**A supplementary documentation to the Swiss TIMES Energy System Model (STEM)**

# Updates on transportation module and development of STEM elastic variant


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# 1. Introduction

Original documentation of the Swiss TIMES Energy system Model (STEM) [13] serves as the starting point for this supplementary document. A number of input data in STEM have been updated and some additional structural changes are implemented to generate new insights. Representation of the transportation sector has been reviewed and the model is recalibrated to the year 2015 energy data. Key updates include energy consumption [2], fuel efficiency [1], vehicle stocks [4], future mobility demand developments [9], etc. The number of intra-annual timeslices in STEM is increased from 144 to 288, representing four seasons and three types of days at the hourly level[1]. In addition, vehicle technology in personal transportation (e.g. cars, two wheelers, buses, etc.) are updated based on new technology assessments [6][7]. The representation of electric vehicles is extensively enhancement as the storage algorithm in TIMES is well understood. In the current version of STEM, an option for vehicle to grid is enabled. In the personal transportation mode, a new consumer segment for personal transport is introduced based on the 2015 Swiss travel survey data [3]. For the other modes (buses, two wheelers, etc.), vehicle segmentations are introduced based vehicle size, i.e. engine power. This document aimed to highlight the changes in model structure, input data and assumptions and supplements the original STEM documentation [13].

In STEM, demands for mobility services are fixed (i.e. inelastic); and therefore the exogenously defined demands must be supplied at any cost. Within in the scope of the Joint Activity on SCCER CREST-Mobility, we extended the scope of STEM and implemented TIMES elastic variant [14] for the private mobility demands. With the elastic variant, the mobility demand becomes elastic. For a given policy, the demand can asymmetrically change (increase or decrease) depending on price elasticity. The development of the elastic variant is described in section 4.

## 1.1. Fuel demand and modes of transportations

This Swiss transport sector accounts for one-third of final energy demand. Three-fourth of the transport fuel is used for personal transportation (Figure 1). The private car fleet alone consumes one half of the fuel used in the personal transportation (Figure 2). STEM covers two broad transportation service demand, *viz.* personal and freight transports, which are exogenously defined in vehicle kilometre (*vkm*) and tonne kilometre (*t-km*) respectively. The model includes ten modes of transport as elucidated in Figure 2. The model is calibrated for year 2015 in terms of final energy use[2], vehicle fuel efficiency, vehicle stocks, annual driven vehicle kilometres, etc. Aviation (national and international) and other transport fuels (military application) are not explicitly modelled, but they are included to balance the Swiss final energy balance. To meet the transport demands, a wide range of existing and future vehicle technologies (e.g. cars, buses, and trucks) and fuel supply options are depicted in STEM. A high level of detail is included for personal transportation with a wide range of alternative drivetrains and fuels (see Table 3). Figure 3 shows an overarching reference energy system (RES) of the transport module and its link to other modules in STEM.

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[1] Weekday, Saturdays and Sundays in Summer, Fall, Winter and Spring.

[2] It should be noted that the transport fuel consumption in the Swiss energy statistics includes tank tourism [1], i.e. cross-border tanking to benefit from fuel price/tax differences. The tank tourism is excluded for the estimation of ESDs based on [1]. However, to balance the national energy statistics, the estimated net tank tourism fuel is included as an exogenous demand, which is linearly phased out (i.e. excluded) after 2020.

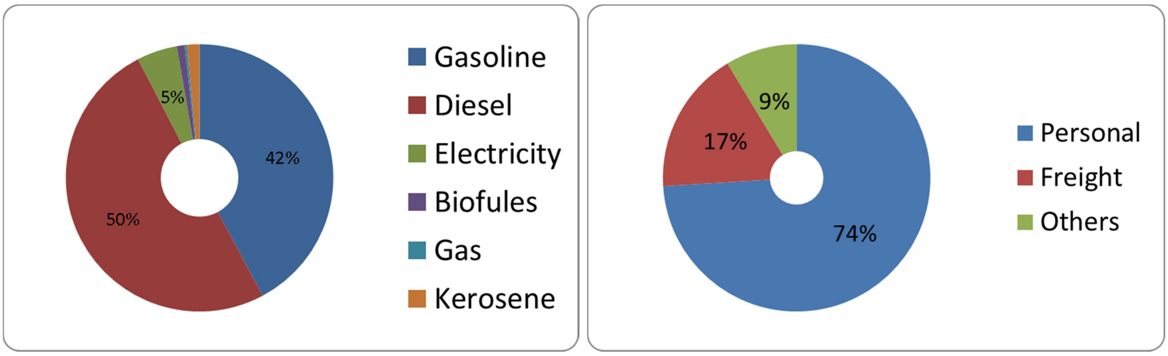


Figure 1: Transport sector energy consumption by fuels and fleets in 2015

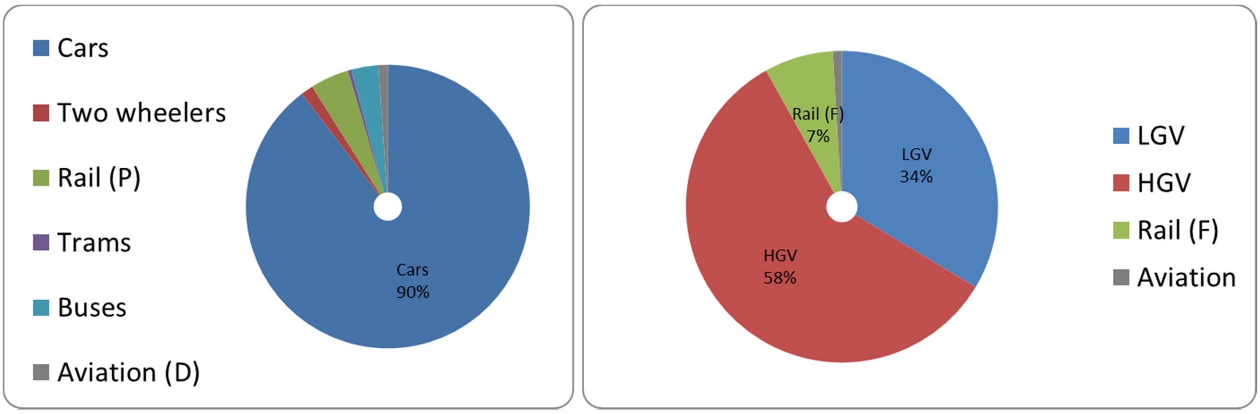
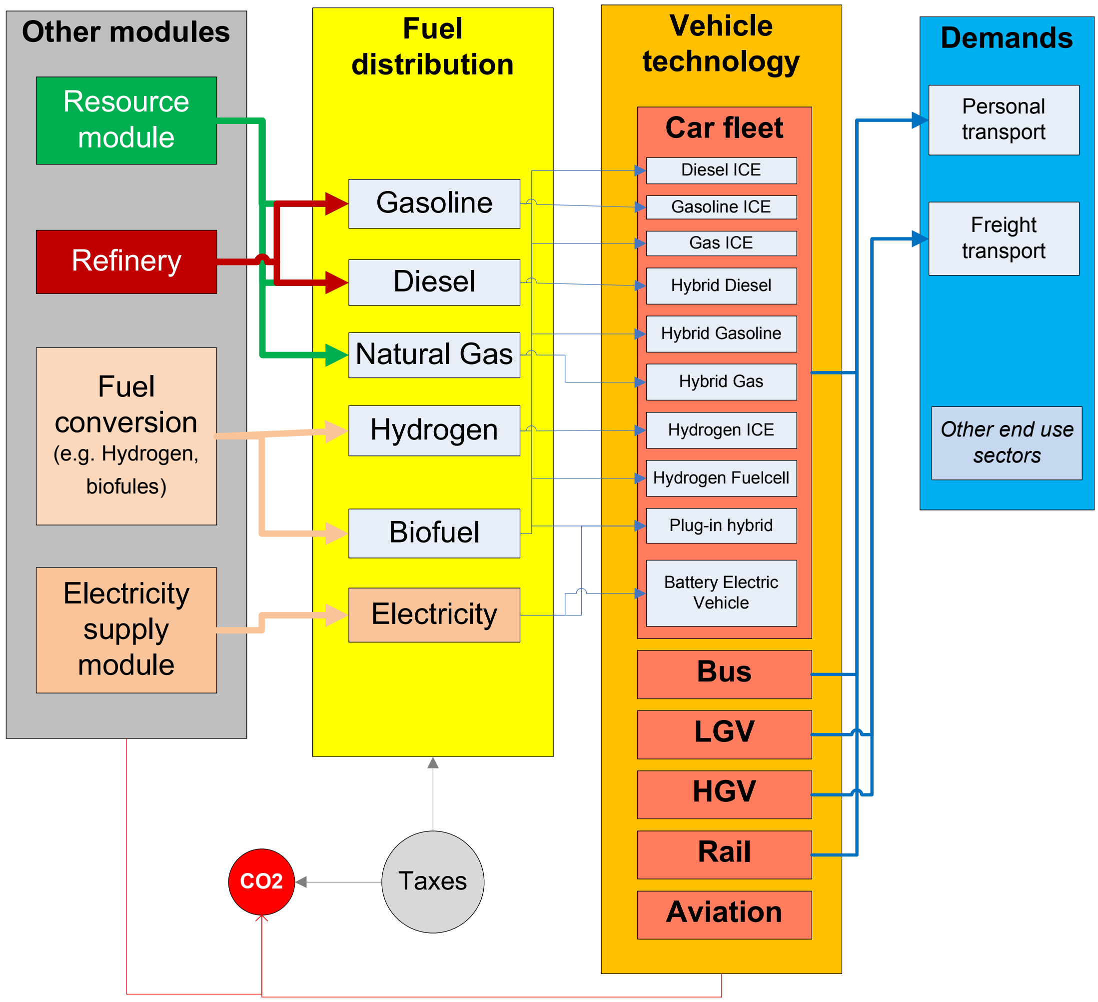


Figure 2: Share of energy use in personal and freight transportation in 2015

Table 1: Transport sector energy use by mode and fuel type in 2015

| Modes/fuel type | Diesel | Gasoline | Kerosene | Gas | Bio-fuels | Electricity | Total |
|---|---|---|---|---|---|---|---|
| Aviation (D) | | | 3.5 | | | | 3.5 |
| Cars | 62.5 | 93.1 | | 0.1 | 1.4 | 0.1 | 157.1 |
| Two wheelers | 0.0 | 2.5 | | | | 0.1 | 2.5 |
| Rail (Personal) | 0.0 | | | | | 7.7 | 7.7 |
| Trams/Trolley buses | | | | | | 0.7 | 0.7 |
| Buses | 5.1 | 0.0 | | 0.1 | 0.1 | 0.1 | 5.4 |
| Light goods vehicles | 11.9 | 1.8 | | 0.1 | 0.2 | 0.1 | 13.9 |
| Heavy good vehicles | 23.6 | 0.0 | | 0.1 | 0.3 | 0.0 | 24.0 |
| Rail (Freight) | 0.4 | | | | | 2.5 | 2.9 |
| Shipping | 1.6 | | | | | | 1.6 |
| Others | 12.8 | 1.7 | 0.0 | 0.4 | 0.3 | -0.2 | 15.1 |
| **Total** | **117.9** | **99.0** | **3.5** | **0.7** | **2.2** | **11.4** | **234.4** |

Source: BFE [1]




LGV—Light good vehicle, HGV—heavy goods vehicle

Figure 3: Simplified RES of the transport module

## 1.2. **Methodology**

In STEM, transportation demands are exogenously defined in vkm or tkm. For a given demand, the model finds the least cost mobility supply in terms of vehicles type and fuel demand by accounting for energy supply side and environmental constraints, i.e. STEM is a cost optimization model. As the energy system model, it account for full supply chain of energy and emission steams in Switzerland. We included vehicle stocks from 2010 to 2016 and their retirement trajectory based on historical survival curves. The gap arises from the withdrawal (retirement) of vehicles stock is replaced by new vehicles. A range of new/emerging vehicle technologies of different drivetrain and fuels are included in the model (e.g. see Table 9). The investment decision of new vehicles is based on capital cost of new vehicles, its operational cost, and fuel cost. The latter is endogenously determined in the model by considering the fuel production chain, i.e. from primarily energy supply through conversion and distribution to the vehicles. Consequently, the transport module has interlinks to other demand and supply sectors in STEM (see Figure 3). Direct $CO_2$ emissions from the vehicles (on road) are tracked at vehicle level based on fuel consumption and carbon content of fuels. Emission associated with fuel production and conversion are traced back from other modules so that energy system wide $CO_2$ emissions are fully accounted. Energy and environmental policy measures/targets (e.g. vehicle $CO_2$ emission standards or mitigation targets) are implemented via constraints, which must be fulfilled in the optimisation. The model outputs relevant to the transport sector include, but not limited to, vehicles stock turnover, their fuel consumption, $CO_2$ emission, investment and operational cost, etc. As an energy system model, STEM also generates insights on electricity supply and emissions from other endues and energy conversion sectors.

In the standard version of STEM, all demands are inelastic, i.e., demands must be met by fulfilling supply side constraint. However, in real world, demands are elastic and response to price (and other behaviour). Therefore elastic demand feature of TIMES framework is enabled in STEM. With the elastic version, the demand can raise or fall in response to price triggered by any policy measures and targets. The methodology of STEM elastic variant is described in section 4.

## 2. **Personal transportations**

In this section, modelling of car fleet is described in details while a similar method is used for the other transportation modes. Thus, for other transportation modes, model structural variation (with respect to the car mode) and input data are explained. For the national and international aviation and other transport demand, fuels (e.g. kerosene, gasoline and diesel) are used as demands, i.e. there is no alternative vehicle options modelled.

### 2.1. **Car transportation**

In Swiss car fleet, annual vkm in 2015 was 56 billion vehicle kilometre (BVkm) which is driven with 4.49 million cars. For the calibration, these existing car stock is modelled in five aggregated vehicle categories by fuel type and drivetrain *viz.* gasoline (ICE and hybrid), diesel (IEE), battery electric car and compressed natural gas (ICE) (see Table 2). The aggregated[3] fuel efficiencies for the existing car fleet is adopted from the Swiss national greenhouse gas inventory and BFE [1]. All the existing vehicle stocks are assumed to be retired linearly over the next 18 years[4] based on survival probability curve (see Figure 4).

At the demand side, the whole car fleet is modelled as a single demand (in vkm), without distinguishing between different usage patterns.[5] This means that STEM does not seek to optimise the choice between a large and small car (since a cost optimisation framework is less suited for this purpose)[6], but rather the choice of vehicle drivetrain or fuel type are optimised. We assumed, within a size category, cars has similar performance characteristics and therefore substitutable in terms of performance. Nevertheless, changes to the size distribution of the car fleet over the model horizon can be specified as scenario variable.

Table 2: Characteristics of existing car fleet in 2015

| | | |
|---|---|---|
| Total vehicle kilometres | (million *vkm*) | 56,62 |

[3] The fuel efficiency is the Swiss national average that could also include efficient hybrid- and inefficient old cars.

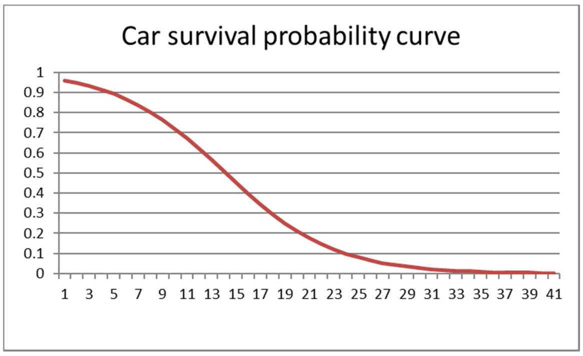
[4] Though some vehicles are used for longer than 18 years, for computation and numerical reason, we cut-off in 18 years.

[5] In Joint Activity on SCCER Mobility-CREST, the private car transportation demands are being segmented by different consumer groups, e.g. by household type and prominent usage patterns (long vs short distance commuting).

[6] In a cost optimization framework, small cars will be attractive due to their lower fuel consumption and lower purchase price. That is, the choice of a larger car is driven by behaviour factors and preferences unrelated to cost.

| | | |
|---|---|---|
| Total number of cars | (million) | 4.49 |
| Assumed (remaining) lifetime | (*years*) | 18* |
| Cars by fuel type | Fuel efficiency (*MJ/km*) | No. of cars (million) |
| Gasoline ICE | 2.77 | 3.17 |
| Gasoline (hybrid) | 2.44* | 0.02 |
| Diesel | 2.80 | 1.21 |
| Natural gas (and others) | 2.58 | 0.003 |
| BEV | 1.53 | 0.007 |

Source: BFS [3][1][4]




Source: BFS [3]

Figure 4: Car survival probability curve

### 2.1.1. Car technologies

In addition to the existing vehicle technologies, a range of new and future vehicle technologies are represented with alternative fuels and drivetrain options. Table 3 shows the characterisation of medium size cars while the details for the other car sizes are included in the Appendix. New vehicle technologies are depicted with two vintages (current and future) reflecting improvements in fuel efficiency and/or cost reductions over future time periods. The technical characterization and capital cost of cars are based on [6][7] and shown in Table 3. An annual driving distance of 9300 – 15000 km per year[7] and operational lifetime of 16 years are assumed for all car technologies. However, the annual driving distance is reduced over the lifetime of the car based on Swiss travel survey data [3], i.e. aged cars are driven lesser compared to new cars.

Table 3: Characteristics of medium (100-140 kW) size car technologies in STEM

| **Vintage year** | **Drivetrain and fuel type*** | **Car size**** | **Battery size or tank size** | **Fuel effi-ciency (tank to wheel)** | **Purchase price** | **Maintenance cost** | **Range per charge/ fuel-ling** |
|---|---|---|---|---|---|---|---|

[7] For the four size, annual driven distance is estimated to be 9360 km, 13180 km, 15170 km, 12710 km.

| | | | (kWh) | (MJ / km) | (CHF) | (CHF/year) | (km) |
|---|---|---|---|---|---|---|---|
| current | BEV | Medium | 48 | 0.76 | 58387 | 998 | 181 |
| current | FCEV | Medium | 167 | 1.37 | 79837 | 1114 | 437 |
| current | HEV-p | Medium | 271 | 1.53 | 45738 | 1003 | 638 |
| current | ICEV-d | Medium | 373 | 2.38 | 46204 | 1003 | 565 |
| current | ICEV-g | Medium | 355 | 2.80 | 46825 | 1003 | 455 |
| current | ICEV-p | Medium | 330 | 2.62 | 40614 | 1003 | 452 |
| current | PHEV | Medium | 280[#] | 1.61 | 50283 | 1035 | 37[#] |
| future | BEV | Medium | 73 | 0.61 | 49878 | 836 | 344 |
| future | FCEV | Medium | 133 | 1.02 | 53025 | 836 | 470 |
| future | HEV-p | Medium | 190 | 1.22 | 43540 | 1003 | 559 |
| future | ICEV-d | Medium | 261 | 1.59 | 45587 | 1003 | 592 |
| future | ICEV-g | Medium | 248 | 1.66 | 41315 | 1003 | 539 |
| future | ICEV-p | Medium | 231 | 1.62 | 40881 | 1003 | 512 |
| future | PHEV | Medium | 210 | 0.94 | 47558 | 1003 | 99 |

** Medium – 100-140 kW
* BEV: Battery Vehicle, FCEV: Hydrogen Fuel Cell, ICE: internal combustion engine, PHEV: Plug-in hybrid electric vehicle, -p: petrol, -d: diesel, -g: gas
Maintenance cost does not include fuel costs
# Wt. efficiency between petrol drive and electric drive. Battery size in PHEV

(Source file: M:\STEM\Input Databases\TransportData\STEM_TRA_VehicleData_v1.xlsx )

Source: Cox, 2019 [10][11]

### 2.1.2. Electric mobility

For the car fleet, two types of electric vehicle—viz. pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—are represented in STEM. For the PHEV, separate electric- and gasoline/diesel-mode efficiencies are implemented. The model has flexibility to choose pure gasoline/diesel, if the electricity cost is prohibitively expensive in a season or period. However, the electric drive is limited to battery size (Table 3). For the both types of electric car (i.e. BEV, PHEV), the time of charging is unconstrained (except on road time in Figure 6), but constraints are included to control the rate of charging based on typical household fuse of 220/440 volt and 16 ampere. In additional, a fast (or super-fast) charging option is included in STEM with additional infrastructure cost. Though cost of charging infrastructure is not fully implemented, need for energy and power for fast charging is fully accounted, i.e. electricity sector module account for the need electricity generation capacity for e-mobility.

Batteries in e-mobility is foreseen as electricity storage technology for energy system with high share of renewable; and therefore we include an option for vehicle to grid (V2G), i.e. electricity from car batteries can be fed into electricity grid [15]. Figure 5 shows the grid to vehicle and V2G flows in the model. In the V2G option, neither the batteries' cyclic lifetime nor potentiation degradation of battery due to erupted operation is accounted. Nevertheless, the model is constrained to draw only one-third of the stored electricity from car batteries and 10% of the annual storage.

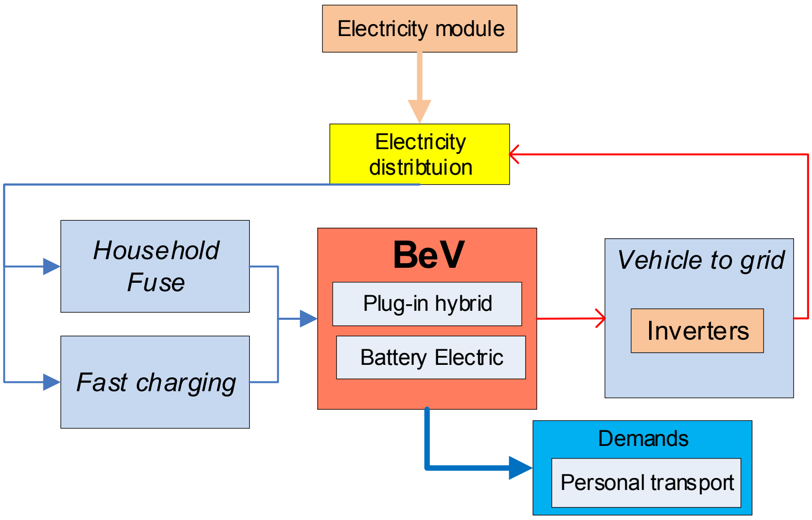



Figure 5: Vehicle to grid in STEM transport module

2.1.3. Transport demand patterns

For the e-mobility, it is important to know the charging timings. For this purpose, we have to define car usage profile, i.e. on road timings. For cars, typical usage patterns are estimated based on Swiss travel survey (micro-census data) from 2015 [3]. Figure 8 shows car usage pattern (i.e. on road time) on weekdays and weekends. We have normalized total annual car demand to follow this pattern and do not differentiate across the four seasons. The inverse curve of the on-road time is used for possible battery charging time for the BEV and PHEV, i.e. charging is possible when the car is not being used.

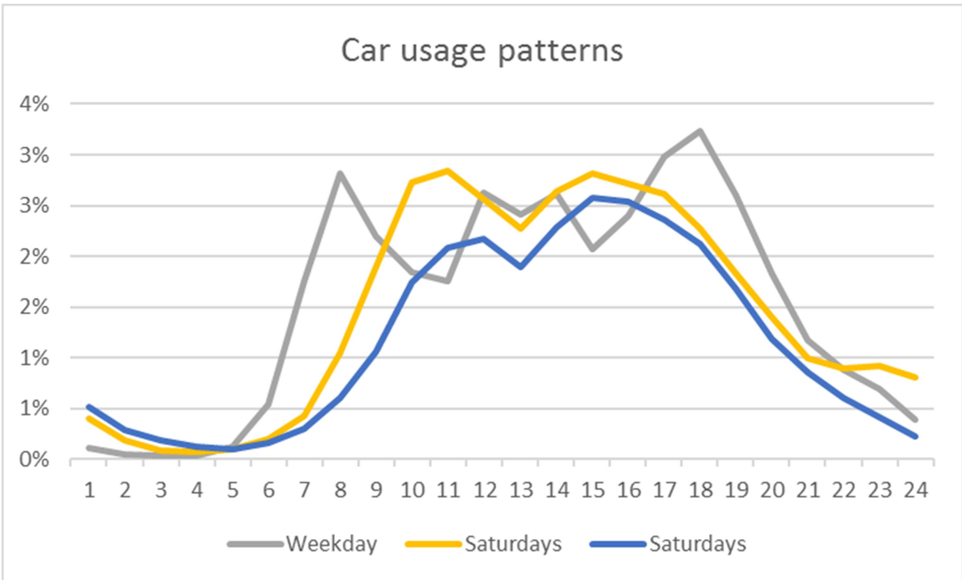



Figure 6: Typical weekly usage pattern of cars

Similar to the car technologies, new and alternative vehicles are represented for other transport demands. Table 4 and Table 5 show vehicle technology characteristics of other transportation modes. Most of these technical and cost data are adopted from PSI's analysis on transport vehicle technology assessment and other data sources [10][11][6][7].

Table 4: Characteristics of two wheelers

| Year | Drivetrain and fuel | Size | Battery size | Fuel effi-ciency | Purchase cost | Maintenance cost | Driving range | Life |
|---|---|---|---|---|---|---|---|---|
| | | | *kWh* | *KJ/km* | *CHF* | *CHF/year* | *km* | *years* |
| 2015 | BEV | <4kW | 2 | 91 | 5376 | 73 | 60 | 10 |
| 2015 | BEV | 4-11kW | 4 | 161 | 9203 | 114 | 80 | 16 |
| 2030 | FCEV | <4kW | | 216 | 5338 | 67 | 100 | 10 |
| 2030 | FCEV | 4-11kW | | 370 | 8037 | 106 | 150 | 16 |
| 2050 | ICEV | <4kW | | 457 | 2536 | 61 | 100 | 10 |
| 2050 | ICEV | 4-11kW | | 795 | 4240 | 96 | 150 | 16 |

Source: Cox, 2016 [6]

## 2.2. Buses

For the bus fleet, number of buses in the public transport (5410 in 2015) and private buses (2896 in 2015) are included in the model. However, total number of buses (8303 in 2015) is not comparable with BFS's personal transportation vehicles[8]. Nevertheless, we stuck to these data for consistency. Based on the total vehicle kilometre, annual millage was calculated to be about 50,000 km and 45,000 km for public and private buses, respectively. For the estimation of buses by fuel type, BFS data for articulated buses (i.e. Glenkbus) and coach buses (i.e. Gesellschaftswagen) are adopted, respectively. Figure 7 shows the estimated bus type in year 2015. To account for the peak hours, the public transport usage pattern is implemented as in Figure 8. In addition to the existing bus fleet, a range of new and future buses are included. Their techno-economic performances are shown in Table 5.

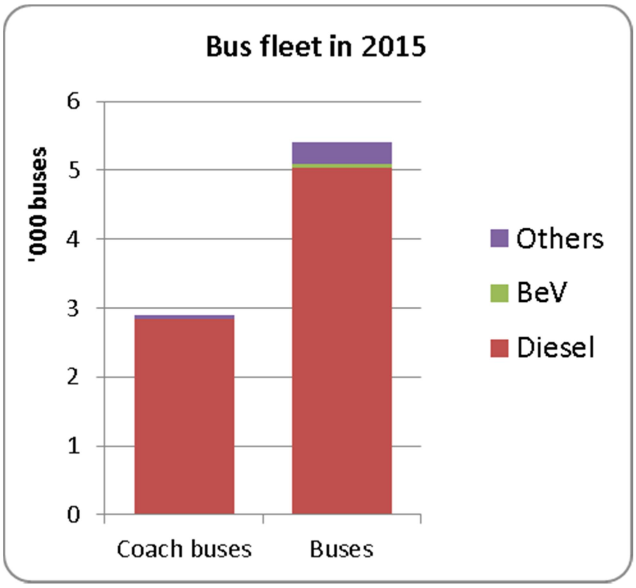
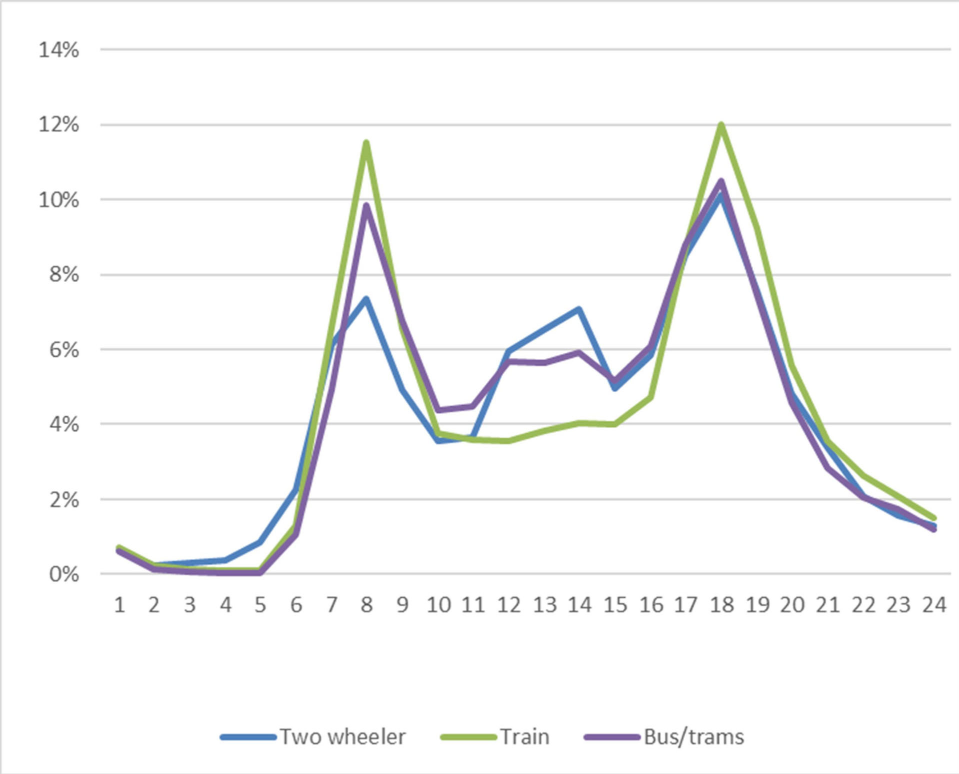



Figure 7: Vehicle type in bus fleet in 2015

[8] BFS personal transport vehicle statistics has about 62436 vehicles in 2015 in five categories, viz., Leichter Motorwagen, Schwerer Motorwagen, Gesellschaftswagen, Kleinbus and Gelenkbus.

Table 5: Characteristics of mid-size (140 kW) buses

| Year | Drivetrain and fuel | Battery size | Fuel efficiency (tank to wheel) | Purchase cost | Maintenance cost | Driving range | Life |
|---|---|---|---|---|---|---|---|
| | | *kWh* | *KJ/km* | *CHF* | *CHF/year* | *km* | *years* |
| 2015 | BEV-LR | 252 | 3634 | 437594 | 81888 | 200 | 10 |
| 2015 | BEV-SR | 57 | 3414 | 307688 | 36517 | 12 | 10 |
| 2015 | FCEV | | 7298 | 518654 | 86671 | 500 | 10 |
| 2015 | HEV-D | | 8882 | 211664 | 49306 | 500 | 10 |
| 2015 | ICEV-CNG | | 12188 | 155462 | 32592 | 500 | 10 |
| 2015 | ICEV-D | | 11433 | 145030 | 32592 | 500 | 10 |
| 2030 | BEV-LR | 214 | 3083 | 181533 | 21634 | 200 | 10 |
| 2030 | BEV-SR | 49 | 2952 | 146259 | 21634 | 12 | 10 |
| 2030 | FCEV | | 5914 | 208701 | 21634 | 500 | 10 |
| 2030 | HEV-D | | 7569 | 179288 | 31507 | 500 | 10 |
| 2030 | ICEV-CNG | | 10331 | 153286 | 32964 | 500 | 10 |
| 2030 | ICEV-D | | 9718 | 145564 | 32964 | 500 | 10 |
| 2050 | BEV-LR | 177 | 2548 | 154919 | 21469 | 200 | 10 |
| 2050 | BEV-SR | 41 | 2481 | 139144 | 21469 | 12 | 10 |
| 2050 | FCEV | | 4570 | 173149 | 21469 | 500 | 10 |
| 2050 | HEV-D | | 6203 | 177687 | 31953 | 500 | 10 |
| 2050 | ICEV-CNG | | 8546 | 151666 | 33499 | 500 | 10 |
| 2050 | ICEV-D | | 8066 | 146331 | 33499 | 500 | 10 |




(Source file: BFS_VehicleData_2017_V1.xlsx).

Source: BFS, 2005 [3]

Figure 8: Typical mobility usage pattern of public transport and two wheeler

In the public transportation mode, tram and trolley buses are modelled separately to account for total personal transportation demands. Since these two fleets are electric driven, no alternative fuel or power train is included. To account for electricity demand for these mode of transportation, mobility usage pattern of train is applied (Figure 8).

## 2.3. Rails

Rail transportation for passenger and freight are included in STEM. For calibration, based on total rail kilometre [8], no of trains [8], total electricity/diesel used in railways [1], average annual vkm per train and fuel efficiency are estimated. For the break up between diesel and electric train, fuel efficiency of diesel driven is fixed (by assuming xx% high fuel use per km) and thereby diesel driven vkm is also fixed based on diesel use. The remaining vkm is assumed to be met with electric trains.

Table 6: Status-quo of rail transport for passenger and freights in 2015

# 3. Freight transportations

The freight transport comprises of road and rail freights. For the former, a range of vehicle options are included in STEM, while the latter is not fully modelled.

### 3.1. Light and heavy good vehicle

The existing vehicle stock of light duty and heavy good trucks are included in the model. For the future year, three new vehicles option driven on diesel, hydrogen and electricity. We have not fully completed the assessment of trucks. Thus, we adopted technology performance from IEA and adjusted to Swiss condition in terms of fuel efficiency.

Table 7: Technical and economic characteristics of trucks

| Year | Drivetrain and fuel | Fuel efficiency (tank to wheel) | Purchase cost |
|---|---|---|---|
| | Heavy duty trucks | *MJ/km* | *000' CHF* |
| 2020 | TFHGV-ICEDSL | 11 | 145 |
| | TFHGV-ICENGA | 12 | 155 |
| | TFHGV-HYBDSL | 8 | 212 |
| | TFHGV-BEVELC | ?? | ?? |
| | TFHGV-FCLH2O | 7 | 519 |
| 2030 | TFHGV-ICEDSL | 9 | 146 |
| | TFHGV-ICENGA | 10 | 153 |
| | TFHGV-HYBDSL | 7 | 179 |
| | TFHGV-BEVELC | ?? | ?? |
| | TFHGV-FCLH2O | 6 | 209 |
| 2050 | TFHGV-ICEDSL | 8 | 146 |
| | TFHGV-ICENGA | 8 | 152 |
| | TFHGV-HYBDSL | 6 | 178 |
| | TFHGV-BEVELC | ?? | ?? |
| | TFHGV-FCLH2O | 4 | 173 |
| Note: TFHGV – Freight transportation heavy duty trucks; -ICEDSL – Internal combustion engine-diesel fuel; -ICENGA – Internal combustion engine with gas fuels, -HYBDSL – hybrid Diesel engine, BEV-ELC – Battery electric, -FCLH2O – hydrogen fuel cell electric<br><br>Learning rates are based on large size SUV cars and IEA [17] | | | |

Source: IEA [17] and own estimates

For the other transport modes only an annual demand is specified without a detailed demand curve at this stage.

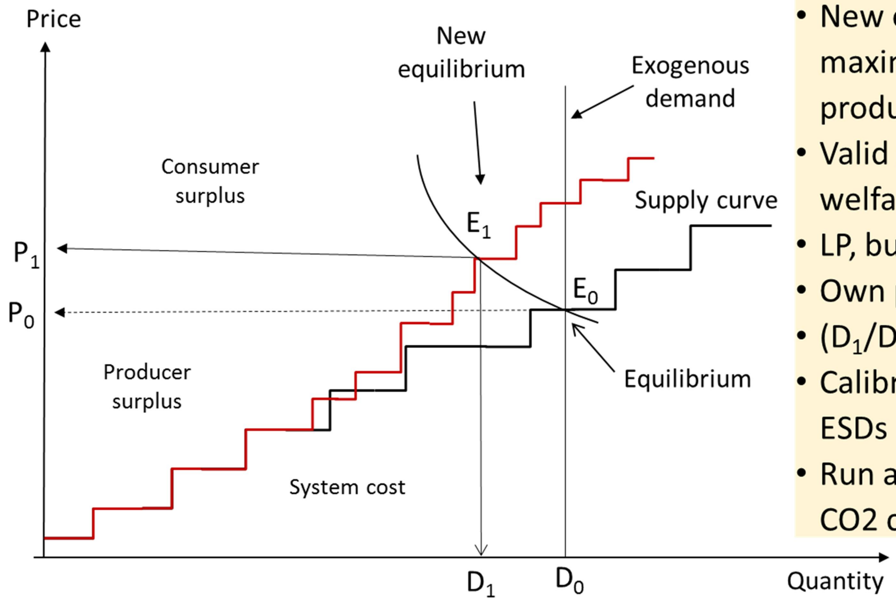
## 4. Elastic demand for transportation

In the earlier version of STEM, energy service demands in the transport (and other) sector are inelastic, i.e. the exogenously defined vkm or tkm must be supplied at any cost. Though the model has many supply side options, such as fuel substitution and alternative vehicle technologies, there is no mechanism to induce demand side changes. Future mobility demand can be influenced by many factors such as behavioural change in response to price or income, societal change due to education, awareness, etc. As a cost optimization model, we focus on price driven behavioural change. Thus, an elastic variant of TIMES framework is implemented. The elastic variant enables demand to be elastic, i.e. demand can raises and fall in response to price change (for a given price elasticities). Since the STEM model is energy service driven, the demand response is not merely related to fuel, but the entire supply chain, including cost of vehicle and infrastructure.

### 4.1. Methodology

In microeconomics, energy supply curve is represented by their inverse production function, that plots the marginal production cost of an energy commodity (vertical axis) as a function of the quantity supplied (horizontal axis). In TIMES, supply curve of a commodity is entirely determined endogenously by the model. The commodity is produced by a certain technology or set of technologies in a strictly linear fashion (Figure 9). As the quantity produced increases, one or more resources in the supply mix (either a technological potential or some resource's availability) is exhausted, and therefore the system must start using a different (more expensive) technology or set of technologies in order to produce additional units of the commodity, albeit at higher unit cost. Thus, each change in production mix generates one step of the staircase production function with a value higher than the preceding step. In a similar analogy, TIMES model defines a series of inverse demand functions. In the case of demands, two cases are distinguished. First, if the commodity in question is an energy carrier whose production and consumption are endogenous to the model, then its demand function is implicitly constructed within TIMES, and is a step-wise constant, decreasing function of the quantity demanded, as illustrated in Figure 9.

In TIMES elastic, demand (for an energy service) is defined by the user via the specification of the own price elasticity. The demand curve is a smoothly decreasing curve as illustrated in Figure 9. The supply-demand equilibrium is at the intersection (point $E_0$) of the supply function and the demand function, and corresponds to an equilibrium quantity $D_0$ and an equilibrium price $P_0$. At price $P_0$, suppliers are willing to supply the quantity $D_0$ and consumers are willing to buy exactly that same quantity $D_0$. Of course, the TIMES equilibrium concerns a large number of commodities simultaneously, and thus the equilibrium is a multi-dimensional analog of the above, where $D_0$ and $P_0$ are now vectors rather than scalars.




- New equilibrium: maximize consumer & producer surplus
- Valid measure of social welfare
- LP, but not linear functions
- Own price elasticities
- $(D_1/D_0) = (P_1/P0)^{-E}$
- Calibrate to base case ESDs
- Run alternate cases (e.g., CO2 constraint

Figure 9: TIMES elastic demand functions

As already mentioned, the demand curves of most TIMES energy commodities are implicitly constructed endogenously as an integral part of the solution of the LP. For each demand, user explicitly defines its own price elasticity, i.e. each energy service demand is assumed to have a constant own price elasticity *E* function of the form (see eq.1).

$$(D_1/D_0) = (P_1/P_0)^E$$

Where, $D_0$ and $P_0$ are reference pair of demand and price of energy service demand and *E* is the price elasticity of that demand. $D_0$ is the demand projection estimated by the user in the reference scenario and $P_0$ is the shadow price of that energy service demand in the dual solution of the reference case scenario, i.e. the parameters, $D_0$, $P_0$ are obtained by solving a reference scenario in STEM. When demands are elastic, TIMES computes a new supply/demand equilibrium, where the new demand adjusts to changes in price. The prevailing demand prices are the marginal costs of the demand categories (i.e. $P_1$ in Figure 9). A priori this seems to be a difficult task, because the demand prices are computed as part of the dual solution to that optimization problem.

The elastic variant of TIMES has a non-linear objective function which is piece-wise linearized, which approximate the integrals. This is the same as saying that the inverse demand curves are approximated by staircase functions, as illustrated in Figure 9. By so doing, the resulting optimization problem becomes linear again. The precise manner in which the demand functions are discretized and incorporated in the TIMES objective function is explained in TIMES documentation [14]. The linearization proceeds as follows.

- For each demand category $D_i$, and each time period *t*, the user selects a range $R(t)_i$, i.e. the distance between some values $D_i(t)_{min}$ and $D_i(t)_{max}$. The user estimates that the demand value $D_i(t)$ will always remain within such a range, even after adjustment for price effects (for instance the range could be equal to the reference demand $D_i(t)$ plus or minus 10%).
- Select a grid that divides each range into a number n of equal width intervals. Let ßi(t) be the resulting common width of the grid, ßi(t)= Ri(t)/n. See Figure 9 for a sketch of the non-linear expression and of its step-wise constant approximation. The number of steps, n, should be chosen so that the step-wise constant approximation remains close to the exact value of the function.
- For each demand segment $D_i(t)$ define n step-variables (one per grid interval).

Besides selecting elasticities (see Table 8) for the various demand categories, one needs to know price at each demand function in each time period. To determine such a price, we perform a reference scenario of the inelastic TIMES model (with exogenous $D_0$, and use the resulting shadow prices[9] $P_0$ for all demand constraints, in all time periods).

It is important to note that, instead of maximizing the net total surplus, TIMES minimizes its cost. For this and other reasons, it is inappropriate to pay too much attention to the meaning of the absolute objective function values. Rather, examining the difference between the objective function values of two scenarios is a far more useful exercise. That difference is of course, the negative of the difference between the net total surpluses of the two scenario runs. With elastic demands, the model shed insights on a cost resulting from the loss of welfare due to the reduction (or increase) of demands in a given policy scenario compared to the base/reference scenario.

[9] The conventional interpretation of shadow prices as the marginal costs of commodity is inaccurate. Rather, the shadow price is, by definition, the marginal system value of a resource, rather than the marginal cost of procuring that commodity.

We have complied mobility related price elasticities from literature and summarised in Table 8.

Table 8: Personal transport elasticise

| | Long-term | Short-term | Comment |
|---|---|---|---|
| **Price** elasticity (gasoline de-mand) | -0.34[10] | | |
| **Price** elasticity in Swiss border regions | -1.5[11] | | Higher elasticity due to tank tourism |
| **Price** elasticity (gasoline de-mand) | -0.34[12] (“weakly sensitive“) | -0.09 | International comparison: In Switzerland, consumers could be less sensitive to price because their income is relatively high and fuel prices relatively low. |
| **Price** elasticity (fuel demand) | -0.27 [12] (“weakly sensitive“) | -0.08 | |
| **Income** elasticity (gasoline de-mand) | 0.67 [12] | | First necessity good (increase in income implies a less than proportional increase in quantity) |
| **Income** elasticity (fuel demand) | 0.76 [12] | | |
| **GDP/capita** | | no sign. impact | consumers need time before reacting to income variations |
| 1% increase of **#gasoline-powered cars per driver** | 0.8% in-crease of gasoline consumption | | smaller than 1 due to increasing technical efficiency: new vehicles are more efficient than older ones |
| 1% increase of **overall vehicle stock per driver** | 0.6% in-crease of fuel con-sumption | | - smaller in comparison to gasoline cars, maybe due to higher efficiency of diesel-powered vehicles<br>- smaller than 1 due to increasing technical efficiency: new vehicles are more efficient than older ones |

Application of STEM for various scenario analysis will be discussed in separate report.

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Annex

Table 9: Private car costs and fuel efficiencies

| Vintage year | Drivetrain and fuel type* | Car size** | Battery size or tank size | Fuel efficiency (tank to wheel) | Purchase cost | Maintenance cost *** | Driving range per charge/fuelling |
|---|---|---|---|---|---|---|---|
| | | | *kWh* | *KJ/km* | *CHF* | *CHF/year* | *km* |
| 2015 | BEV | Large | 54 | 0.83 | 76392 | 1347 | 187 |
| | BEV | Medium | 48 | 0.76 | 58387 | 998 | 181 |
| | BEV | Small | 30 | 0.62 | 31698 | 515 | 139 |
| | BEV | SUV | 48 | 0.93 | 56520 | 964 | 148 |
| | FCEV | Large | 200 | 1.50 | 105696 | 1527 | 480 |
| | FCEV | Medium | 167 | 1.37 | 79837 | 1114 | 437 |
| | FCEV | Small | 133 | 1.13 | 43719 | 568 | 426 |
| | FCEV | SUV | 200 | 1.69 | 76187 | 1055 | 426 |
| | HEV-p | Large | 330 | 1.66 | 60155 | 1331 | 716 |
| | HEV-p | Medium | 271 | 1.53 | 45738 | 1003 | 638 |
| | HEV-p | Small | 153 | 1.28 | 24434 | 514 | 430 |
| | HEV-p | SUV | 330 | 1.91 | 43371 | 963 | 623 |
| | ICEV-d | Large | 440 | 2.61 | 60782 | 1331 | 608 |
| | ICEV-d | Medium | 373 | 2.38 | 46204 | 1003 | 565 |
| | ICEV-d | Small | 240 | 1.94 | 24676 | 514 | 446 |
| | ICEV-g | Large | 432 | 3.08 | 61643 | 1331 | 504 |
| | ICEV-g | Medium | 355 | 2.80 | 46825 | 1003 | 455 |
| | ICEV-g | Small | 200 | 2.28 | 24976 | 514 | 317 |
| | ICEV-g | SUV | 432 | 3.29 | 44545 | 963 | 473 |
| | ICEV-p | Large | 389 | 2.88 | 53500 | 1331 | 486 |
| | ICEV-p | Medium | 330 | 2.62 | 40614 | 1003 | 452 |
| | ICEV-p | Small | 212 | 2.14 | 21575 | 514 | 356 |
| | ICEV-p | SUV | 389 | 3.08 | 38732 | 963 | 454 |
| | ICEV-p | SUV | 389 | 3.08 | 38732 | 963 | 454 |
| | PHEV | Large | 342 | 1.71 | 66499 | 1383 | 598 |
| | PHEV | Medium | 280 | 1.61 | 50283 | 1035 | 535 |
| | PHEV | Small | 160 | 1.36 | 27591 | 535 | 373 |
| | PHEV | SUV | 342 | 1.98 | 48906 | 1003 | 532 |
| 2040 | BEV | Large | 82 | 0.66 | 65455 | 1109 | 356 |
| | BEV | Medium | 73 | 0.61 | 49878 | 836 | 344 |
| | BEV | Small | 46 | 0.50 | 26837 | 428 | 262 |
| | BEV | SUV | 73 | 0.75 | 48135 | 802 | 279 |
| | FCEV | Large | 160 | 1.11 | 70260 | 1109 | 518 |
| | FCEV | Medium | 133 | 1.02 | 53025 | 836 | 470 |
| | FCEV | Small | 107 | 0.85 | 28544 | 428 | 453 |
| | FCEV | SUV | 160 | 1.27 | 50777 | 802 | 453 |
| | HEV-p | Large | 231 | 1.32 | 57303 | 1331 | 628 |
| | HEV-p | Medium | 190 | 1.22 | 43540 | 1003 | 559 |
| | HEV-p | Small | 107 | 1.03 | 23238 | 514 | 374 |
| | HEV-p | SUV | 231 | 1.54 | 41376 | 963 | 541 |
| | ICEV-d | Large | 308 | 1.73 | 59965 | 1331 | 640 |
| | ICEV-d | Medium | 261 | 1.59 | 45587 | 1003 | 592 |
| | ICEV-d | Small | 168 | 1.33 | 24380 | 514 | 456 |
| | ICEV-g | Large | 302 | 1.81 | 54428 | 1331 | 601 |
| | ICEV-g | Medium | 248 | 1.66 | 41315 | 1003 | 539 |
| | ICEV-g | Small | 140 | 1.38 | 21983 | 514 | 366 |
| | ICEV-g | SUV | 302 | 1.99 | 39465 | 963 | 545 |
| | ICEV-p | Large | 272 | 1.77 | 53843 | 1331 | 553 |
| | ICEV-p | Medium | 231 | 1.62 | 40881 | 1003 | 512 |
| | ICEV-p | Small | 148 | 1.36 | 21756 | 514 | 394 |
| | ICEV-p | SUV | 272 | 1.96 | 38972 | 963 | 501 |
| | ICEV-p | SUV | 272 | 1.96 | 38972 | 963 | 501 |
| | PHEV | Large | 257 | 0.97 | 62929 | 1331 | 618 |
| | PHEV | Medium | 210 | 0.94 | 47558 | 1003 | 550 |
| | PHEV | Small | 123 | 0.82 | 25998 | 514 | 395 |
| | PHEV | SUV | 257 | 1.16 | 46245 | 963 | 543 |

Note: All cars are assumed to have a lifetime of 16 years with declining driven km over the lifetime based on survival probability curve.
* BEV: Battery Vehicle, FCEV: Hydrogen Fuel Cell, ICE: internal combustion engine, PHEV: Plug-in hybrid electric vehicle, -p: petrol, -d: diesel, -g: gas
** Car size are based on following engine size and annual vkm are given in parenthesis: Small - <60 kW (9360 km), Medium 60-100 kW (13200 km), Large 100-140 kW (15200 km), SUV >140 kW (12700 km).
*** Maintenance cost does not include fuel costs

Source: Cox and Bauer [11]

Table 10: Two wheeler technical and economic characteristics

| Year | Drivetrain and fuel | Size | Battery size | Fuel efficiency (tank to wheel) | Purchase cost | Maintenance cost | Driving range | Life |
|---|---|---|---|---|---|---|---|---|
| | | **kW** | *kWh* | *KJ/km* | *CHF* | *CHF/year* | *km* | *years* |
| 2015 | BEV | <4kW | 2 | 91 | 5376 | 73 | 60 | 10 |
| 2015 | BEV | 4-11kW | 4 | 161 | 9203 | 114 | 80 | 16 |
| 2030 | FCEV | <4kW | | 216 | 5338 | 67 | 100 | 10 |
| 2030 | FCEV | 4-11kW | | 370 | 8037 | 106 | 150 | 16 |
| 2050 | ICEV | <4kW2s | | 457 | 2536 | 61 | 100 | 10 |
| 2050 | ICEV | 4-11kW2s | | 795 | 4240 | 96 | 150 | 16 |

Source: Cox and Mutel [6]

Table 11: Technical and economic characteristics of buses

| Vintage year | Drivetrain and fuel | Battery size | Fuel efficiency (tank to wheel) | Purchase cost | Maintenance cost | Driving range | Life |
|---|---|---|---|---|---|---|---|
| | | *kWh* | *KJ/km* | *CHF* | *CHF/year* | *km* | *years* |
| 2015 | BEV-LR | 380 | 5465 | 915755 | 128834 | 200 | 12 |
| 2015 | BEV-LR | 569 | 8198 | 1628473 | 203761 | 200 | 12 |
| 2015 | BEV-LR | 252 | 3634 | 437594 | 81888 | 200 | 10 |
| 2015 | BEV-LR | 183 | 2641 | 188899 | 52248 | 200 | 8 |
| 2015 | BEV-SR | 86 | 5134 | 720374 | 64007 | 12 | 12 |
| 2015 | BEV-SR | 128 | 7701 | 1335412 | 106523 | 12 | 12 |
| 2015 | BEV-SR | 57 | 3414 | 307688 | 36517 | 12 | 10 |
| 2015 | BEV-SR | 41 | 2481 | 94504 | 17544 | 12 | 8 |
| 2015 | FCEV | 0 | 10912 | 981305 | 117163 | 500 | 12 |
| 2015 | FCEV | 0 | 16257 | 1644485 | 159280 | 500 | 12 |
| 2015 | FCEV | 0 | 7298 | 518654 | 86671 | 500 | 10 |
| 2015 | FCEV | 0 | 5267 | 234373 | 51090 | 500 | 8 |
| 2015 | HEV-D | 0 | 13229 | 458595 | 76083 | 500 | 12 |
| 2015 | HEV-D | 0 | 19623 | 817956 | 114166 | 500 | 12 |
| 2015 | HEV-D | 0 | 8882 | 211664 | 49306 | 500 | 10 |
| 2015 | HEV-D | 0 | 6367 | 70854 | 23730 | 500 | 8 |
| 2015 | ICEV-CNG | 0 | 18360 | 330312 | 55794 | 500 | 12 |
| 2015 | ICEV-CNG | 0 | 27498 | 623433 | 90348 | 500 | 12 |
| 2015 | ICEV-CNG | 0 | 12188 | 155462 | 32592 | 500 | 10 |
| 2015 | ICEV-CNG | 0 | 8631 | 52802 | 13955 | 500 | 8 |
| 2015 | ICEV-D | 0 | 17256 | 308000 | 55794 | 500 | 12 |
| 2015 | ICEV-D | 0 | 25876 | 602547 | 90348 | 500 | 12 |
| 2015 | ICEV-D | 0 | 11433 | 145030 | 32592 | 500 | 10 |
| 2015 | ICEV-D | 0 | 8070 | 44177 | 13955 | 500 | 8 |
| 2030 | BEV-LR | 321 | 4629 | 397848 | 43523 | 200 | 12 |
| 2030 | BEV-LR | 482 | 6934 | 724708 | 76594 | 200 | 12 |
| 2030 | BEV-LR | 214 | 3083 | 181533 | 21634 | 200 | 10 |
| 2030 | BEV-LR | 155 | 2235 | 74421 | 5756 | 200 | 8 |
| 2030 | BEV-SR | 74 | 4433 | 345748 | 43523 | 12 | 12 |
| 2030 | BEV-SR | 111 | 6639 | 646672 | 76594 | 12 | 12 |
| 2030 | BEV-SR | 49 | 2952 | 146259 | 21634 | 12 | 10 |
| 2030 | BEV-SR | 36 | 2141 | 45587 | 5756 | 12 | 8 |
| 2030 | FCEV | 0 | 8841 | 429709 | 43523 | 500 | 12 |
| 2030 | FCEV | 0 | 13176 | 751184 | 76594 | 500 | 12 |
| 2030 | FCEV | 0 | 5914 | 208701 | 21634 | 500 | 10 |
| 2030 | FCEV | 0 | 4266 | 91520 | 5756 | 500 | 8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2030 | HEV-D | 0 | 11259 | 348717 | 54441 | 500 | 12 |
| 2030 | HEV-D | 0 | 16689 | 648917 | 88742 | 500 | 12 |
| 2030 | HEV-D | 0 | 7569 | 179288 | 31507 | 500 | 10 |
| 2030 | HEV-D | 0 | 5424 | 67283 | 13423 | 500 | 8 |
| 2030 | ICEV-CNG | 0 | 15565 | 318550 | 56210 | 500 | 12 |
| 2030 | ICEV-CNG | 0 | 23266 | 618528 | 90818 | 500 | 12 |
| 2030 | ICEV-CNG | 0 | 10331 | 153286 | 32964 | 500 | 10 |
| 2030 | ICEV-CNG | 0 | 7260 | 50969 | 14275 | 500 | 8 |
| 2030 | ICEV-D | 0 | 14668 | 308566 | 56210 | 500 | 12 |
| 2030 | ICEV-D | 0 | 21947 | 603219 | 90818 | 500 | 12 |
| 2030 | ICEV-D | 0 | 9718 | 145564 | 32964 | 500 | 10 |
| 2030 | ICEV-D | 0 | 6807 | 44591 | 14275 | 500 | 8 |
| 2050 | BEV-LR | 265 | 3815 | 324134 | 43337 | 200 | 12 |
| 2050 | BEV-LR | 396 | 5699 | 632217 | 76391 | 200 | 12 |
| 2050 | BEV-LR | 177 | 2548 | 154919 | 21469 | 200 | 10 |
| 2050 | BEV-LR | 128 | 1844 | 52431 | 5684 | 200 | 8 |
| 2050 | BEV-SR | 62 | 3714 | 303162 | 43337 | 12 | 12 |
| 2050 | BEV-SR | 92 | 5548 | 599327 | 76391 | 12 | 12 |
| 2050 | BEV-SR | 41 | 2481 | 139144 | 21469 | 12 | 10 |
| 2050 | BEV-SR | 30 | 1795 | 39563 | 5684 | 12 | 8 |
| 2050 | FCEV | 0 | 6822 | 341585 | 43337 | 500 | 12 |
| 2050 | FCEV | 0 | 10157 | 648220 | 76391 | 500 | 12 |
| 2050 | FCEV | 0 | 4570 | 173149 | 21469 | 500 | 10 |
| 2050 | FCEV | 0 | 3296 | 63812 | 5684 | 500 | 8 |
| 2050 | HEV-D | 0 | 9204 | 344262 | 54929 | 500 | 12 |
| 2050 | HEV-D | 0 | 13617 | 646710 | 89289 | 500 | 12 |
| 2050 | HEV-D | 0 | 6203 | 177687 | 31953 | 500 | 10 |
| 2050 | HEV-D | 0 | 4446 | 66247 | 13825 | 500 | 8 |
| 2050 | ICEV-CNG | 0 | 12875 | 316232 | 56807 | 500 | 12 |
| 2050 | ICEV-CNG | 0 | 19224 | 614634 | 91493 | 500 | 12 |
| 2050 | ICEV-CNG | 0 | 8546 | 151666 | 33499 | 500 | 10 |
| 2050 | ICEV-CNG | 0 | 5950 | 49591 | 14729 | 500 | 8 |
| 2050 | ICEV-D | 0 | 12171 | 309380 | 56807 | 500 | 12 |
| 2050 | ICEV-D | 0 | 18186 | 604184 | 91493 | 500 | 12 |
| 2050 | ICEV-D | 0 | 8066 | 146331 | 33499 | 500 | 10 |
| 2050 | ICEV-D | 0 | 5598 | 45187 | 14729 | 500 | 8 |
| Note: ICE – Internal combustion engine; FCEV – Hydrogen fuel cell bus, HEV-D- Hybrid electric (diesel) -LR – Long range buses, -SR – short range buses, CNG – Compressed natural gas | | | | | | | |

Source: Cox [16]