avoided external cost *vs* diesel (%)	Ratio of subsidisation to avoided external cost
CNG	Step 1	32	€287,760	-4.45%	-0.31%
	Step 2	50	€449,625	+2.83%	+0.50%
	Step 3	81	€728,393	-6.82%	-0.25%
mixCNG	Step 1	31	€278,768	-5.33%	-0.26%
	Step 2	43	€386,678	-13.70%	-0.10%
	Step 3	76	€683,430	-20.41%	-0.08%
bioCNG	Step 1	4	€35,970	-12.60%	-0.08%
	Step 2	19	€170,858	-3.25%	-0.40%
	Step 3	70	€629,475	-20.46%	-0.08%

5 Conclusion and policy implications

This paper set out to determine the economic conditions under which it is both economically and environmentally beneficial to support switch to CNG for HDV. This investigation helps to explain why there has not yet been mass supply chain-wide energy transition in Europe. The model we deployed, based on data on French automaker Renault's real supply chain flows, estimated the profitability and conversion conditions of each route served. Even though the flows considered are mainly situated in highly-industrial northern France, the constraints of this fiercely competitive industry apply to practically all sectors. Detours to reach refuelling stations were identified as the key factor, influencing performances and unexpectedly pushing the CNG GHG emissions above diesel GHG emissions. We also showed that a WtW carbon tax or subsidisation was able to influence the uptake of partially-biosourced CNG to cut emissions by up to 76%, in which cases the external costs reduction in terms of air pollution, noise and GHG was 50% with bioCNG compared to the same route using diesel fuel.

Despite the relatively limited scope of our dataset, which is confined to an automotive supply chain in France, the results presented in this study are robust and significant enough to draw up some general policy recommendations. Barriers to NGV adoption—like the allied policy instruments—are common to many countries (Yeh, 2007). Here we compare the effectiveness of policies for incentivising NGV use for long-distance HDV, which can apply to countries at a similar stage of NGV adoption as in France. This study points to 4 policy recommendations to support the development of CNG as an alternative fuel for HDVs. Points two and three lead out from point one, while point four stands on its own:

(i) To reduce transport GHG emissions, public policies should encourage the use of biosourced or partially-biosourced CNG and deter from using entirely fossil-based CNG. Fossil CNG does not represent a viable low-carbon alternative to diesel for long-distance HDVs. In this study, comparative emissions for the same trips ranged between +0.01% and +9.6% for fossil CNG *vs* diesel but between -75.8% and -74.2% for bioCNG *vs* diesel. Efforts to decarbonise transport through the use of natural gas must therefore be based on biosourced natural gas, in accordance with the International Energy Agency recommendations (IEA, 2010).

(ii) Developing a local methanisation industry is a key prerequisite to drive a significant shift toward natural gas for goods transport. A right-sized methanisation infrastructure would ensure a sufficient supply of biosourced gas to meet growing demand while giving government and industry an opportunity to create jobs in the farming sectors that cannot relocate, and thereby help reduce dependency on imported fossil gas and oil (Balat & Balat, 2009).

(iii) Carbon tax should encompass the full life-cycle emissions (Well-to-Wheel instead of Tank-to-Wheel (TtW) emissions) of fuel in order to encourage biofuels such as biosourced CNG without actually raising the price of carbon. Taxing only the combustion part of natural gas (TtW) implies that CNG and bioCNG are taxed at the same level: there is no financial incentive for bioCNG over CNG. Based on the results of this study, fossil CNG emits more than diesel once consumptions of the real engines and refuel detours are taken into account, which means that a TtW carbon tax would counterproductively encourage the use of diesel over natural gas.

(iv) Governments should subsidise purchases of bioCNG HDV. Biosourced and partially-biosourced CNG are not yet profitable compared to diesel. The level of subsidy should be high enough to cover the potential fluctuation in oil and gas prices to create a steady and reassuring environment for industries to adopt bioCNG. Our model found that a minimum subsidy level set at 8% of purchase price would be sufficient to make the investment in CNG trucks profitable without companies having to engage massively in order to attain economies of scale. Incentivisations should be capped at 22%, which is the level that would fully subsidise the additional cost of purchasing a natural gas HDV. Subsidies could be made conditional on the use of bioCNG; this measure would be complementary with moves to extend the scope of carbon tax to life-cycle emissions.

Future research could usefully extend our methodology in a number of directions. Other modalities of real flows, such as congestion, road gradients, average speeds and payload, could all be refined. These parameters play a role in both the economic and ecological sides of the equation (Hausberger *et al.*, 2009). This would make our already robust results even more accurate in terms of costs and emissions estimates, but would also allow us to refine and add parameters to our study of externalities. The logical extension of this study would be to reach out into other companies and countries and transborder trips, to gain a broader-picture perspective on multi-context economic situations

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