Institute of Transport Economics
Norwegian Centre for Transport Research

Summary:

Vehicle fleet forecasts based on stock-flow modeling

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Author(s): Lasse Fridstrøm, Vegard Østli
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Relying on a stock-flow cohort model of the Norwegian motor vehicle fleet, we examine the prospects for radical greenhouse gas abatement through automobile, bus and freight vehicle fleet renewal. Under highly optimistic assumptions regarding market uptake of zero and low emission vehicles, CO_2 exhaust emissions from the motor vehicle fleet could be halved between 2015 and 2031. This, however, presupposes that virtually all passenger cars, buses and cargo vans sold in 2030 be emission free. Achieving these targets will be quite challenging. Under somewhat less demanding assumptions, based on trend extrapolation, the stock-flow model projections suggest an about 20 per cent reduction in GHG emissions from Norwegian road transportation between 2015 and 2030.

Objective

Road transportation is a major source of greenhouse gas (GHG) emissions, and one that, except for electric vehicles, is not covered by the European Union's emissions trading system (EU ETS). In 2015, road transportation represented roughly 19 per cent of total GHG emissions in Norway, and about 38 per cent of the emissions not covered by EU ETS.

European and Norwegian climate policy goals suggest that by 2030, GHG emissions should be cut by 40 per cent compared to the 1990 level. If such a target were to be applied verbatim to road transportation in Norway, it would require that emissions be more than halved – indeed, cut by 55 per cent – between 2015 and 2030, since emissions on the road have already increased 32 per cent between 1990 and 2015.

Barring massive reductions in the mobility of people and goods, and in view of the very limited potential for emission cuts through modal shifts, the most promising strategy left appears to be that of technological innovation through vehicle fleet renewal. Internal combustion engine (ICE) vehicles must be replaced by zero and low emission alternatives such as battery (BEV), plug-in hybrid (PHEV) or fuel cell electric vehicles (FCEV). In addition, renewable biofuel could come into widespread use in whatever ICE or hybrid vehicles be still in operation 15 years ahead.

In their proposed climate strategy document, the Norwegian transportation agencies have suggested the following targets. By 2025 all new passenger cars and transit buses sold should be zero emission vehicles, i. e. BEVs or FCEVs. By 2030, the same should apply to all new light duty freight vehicles, to 75 per cent of all new inter-urban buses and coaches, and to 50 per cent of all new heavy duty freight vehicles.

If these targets, which apply to the *flow* of new vehicles only, were met, would that ensure a more than 50 per cent cut in the emissions from the vehicle *stock* by 2030? To examine this question, a *stock-flow model* of the vehicle fleet is called for.

The BIG[1] stock-flow model

Let $A_{i,j}^{m,n}$ $(i=1,2,....,I^m;\ j=1,2,...,J; m=1,2,...,M; n=2010,2011,...,N)$ denote the *stock* of *j-1*-year old vehicles registered in segment *i* of category *m* at the end of year *n*. By vehicle categories, we have in mind a classification into passenger cars, cargo vans, trucks, semi-trailer tractor units, campervans/motorhomes, and buses/coaches. By segments, we shall mean a cross-tabulation between energy carrier (propulsion technology) and vehicle weight. The following 11 energy technologies are specified:

(i) gasoline internal combustion engine (ICE),
(ii) diesel ICE,
(iii) battery electric vehicle (BEV),
(iv) plug-in hybrid electric vehicle (PHEV) with gasoline ICE,
(v) PHEV with diesel ICE,
(vi) non-plug-in hybrid vehicle (HEV) with gasoline ICE,
(vii) HEV with diesel ICE,
(viii) hydrogen fuel cell electric vehicle (FCEV)
(ix) natural gas ICE
(x) kerosene ICE
(xi) other ICE

As an example we show, in Fig. E.1, the stock of passenger cars at year-end 2015, by energy technology and age. In the passenger car category we encompass all vehicles meant to carry at most eight passengers plus driver, including sport-utility vehicles (SUV) and minivans. Note that in the model, vehicle age (*j*) is counted from January 1 of the year of first registration to December 31 of the current year. Since, on average, vehicles enter and leave the stock at mid-year, they are one year younger in reality than in the model.

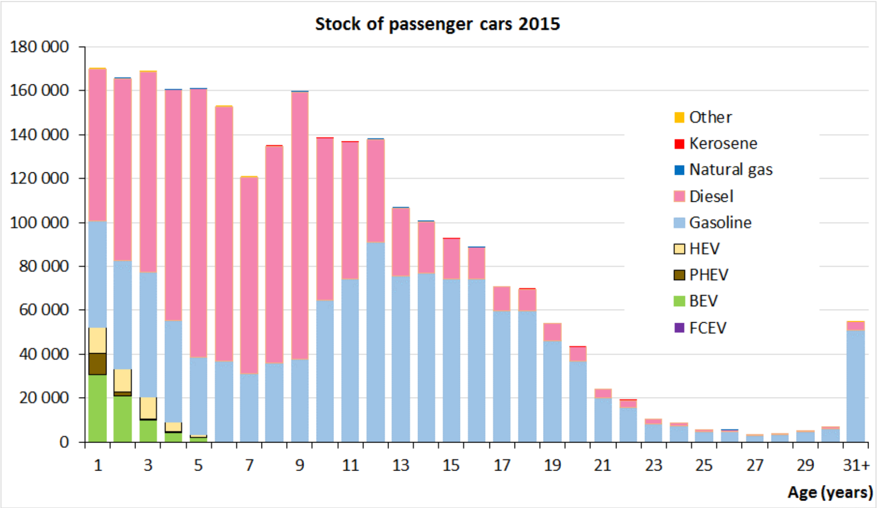

Fig. E.1 Norwegian passenger car stock at year-end 2015, by propulsion technology and age.

Also, let $a_{i,j}^{m,n}$ denote the *flow* between the stocks in years *n-1* and *n*, in other words

$$(1) \quad A_{i,j+1}^{m,n+1} = A_{i,j}^{m,n} + a_{i,j+1}^{m,n+1} = A_{i,j}^{m,n}\left[1+\alpha_{i,j+1}^{m,n+1}\right] \qquad (j=1,2,...,J),$$

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[1] BIG is a Norwegian-language acronym meaning 'vehicle cohort model'.

where the *transition rates* $\left[1+\alpha_{i,j+1}^{m,n+1}\right]$ are defined by

$$(2)\quad \alpha_{i,j+1}^{m,n+1} = a_{i,j+1}^{m,n+1} \Big/ A_{i,j}^{m,n} \qquad (i = 1, ..., I^m;\ j = 1, ..., J; m = 1,..., M; n = 2010,..., N)$$

Most vehicles survive until next year, but not all. Some are scrapped, exported, or temporarily or permanently deregistered. On the other hand, the vehicle stock may be augmented through second hand import or reregistration. All of these *gross* flows combine to form what we shall refer to as the *net flow intensities* $\alpha_{i,j+1}^{m,n+1}$. They measure the relative changes, from one year to the next, in the stock of vehicles $A_{i,j}^{m,n}$ of a given cohort and segment.

In most age brackets the net flow intensity will be negative, and hence the transition rate will be smaller than unity, since scrapping exceeds the sum of second hand import and reregistration.

For modeling purposes we shall assume that the net flow intensities are temporally stable, i. e.

$$(3)\quad \alpha_{i,j}^{m,n} = \alpha_{i,j}^{m\cdot} \qquad \forall i, j, m, n\,.$$

They will, however, vary with vehicle category (*m*), segment (*i*) and age (*j*).

In our model, the second highest age bracket is *j* = 30 years. All vintage vehicles older than 30 years are assembled in the uppermost age bracket (*j* = *J* = 31).

From the Norwegian motor vehicle register we have extracted data for the following six stocks: $A_{i,j}^{m,2010}$, $A_{i,j}^{m,2011}$, $A_{i,j}^{m,2012}$, $A_{i,j}^{m,2013}$, $A_{i,j}^{m,2014}$, $A_{i,j}^{m,2015}$, all of them specified by vehicle category, segment and age.

Invoking the simplification (3), net flow intensities were estimated by forming the weighted averages

$$(4)\quad \hat{\alpha}_{i,j}^{m\cdot} = \frac{a_{i,j}^{m,2011} + a_{i,j}^{m,2012} + a_{i,j}^{m,2013} + a_{i,j}^{m,2014} + a_{i,j}^{m,2015}}{A_{i,j-1}^{m,2010} + A_{i,j-1}^{m,2011} + A_{i,j-1}^{m,2012} + A_{i,j-1}^{m,2013} + A_{i,j-1}^{m,2014}} \qquad (j = 2,3,...,30)\,,$$

where all $a_{i,j}^{m,n}$ follow from equation (1).

At either end of the age span (*j* = 1 and *j* = 31), the flow rates must be defined and computed differently. Specifying the ‘intensities’

$$(5)\quad \alpha_{i,1}^{m,n+1} = \frac{A_{i,1}^{m,n+1}}{\sum_{j=1}^{J} A_{i,j}^{m,n}}\,, \qquad \alpha_{i,31}^{m,n+1} = \frac{A_{i,31}^{m,n+1}}{A_{i,30}^{m,n} + A_{i,31}^{m,n}} - 1$$

we calculate their empirical counterparts by

$$(6)\quad \hat{\alpha}_{i,1}^{m\cdot} = \frac{\sum_{n=2010}^{2014} A_{i,1}^{m,n+1}}{\sum_{n=2010}^{2014} \sum_{j=1}^{J} A_{i,j}^{m,n}}\,, \qquad \hat{\alpha}_{i,31}^{m\cdot} = \frac{\sum_{n=2010}^{2014} A_{i,31}^{m,n+1}}{\sum_{n=2010}^{2014} \left[A_{i,30}^{m,n} + A_{i,31}^{m,n}\right]} - 1.$$

The youngest cohort of vehicles in segment *i* of category *m* is calculated as a certain share of last year's aggregate stock in that segment, i. e. summed across all age groups. The flow of vintage vehicles is calculated as a share of the stocks in the two uppermost age brackets taken together.

Example net flow intensities are displayed graphically in Fig. E.2. The graph reveals that for cars older than 13 years, attrition is markedly higher in years of periodic vehicle inspection, which takes place in odd-numbered years of age as defined in the model. Also, it shows that for vehicles two to five years old, the net flow intensity is often negative, suggesting that second hand car export exceeds second hand import. We suspect this to be due to car rental and leasing companies routinely shifting their vehicles between countries of registration. These companies represent a large share of new passenger car acquisitions.

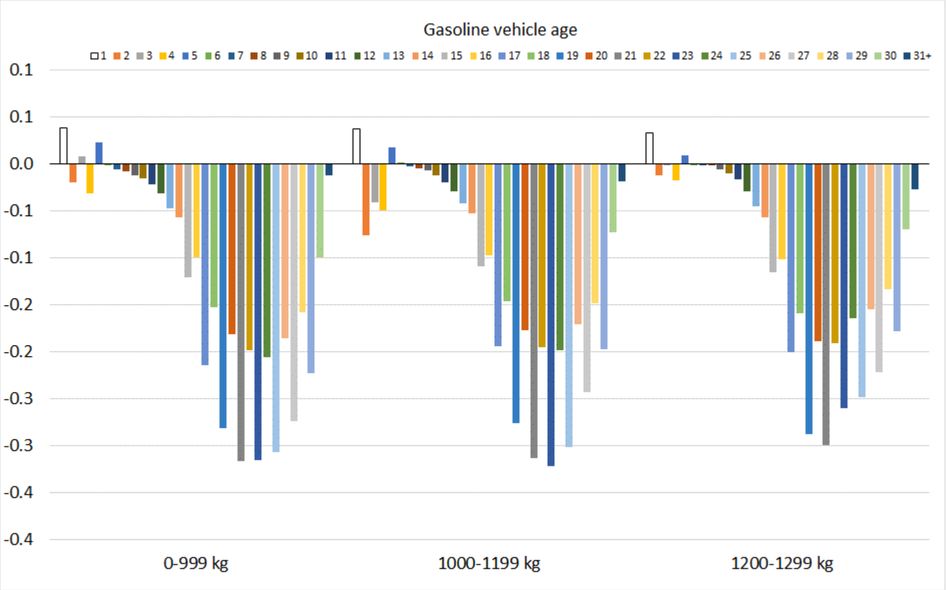

Fig. E.2 Mean net flow intensities 2010-2015 for gasoline cars lighter than 1300 kg, by vehicle age and curb weight.

By compounding the transition rates through the years, one can derive 'survival' curves. However, since our net flow intensity is a sum of positive and negative gross flows due to scrapping, de- or reregistration, or second hand import or export, 'survival' is to be understood as 'survival with Norwegian license plates'. In some cases, when a cohort is augmented through second hand import, 'survival' from one year to the next may exceed 100 per cent. We shall hence refer to the changes in cohort size as *cumulative transition rates* rather than survival rates.

If we denote

$$(7) \quad \xi^{m}_{i,j} = 1 + \alpha^{m\cdot}_{i,j},$$

the cumulative transition rates are given by

$$(8) \quad \pi^{m}_{i,k} = \prod_{j=1}^{k} \xi^{m}_{i,j} = \prod_{j=1}^{k} \left[1 + \alpha^{m\cdot}_{i,j}\right] \qquad (i = 1, 2, \ldots, I^{m};\ k = 1, 2, \ldots, 31).$$

In Figs. E.3 and E.4, we have plotted the cumulative transition rates of heavy duty trucks and semi-trailer tractor units, by type of fuel and weight.

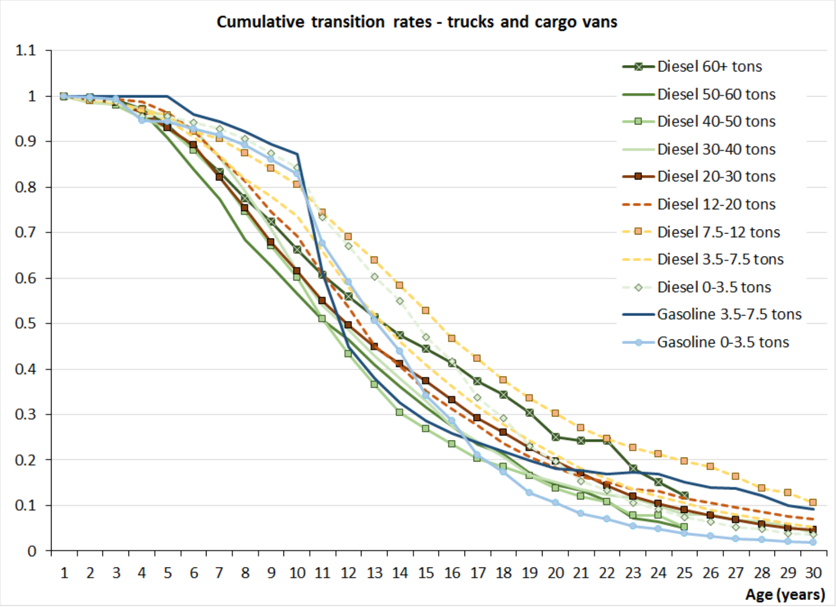

Fig. E.3 Cumulative transition rates for cargo vans and trucks, by fuel type and maximally allowed road train weight (metric tons).

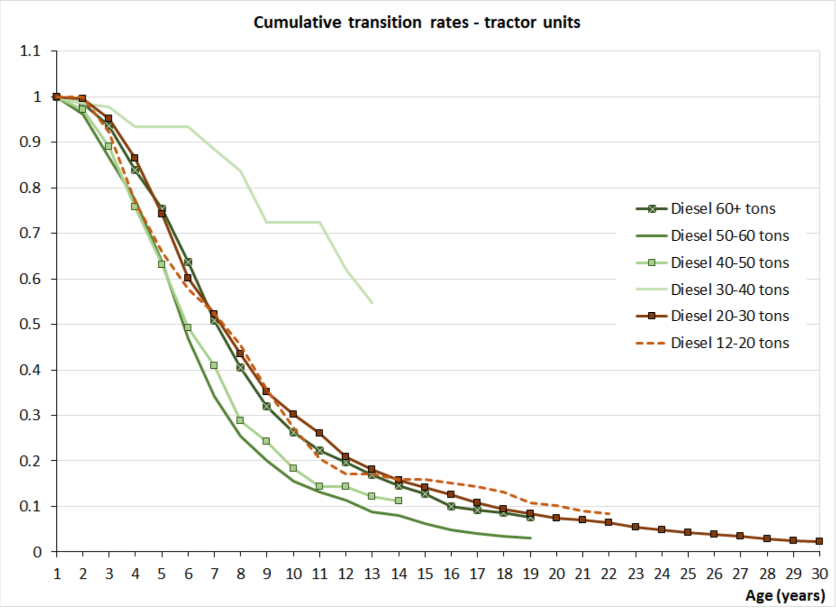

Fig. E.4 Cumulative transition rates for diesel driven heavy duty tractor units, by maximally allowed road train weight (metric tons).

Roughly half of the largest trucks are still carrying Norwegian license plates after 10 years (Fig. E.3). The tractor units, however, appear to last only 5 to 7 years in Norway before half of them are sold abroad or scrapped (Fig E.4).

The domestic 'life expectancy' of a vehicle in segment *i* of category *m* is, in principle, calculable as

$$(9)\qquad \Psi_i^m = \pi_{i,1}^m + \sum_{k=2}^{30} k\left[\pi_{i,k}^m - \pi_{i,k-1}^m\right] + k^*\left[\pi_{i,31}^m - \pi_{i,30}^m\right] \qquad (i = 1, 2, \ldots, I^m),$$

where the mean age of vintage vehicles has been set at $k^* = 40$ years. An example is shown in Fig. E.5.

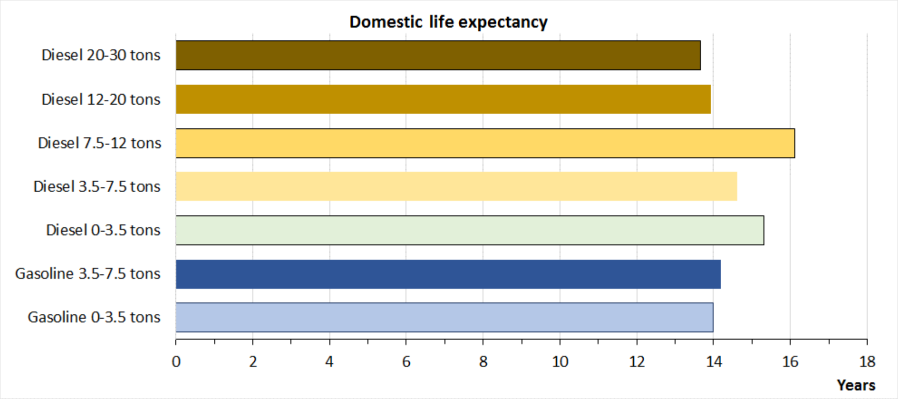

Fig. E.5 Calculated domestic life expectancy of freight vehicles within selected segments.

Let $f_{i,j}^{m,n}$ denote the aggregate fuel consumption in segment *i* and age bracket *j* of vehicle category *m* in year *n*, let $\varphi_{i,j}^{m,n}$ signify the average on-the-road fuel consumption per kilometer, and let $g_{i,j}^{m,n}$ represent the corresponding per vehicle annual mileage. We assume

$$(10)\ \ \varphi_{i,j}^{m,n} = \varphi_{i,j-1}^{m,n-1}\ ,\ g_{i,j}^{m,n} = g_{i,j}^{m,n-1}$$

i. e. the per kilometer fuel consumption $\varphi_{i,j}^{m,n}$ is cohort dependent, but unaltered as the vehicle ages. The annual vehicle miles traveled $g_{i,j}^{m,n}$ are, on the other hand, constant across cohorts, but decrease markedly with vehicle age (Fig. E.6).

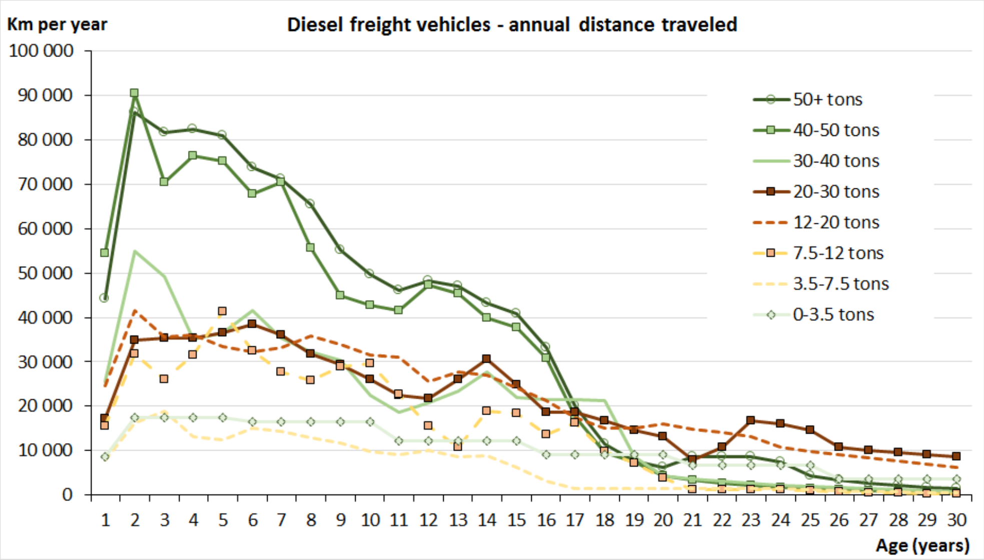

Fig. E.6 Annual vehicle kilometers traveled by diesel driven freight vehicles, by maximally allowed road train weight (metric tons). Source: Heavy duty freight vehicle survey

Now, the aggregate fuel consumption within vehicle category *m* in year *n* is calculable as

$$(11)\quad F^{m,n} = \sum_{i=1}^{I^m}\sum_{j=1}^{31} f_{i,j}^{m,n} = \sum_{i=1}^{I^m}\sum_{j=1}^{31} \varphi_{i,j}^{m,n} g_{i,j}^{m,n} \left[A_{i,j-1}^{m,n-1} + A_{i,j}^{m,n}\right]/2,$$

where we have defined $A_{i,0}^{m,n} \equiv 0 \quad \forall i,m,n$ and estimated the mean size of a vehicle cohort throughout the year as the average between the stocks of January 1 and December 31. On average, new vehicles travel only half a normal distance during their year of first registration (Fig. E.6).

Let γ_i^m denote the number of kilograms of CO_2 emitted through the combustion of one liter of fuel type *i* for vehicles of category *m*. Then the aggregate CO_2 emission from these vehicles in year *n* is given by

$$(12)\quad C^{m,n} = \sum_{i=1}^{I^m}\gamma_i^m \sum_{j=1}^{31} f_{i,j}^{m,n} = \sum_{i=1}^{I^m}\gamma_i^m \sum_{j=1}^{31} \varphi_{i,j}^{m,n} g_{i,j}^{m,n} \left[A_{i,j-1}^{n-1} + A_{i,j}^{n}\right]/2.$$

In our calculations, we have set $\gamma_i^m = 2.32$ $kgCO_2$/liter for gasoline ICE and hybrid vehicles, $\gamma_i^m = 2.68$ $kgCO_2$/liter for diesel ICE and hybrid vehicles, and $\gamma_i^m = 0$ for BEVs and FCEVs. This last assumptions can be justified by the fact that all power plants in the European Union (EU) and Norway are covered by the European cap-and-trade system (EU ETS). Hence, the marginal emission caused by the operation of an electric vehicle is, in principle, zero. We assume hydrogen to be produced through electrolysis.

An ultra-low emission policy scenario

Using the above accounting framework, we have worked out two long-term scenario projections – a *trend* path and an *ultra-low emission policy (ULEP)* path.

The trend path for new vehicles is essentially an extrapolation of the trend observed between 2010 and 2015, as defined in terms the log-odds corresponding to the market shares of the eleven different energy technologies. Log-odds are calculated separately for each vehicle category and weight class. Also, transition rates for vehicles older than one year are extrapolated from rates observed during 2010- 2015.

In the ULEP scenario, however, new vehicle acquisition is modified in such a way as to almost achieve the targets laid down by the transportation agencies, bearing on zero and low emission vehicle market shares in 2025 and 2030.

The assumed market development of new passenger cars in the ULEP scenario is shown in Fig. E.7. The corresponding, more sluggish development in the car passenger stock is shown in Fig. E.8.

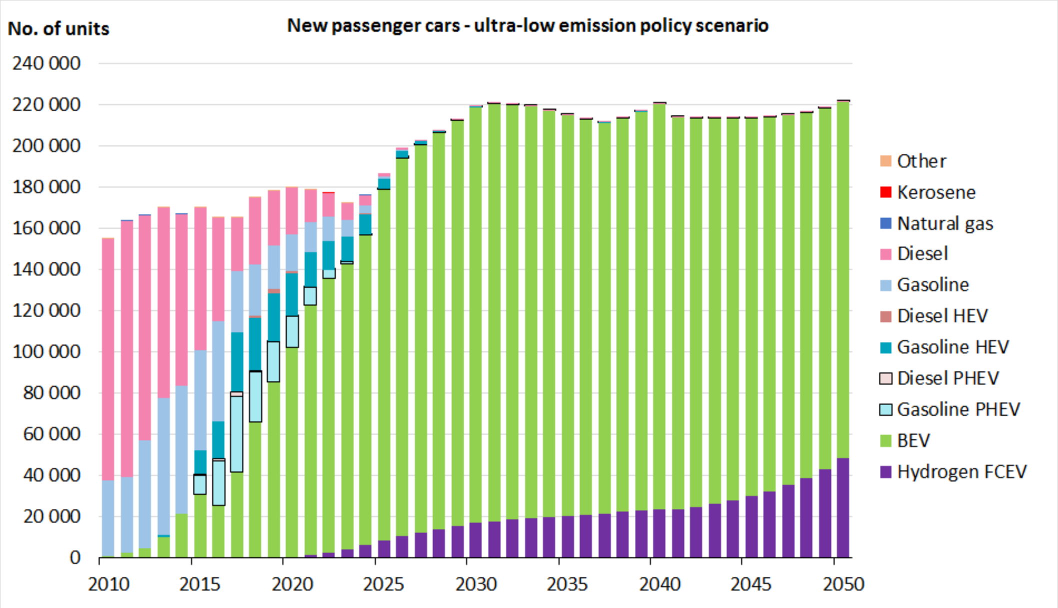

Fig. E.7 Annual flow of new passenger cars under ultra-low emission policy scenario, by propulsion technology.

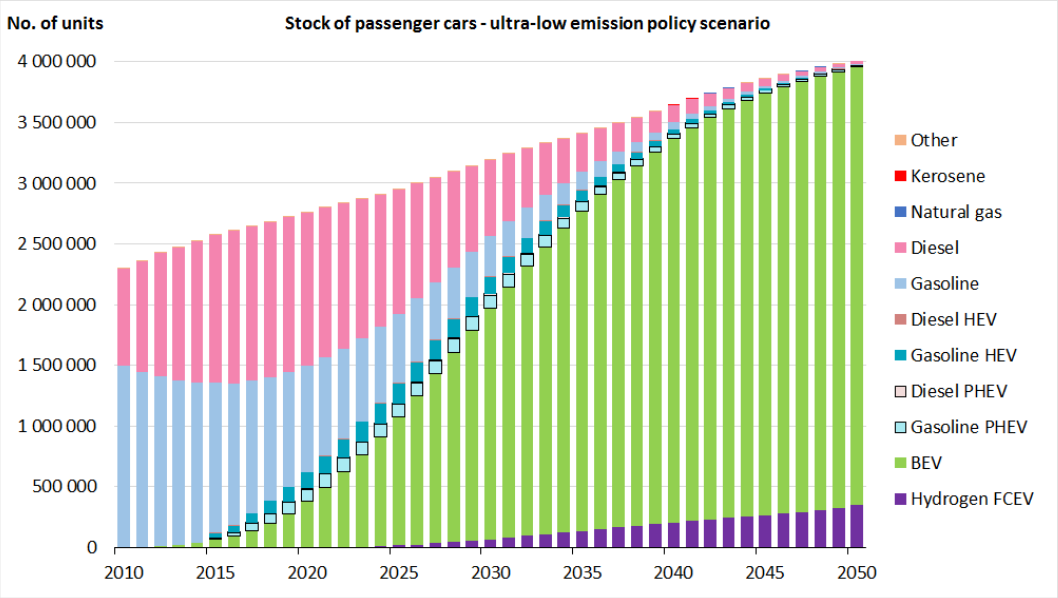

Fig. E.8 Stock of passenger cars at year-end under ultra-low emission policy scenario, by propulsion technology.

In Figs. E.9 and E.10, we show corresponding graphs for the projected light and heavy duty freight vehicle stocks, respectively, under the ULEP scenario. Light duty freight vehicles, also referred to as cargo vans, have – by definition – a maximal weight of 3.5 (metric) tons, including cargo.

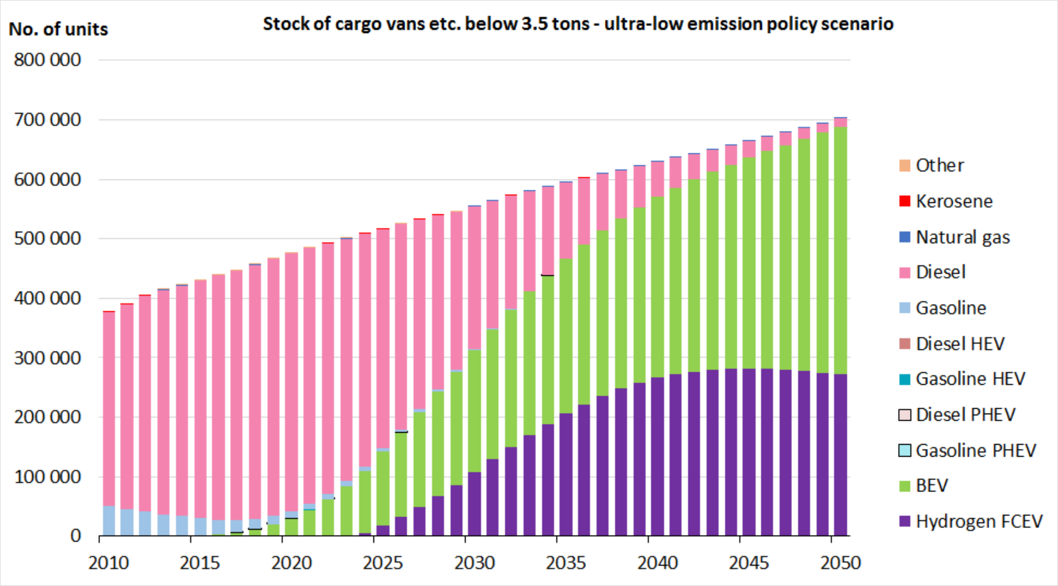

Fig. E.9 Stock of light duty freight vehicles at year-end under ultra-low emission policy scenario, by propulsion technology.

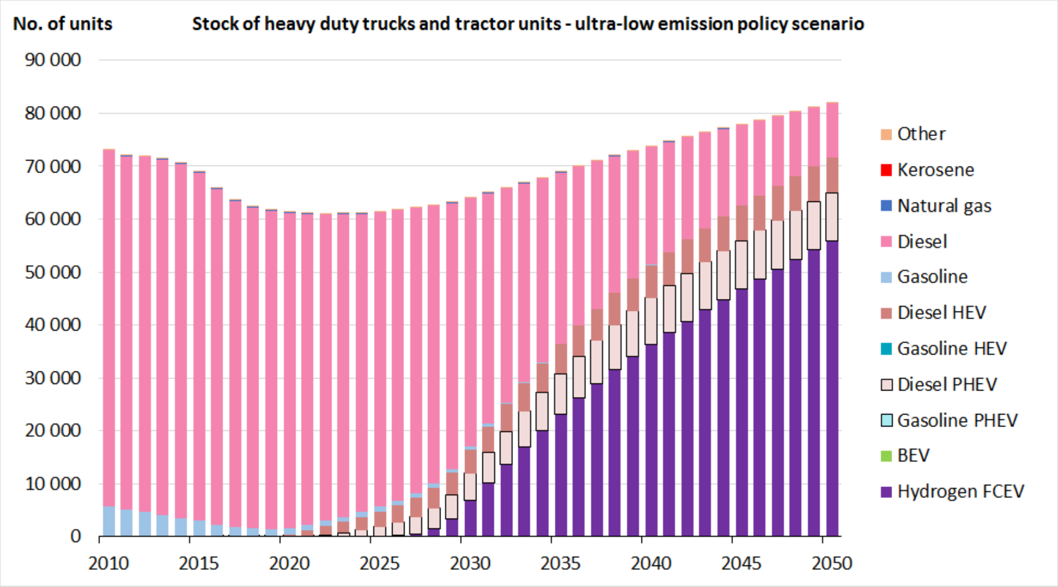

Fig. E.10 Stock of heavy duty freight vehicles (trucks and tractor units) at year-end under ultra-low emission policy scenario, by propulsion technology.

The developments in the fleets of passenger cars, cargo vans, trucks, tractor units, buses and coaches, campervans and motorhomes combine to produce the overall amounts of CO_2 emissions shown in Figs. E.11 or E.12. The former depicts the trend path, to be compared to the latter, which shows the ULEP path.

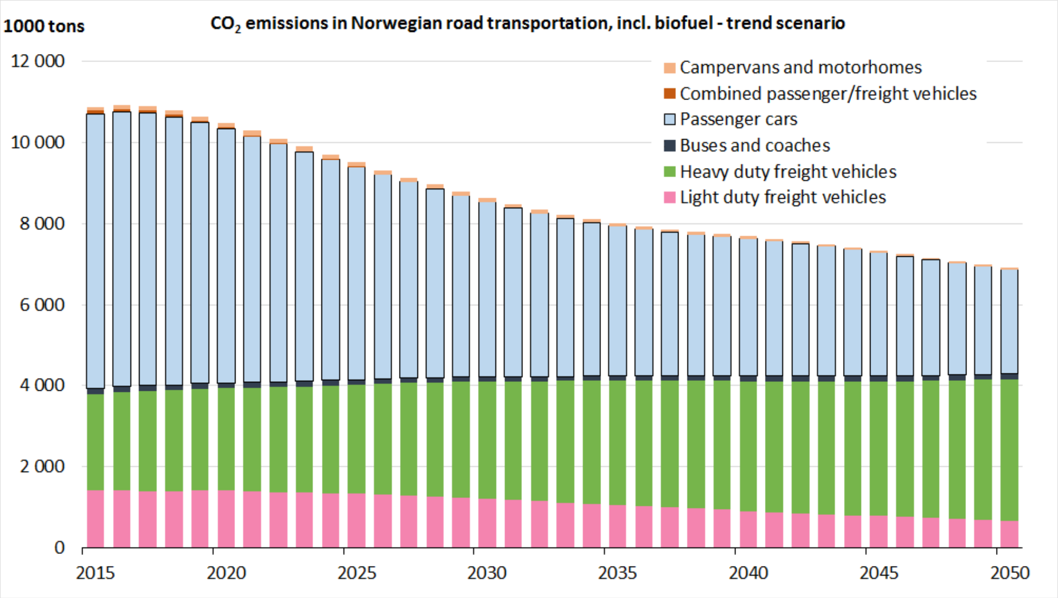

Fig. E.11 Projected metric tons of CO$_2$ emissions from road transportation under trend path, by vehicle category. Biofuel combustion is included.

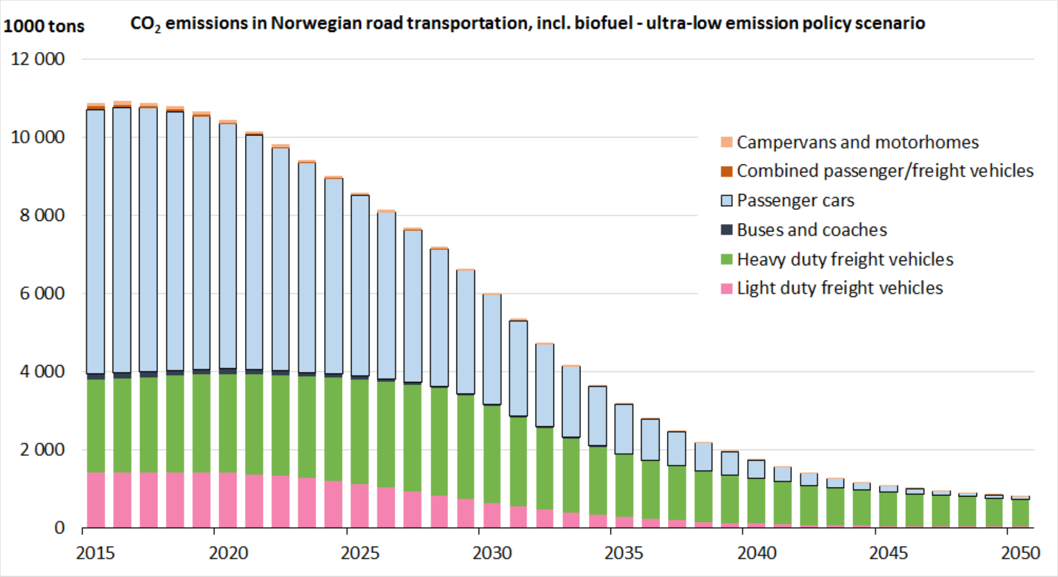

Fig. E.12 Projected metric tons of CO$_2$ emissions from road transportation under ultra-low emission policy path, by vehicle category. Biofuel combustion is included.

According to the ULEP projection, CO$_2$ emissions from road transportation in 2030 is down by 45 per cent from the 2015 level. In the trend scenario, emissions are cut by 21 per cent.

The graphs E.11 and E.12 include emissions from biofuel combustion. It turns out that if the biofuel share of diesel consumed increases from 6.5 per cent in 2015 to 42 per cent in 2030, this would be sufficient, under the trend scenario, to bring road GHG emissions in 2030 down by 40 per cent from the 2015 level, provided the biofuel used is 100 per cent climate neutral (Fig. E.13). For GHG emissions to come down by 55 per cent, a close to 70 per cent biodiesel share would be required.

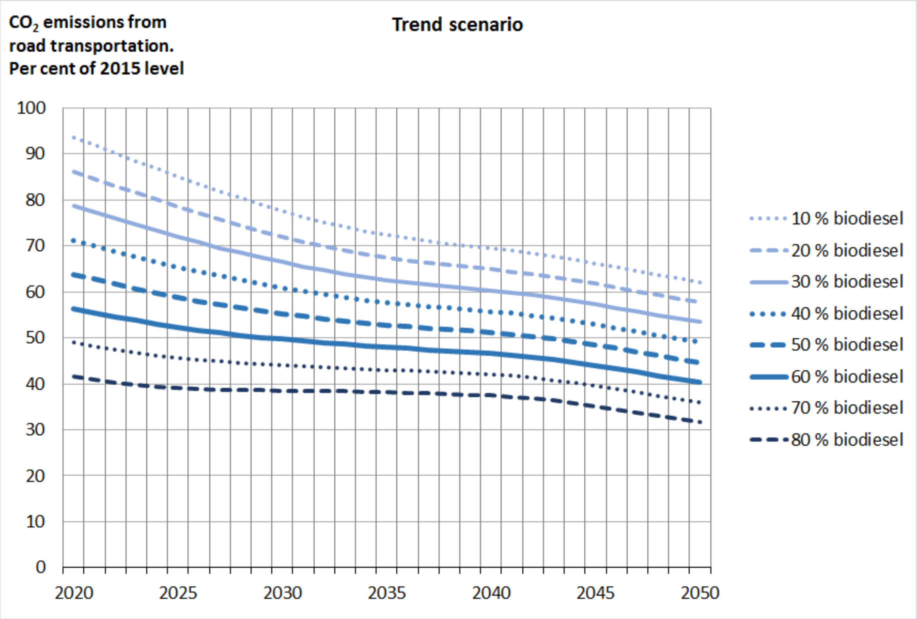

Fig. E.13 Calculated CO_2 emissions from fossil fuel combustion in road transportation, by biofuel share of diesel sold. Trend scenario for Norway 2020-2050.

Under the ULEP scenario, a 30 per cent biodiesel share in 2030 would be sufficient to reach the target of a 55 per cent cut in GHG emissions since 2015 (Fig. E.14).

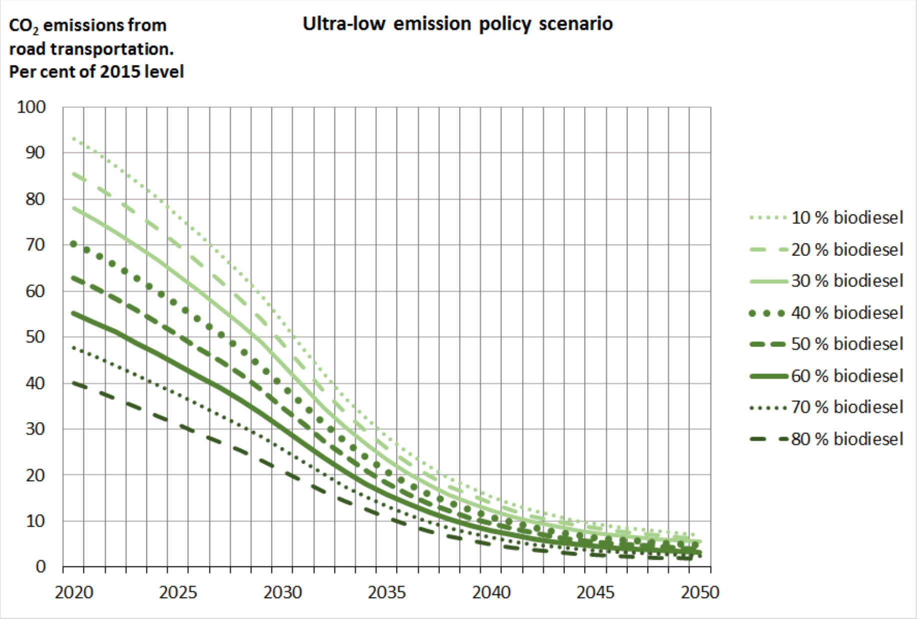

Fig. E.14 Calculated CO_2 emissions from fossil fuel combustion in road transportation, by biofuel share of diesel sold. Ultra-low emission policy scenario for Norway 2020-2050.

Finally, in Fig. E.15 we show the development of the energy mix in road transportation in the ULEP scenario. The share of zero emission technologies – hydrogen and electricity – is projected to grow from 0.35 per cent in 2015 to 26 per cent in 2030 and 89 per cent in 2050.

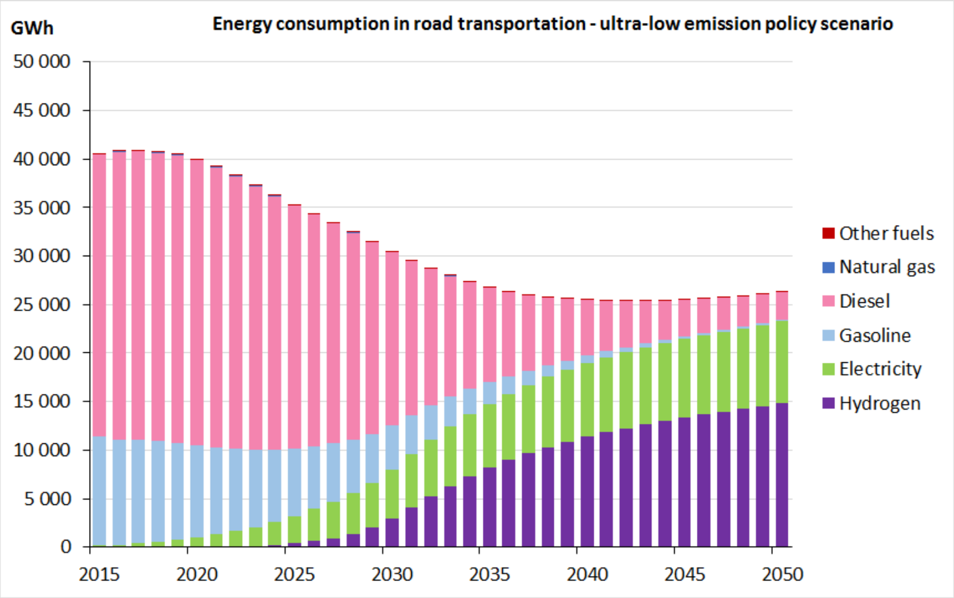

Fig. E.15 Projected energy consumption in road transportation under ultra-low emission policy path, by energy carrier. Biofuel combustion is included. Campervans, motorhomes and combined passenger/freight vehicles are left out.

Time lag between innovation and penetration

The stock-flow cohort model may provide insights into the speed with which technological innovation spreads through the mass of assets affected. An example is shown in Fig. E.16.

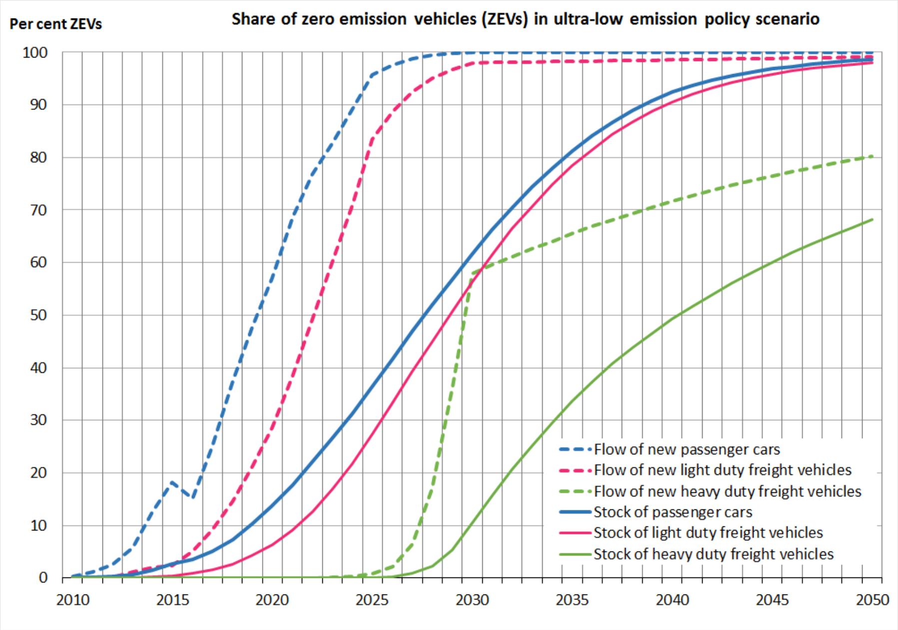

Fig. E.16 Share of zero emission vehicles in flows and stocks of vehicles under ultra-low emission policy path, by vehicle category.

The lag between innovation, as measured by the share of zero emission vehicles (ZEVs) in the flow of new passenger cars, and the penetration of ZEVs into the vehicle stock is seen to vary from 5 years at the 10 per cent level to 15 years at the 90 per cent level. For light duty freight vehicles (cargo vans etc.) the corresponding lags can be read off as 4 and 13 years, respectively. At the 50 per cent level, the lag is 8 years for both of these vehicle categories. The time lag would typically depend on the regularity and speed of innovation, i. e. on how steeply and steadily the new technology expands into the market for new vehicles.

Conclusion

Stock-flow cohort modeling of the vehicle fleet is a useful tool for GHG mitigation planning in road transportation. The stock-flow model ensures consistency between the *stock* in any given year and the annual *flows* of scrapping, new vehicle acquisition, and second hand vehicle import and export. It can be constructed from a few years' detailed data on the vehicle stocks and their annual mileage.

As evidenced by the BIG stock-flow model, there is considerable inertia in vehicle fleet developments. It may take 5 to 15 years before innovations affecting the flow of new vehicles have penetrated similarly into the stock. The time lag would depend on the velocity of vehicle fleet turnover and on the speed and steadiness of the technological diffusion process.

The ambitious targets for new vehicle purchases in 2025 and 2030, laid down by Norwegian transportation agencies, would – if met – pave the ground for massive GHG emission cuts in the decades to come. Under highly optimistic assumptions regarding market uptake of zero and low emission vehicles, CO_2 emissions from the Norwegian motor vehicle fleet could be halved between 2015 and 2031.

This is not to say that large cuts in emissions will come easy. There is a risk that downward-bending emission curves be misinterpreted as prophecies, in which case they might give rise to complacency rather than to effective policy intervention.

What the stock-flow model shows is that *if* some rather brave assumptions concerning vehicle purchasing behavior in 2025-2030 are fulfilled, *then* large scale cuts would follow in the long run. But our modeling exercise has little to say about the plausibility of these same assumptions. It remains an open question if there are policy instruments strong enough to induce vehicle customers to behave as presumed in the ultra-low emission policy scenario.

Under somewhat less radical assumptions, based on trend extrapolation, the BIG model projections suggest an about 20 per cent reduction in GHG emissions from Norwegian road transportation between 2015 and 2030. Under no circumstances could the Norwegian vehicle fleet become climate neutral already by 2030.