Prepared for

Concawe

LOW CARBON PATHWAYS

DEEP DIVE ON HEAVY DUTY TRANSPORTATION SECTOR

Aachen, April 2019
FEV Consulting GmbH

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul

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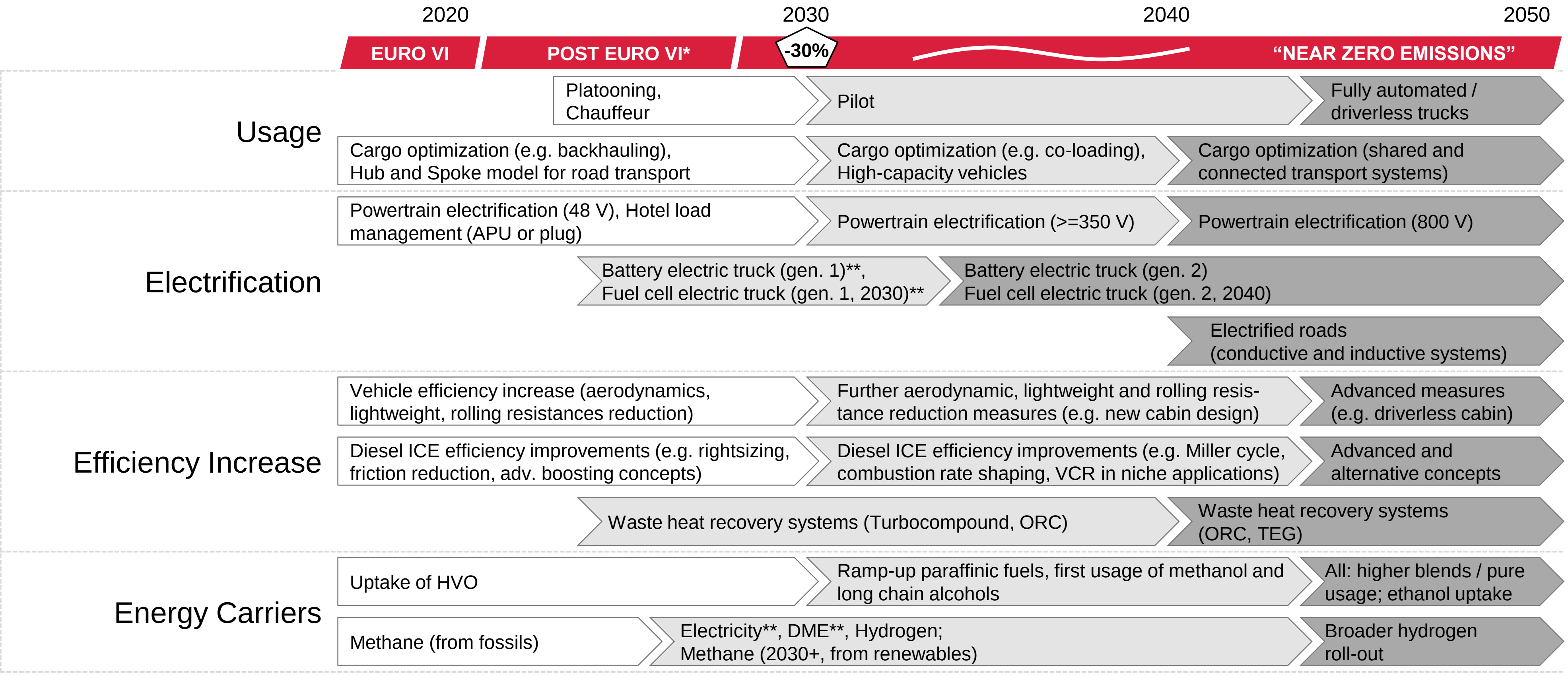
OVERVIEW ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES

HD



2020 | 2030 | 2040 | 2050

EURO VI | **POST EURO VI*** | **-30%** | **"NEAR ZERO EMISSIONS"**

Usage
- Platooning, Chauffeur → Pilot → Fully automated / driverless trucks
- Cargo optimization (e.g. backhauling), Hub and Spoke model for road transport → Cargo optimization (e.g. co-loading), High-capacity vehicles → Cargo optimization (shared and connected transport systems)

Electrification
- Powertrain electrification (48 V), Hotel load management (APU or plug) → Powertrain electrification (>=350 V) → Powertrain electrification (800 V)
- Battery electric truck (gen. 1)**, Fuel cell electric truck (gen. 1, 2030)** → Battery electric truck (gen. 2) Fuel cell electric truck (gen. 2, 2040)
- Electrified roads (conductive and inductive systems)

Efficiency Increase
- Vehicle efficiency increase (aerodynamics, lightweight, rolling resistances reduction) → Further aerodynamic, lightweight and rolling resistance reduction measures (e.g. new cabin design) → Advanced measures (e.g. driverless cabin)
- Diesel ICE efficiency improvements (e.g. rightsizing, friction reduction, adv. boosting concepts) → Diesel ICE efficiency improvements (e.g. Miller cycle, combustion rate shaping, VCR in niche applications) → Advanced and alternative concepts
- Waste heat recovery systems (Turbocompound, ORC) → Waste heat recovery systems (ORC, TEG)

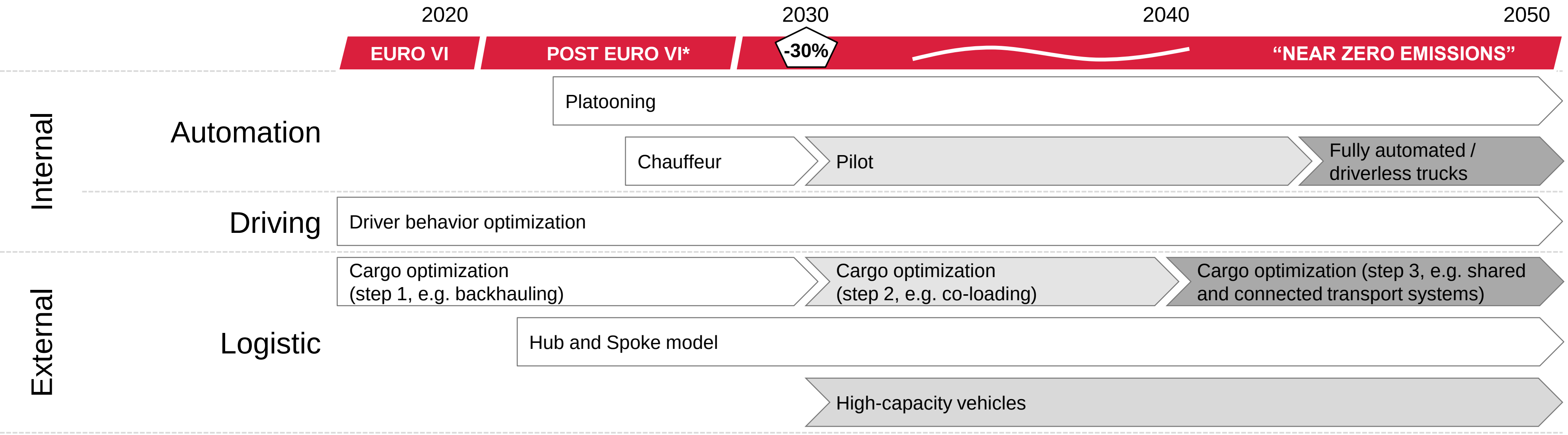
Energy Carriers
- Uptake of HVO → Ramp-up paraffinic fuels, first usage of methanol and long chain alcohols → All: higher blends / pure usage; ethanol uptake
- Methane (from fossils) → Electricity**, DME**, Hydrogen; Methane (2030+, from renewables) → Broader hydrogen roll-out

* FEV scenario; **In dedicated use-cases only
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Usage

USAGE – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



2020 2030 2040 2050

EURO VI | **POST EURO VI*** | **-30%** | **“NEAR ZERO EMISSIONS”**

Internal

Automation
- Platooning
- Chauffeur
- Pilot
- Fully automated / driverless trucks

Driving
- Driver behavior optimization

External

Logistic
- Cargo optimization (step 1, e.g. backhauling)
- Cargo optimization (step 2, e.g. co-loading)
- Cargo optimization (step 3, e.g. shared and connected transport systems)
- Hub and Spoke model
- High-capacity vehicles

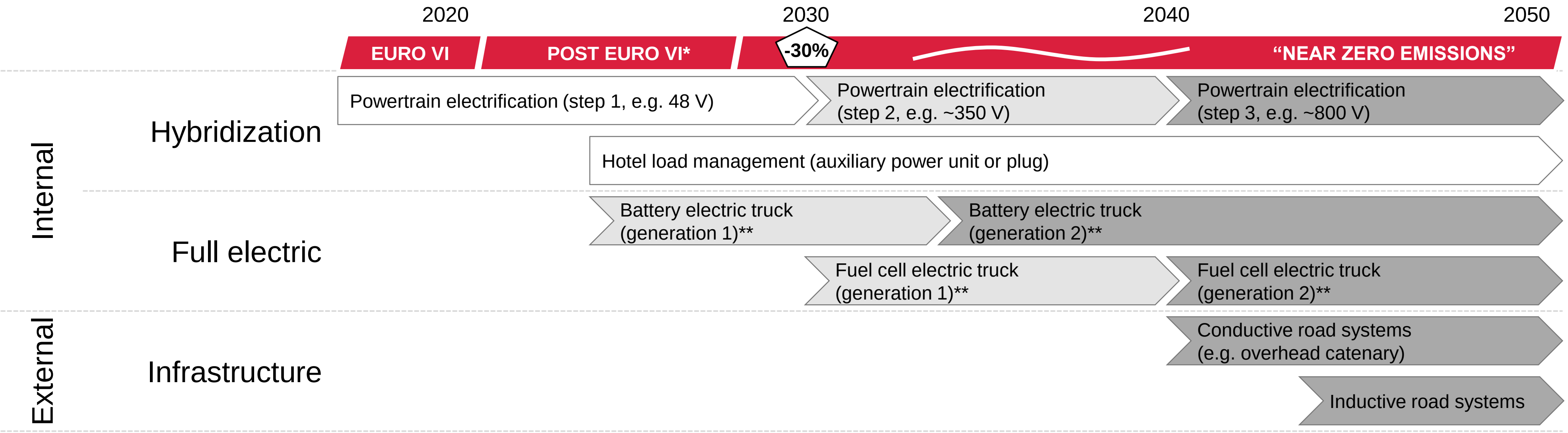
* FEV scenario
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Electrification

ELECTRIFICATION – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES

HD



2020
2030
2040
2050

EURO VI
POST EURO VI*
-30%
“NEAR ZERO EMISSIONS”

Internal

Hybridization

Powertrain electrification (step 1, e.g. 48 V)
Powertrain electrification (step 2, e.g. ~350 V)
Powertrain electrification (step 3, e.g. ~800 V)
Hotel load management (auxiliary power unit or plug)

Full electric

Battery electric truck (generation 1)**
Battery electric truck (generation 2)**
Fuel cell electric truck (generation 1)**
Fuel cell electric truck (generation 2)**

External

Infrastructure

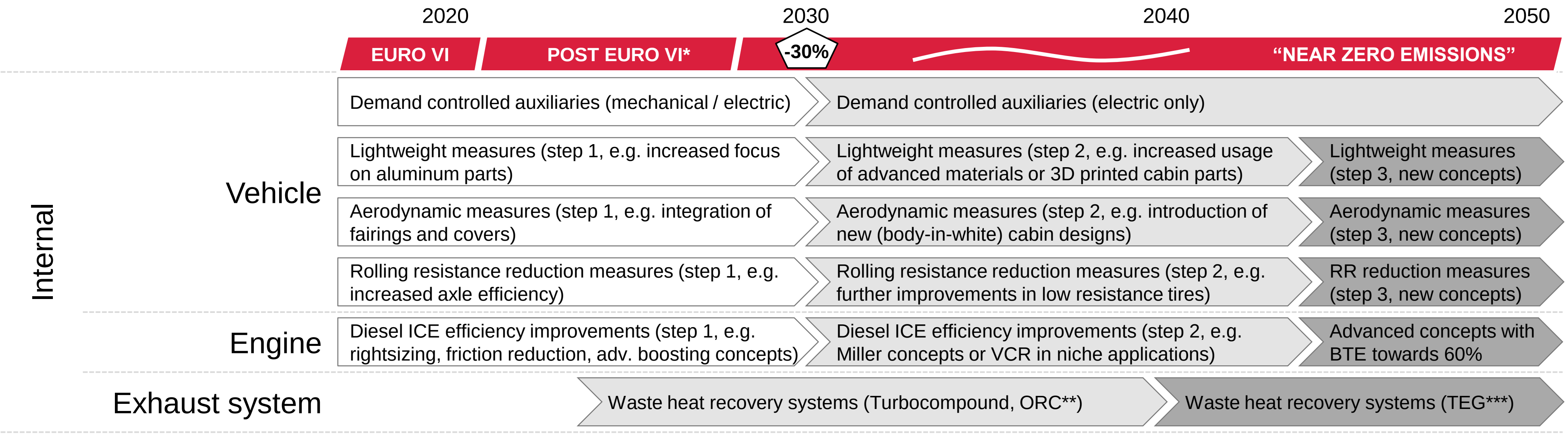
Conductive road systems (e.g. overhead catenary)
Inductive road systems

* FEV scenario; ** In dedicated use-cases only
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Efficiency increase

EFFICIENCY INCREASE – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



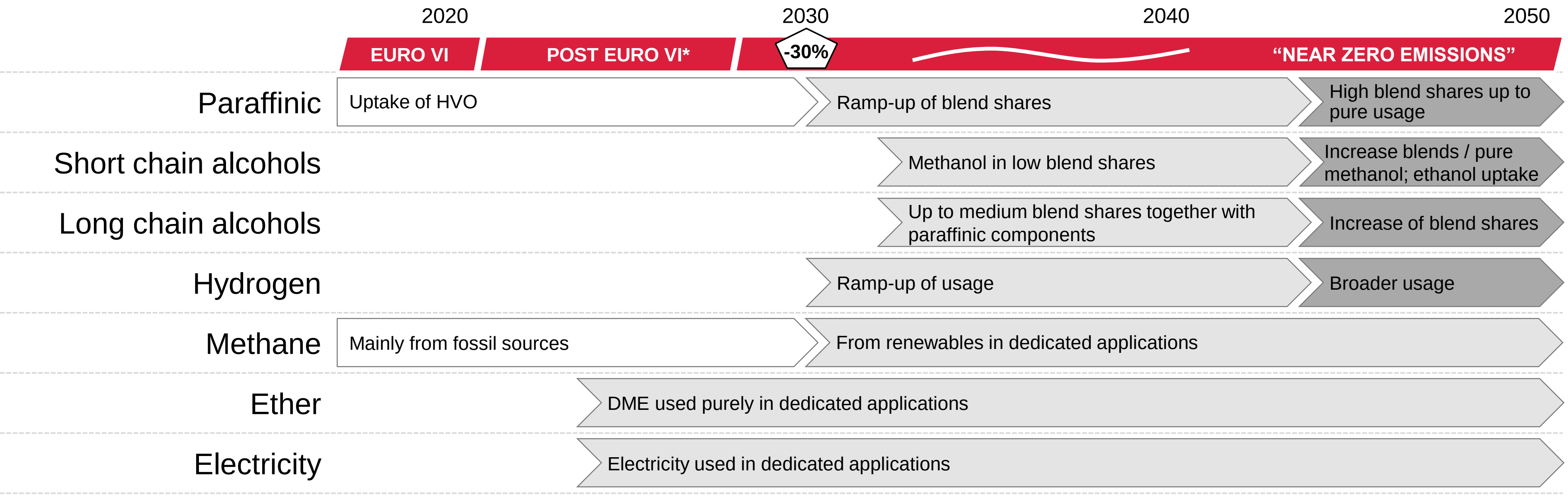
		2020	2030	2040 – 2050
		EURO VI / POST EURO VI*	-30%	“NEAR ZERO EMISSIONS”
Internal	Vehicle	Demand controlled auxiliaries (mechanical / electric)	Demand controlled auxiliaries (electric only)	
		Lightweight measures (step 1, e.g. increased focus on aluminum parts)	Lightweight measures (step 2, e.g. increased usage of advanced materials or 3D printed cabin parts)	Lightweight measures (step 3, new concepts)
		Aerodynamic measures (step 1, e.g. integration of fairings and covers)	Aerodynamic measures (step 2, e.g. introduction of new (body-in-white) cabin designs)	Aerodynamic measures (step 3, new concepts)
		Rolling resistance reduction measures (step 1, e.g. increased axle efficiency)	Rolling resistance reduction measures (step 2, e.g. further improvements in low resistance tires)	RR reduction measures (step 3, new concepts)
	Engine	Diesel ICE efficiency improvements (step 1, e.g. rightsizing, friction reduction, adv. boosting concepts)	Diesel ICE efficiency improvements (step 2, e.g. Miller concepts or VCR in niche applications)	Advanced concepts with BTE towards 60%
	Exhaust system	Waste heat recovery systems (Turbocompound, ORC**)		Waste heat recovery systems (TEG***)

* FEV scenario; ** ORC: Organic Rankine Cycle; *** TEG: Thermo-Electric Generator;
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Roadmap of widespread CO_2 reduction measures: Europe, HD sector, long-haul and regional haul; focus group: Energy carriers

ENERGY CARRIERS – ROADMAP OF WIDESPREAD CO_2 REDUCTION MEASURES



Paraffinic	Uptake of HVO	Ramp-up of blend shares	High blend shares up to pure usage
Short chain alcohols	Methanol in low blend shares	Increase blends / pure methanol; ethanol uptake	
Long chain alcohols	Up to medium blend shares together with paraffinic components	Increase of blend shares	
Hydrogen	Ramp-up of usage	Broader usage	
Methane	Mainly from fossil sources	From renewables in dedicated applications	
Ether	DME used purely in dedicated applications		
Electricity	Electricity used in dedicated applications		

* FEV scenario
Source: FEV

⬠ CO_2 reduction vs. 2019 baseline; European Commission proposal

Platooning affects the competitive position of on-road transport positively and is expected to be applied once regulation has been adapted

2020/30

USAGE – PLATOONING

Characteristics

- Coupling of vehicles using information exchange via Wi-Fi or cell network, to close the gap between them and to reduce the air drag
- Truck to truck as well as truck to car connection is possible
- Step-by-step market introduction expected (2023 and beyond):
  - Starting with small platoons, then increasing number of vehicles
  - Starting with OEM specific platoons, then standardized interfaces
- Vehicle technology impact:
  - Vehicle to vehicle communication
  - Sensors and actuators to perform driving functions by driver and software
  - Human-machine interface to coordinate on- and off-docking as well as provision of current status

Key advantages

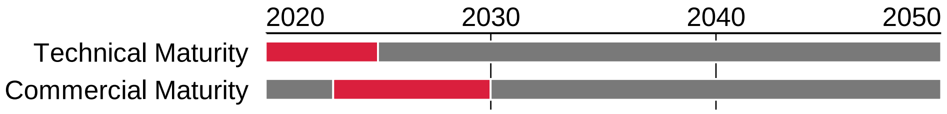
- Increase of productivity and ride comfort for the driver, since the driver of following vehicles can rest
- Decrease of operation cost since fuel savings can be realized
- Decrease of down-time since safety can be enhanced
- Potential to reduce traffic-jams after the technology has been widely rolled out

Key challenges

- Regulation needs to be adapted according to technology maturity
- Only vehicles equipped with platooning technology can participate in a platoon
- Standardization for communication between vehicles of different OEMs

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	1-10%
Relevance for long-haul	High
Relevance for regional-haul	Low



Cross impacts and further comments

- Installed technology increases investment costs, however, if implemented with other automation measures, the cost could be partially leveraged
- Increase on-road transport's competitiveness:
  - Cost per km decreases
  - Ride comfort for drivers increases
  - Travelled kilometers might increase, thus mitigate specific fuel savings
- If fewer congestion can be achieved, this reduces fuel consumption

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Chauffeur function is expected to be combined with Platooning and will increase productivity and comfort of the driver

USAGE – CHAUFFEUR

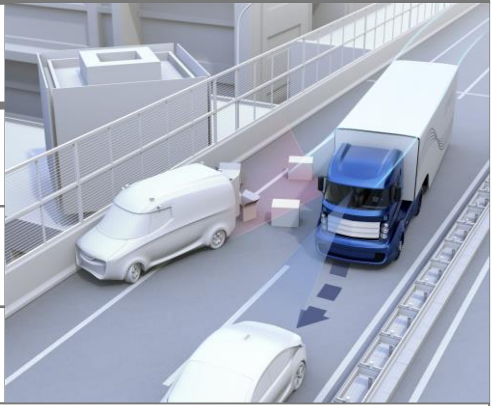
2020/30

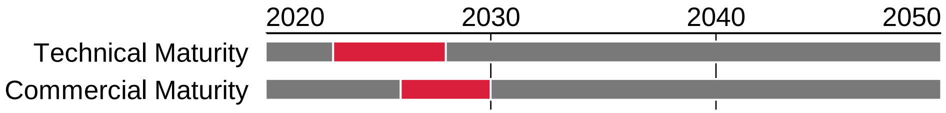
Characteristics

- Chauffeur function to automate driving on highways and in cities within certain boundary conditions (e.g. non-critical situations, equipped roads)
- Step by step market introduction expected:
  - Traffic jam chauffeur
  - Highway chauffeur
  - City chauffeur
- Vehicle technology impact:
  - Vehicle-to-vehicle communication
  - Sensors and actuators to perform driving functions by driver and software
  - Human-machine interface to coordinate on- and off-docking as well as provision of current status

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	1-3%
Relevance for long-haul	Medium
Relevance for regional-haul	Low





Key advantages

- Increase of ride comfort for the driver since he can rest when the vehicle is in chauffeur mode
- Increase of productivity if the driver can account time in chauffeur mode as rest time, thus increases daily mileage
- Decrease of down-time since safety can be enhanced

Key challenges

- Functional safety
- Regulation needs to be adapted according to technology maturity

Cross impacts and further comments

- Installed technology increases investment costs, however, if implemented with other automation measures, the cost could be partially leveraged
- Increase on-road transport’s competitiveness:
  - Cost per km decreases
  - Ride comfort for drivers increases
  - Travelled kilometers might increase, thus mitigate specific fuel savings
- If fewer congestion can be achieved, this reduces fuel consumption
- Change of cabin design (living / working space) would be introduced

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Eco-Coaches have the potential to leverage proven gamification elements and further push fuel savings

2020/30

USAGE – DRIVER BEHAVIOR OPTIMIZATION

Characteristics

- Application of Eco-coach software to engage and motivate the driver for specific driving goals, e.g. low fuel consumption
- Driver training and feedback devices to monitor and reward more fuel-efficient driving
- "Human-focused design" tangents human feelings, insecurities and motivations
- Eco-Coaches are already used in trucks but score very low in "Gamification" discipline
- Top computer games are using nearly five times as many game mechanics as today's Eco-Coaches

Key advantages

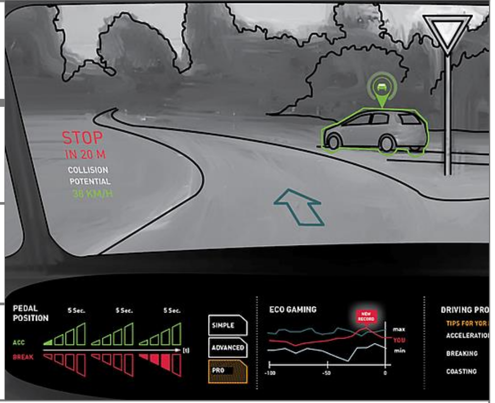
- Good CO_2 cost-benefit ratio and the potential to reduce up to 20% of road accidents
- Promising future: double digit growth rates until 2025, mainly driven by evolving buying criteria, vehicle electrification and an ecological mind shift
- Eco-Coach software is highly scalable

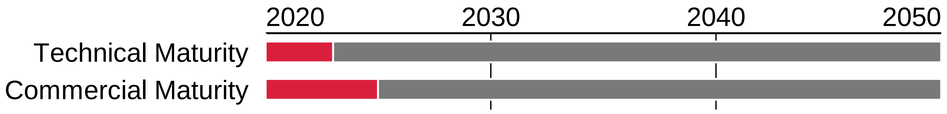
Key challenges

- Technology needs to improve in terms of personalization, customization, flexibility / adaptability, connectivity and incorporate latest research of human behavioral decision psychology
- Official recognition / legislation is missing (no "Eco-credits")
- Increase drivers acceptance and awareness

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	3-9%
Relevance for long-haul	Medium
Relevance for regional-haul	Medium





Cross impacts and further comments

- Eco-Coach relevance is expected to decrease over time due to the growth of trucks' automation
- Still, CO_2 emissions could be reduced on a short horizon
- Together with an adapted legislation and system of "Eco-credits", this technology has a good potential on a fleet scale

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

An improved logistic management (backhauling) can further reduce the share of “empty” transports on European roads

USAGE – CARGO OPTIMIZATION (STEP 1)

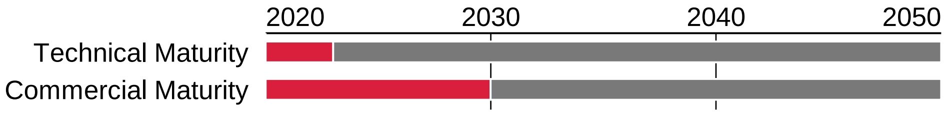
2020/30

Characteristics

- Implementation of measures allowing to increase cargos’ average filling level:
  - Backhauling: postponing or extending “standard journey” to deliver freight also on the returning trip, avoiding a full empty-cargo trip.
- No additional hardware costs because such measures refer to the usage of vehicles (closely linked to a proper planning)
- Currently about 20% of kilometers are run “empty” in EU

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	~2%
Relevance for long-haul	Low
Relevance for regional-haul	Low



Key advantages

- Good CO_2 cost-benefit ratio as no additional hardware is required
- Potential to reduce the road traffic
- High potential in regions where logistics and supply chain operations are less optimized

Key challenges

- Requires collaboration across shippers / operators
- Requires a high level of logistic management
- Currently no existing measures to discourage “empty-runs”

Cross impacts and further comments

- Lower transportation costs per freight unit could shift an amount of goods from rail to road, determining a final increment in road traffic and emissions
- Although backhauling is already used on a small scale, further improvement margins are still expected
- However, due to vehicle-cargo mismatches and delivery constraints, it is not avoidable to have some empty-cargo trips

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[1] CO_2 emission reduction potential system-wise (for the entire transport sector)

Sources: Eurostat; FEV

The hub and spoke model reorganizes logistics in cities, can save fuel and improves air quality by electrification of inner city rides

USAGE – HUB AND SPOKE MODEL

2020/30

Characteristics

- Spokes are drop-off points in the outskirts of the city and are typically approached by heavy-duty vehicles or with bulky products
- Hubs are central distribution centers outside of the city center but in the main city area – medium-duty vehicles distribute from spokes to hubs and light commercial vehicles from hubs to customers / city centers
- Further increase of the use-case oriented design of trucks, e.g. high payload long-haul heavy-duty trucks and agile city light commercial vehicles
- Specialized use-case eases the automated operation of delivery to spokes

Key advantages

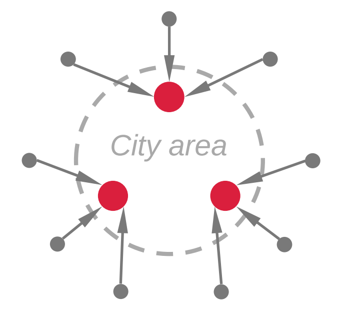
- Fewer heavy-duty vehicles drive into the city which reduces congestion
- Air quality in the city can be improved since electrification of vehicles for intra-city delivery from spokes to hubs and from hubs to customers is easier
- Increased load factor of trucks
- More flexible delivery time and (potentially) quicker delivery

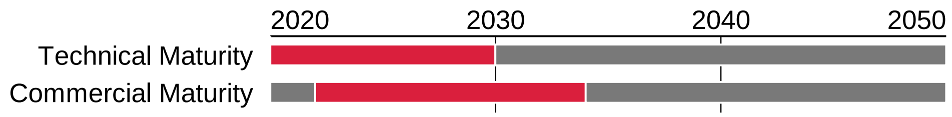
Key challenges

- Locations for the hubs and spokes needs to be available at places where they are required and at competitive costs
- Increase of complexity
- Drop-off spaces for delivery need to be defined to avoid congestion by 2nd row parking

Impact

	Quantitative assessment
CO$_2$ emissions reduction[1]	< 5%
Relevance for long-haul	Medium
Relevance for regional-haul	Low





Cross impacts and further comments

- Further potential with the roll-out of a common “freight container modularization system”
- Potential for electrification of vehicles that move goods between hubs and spokes and to the customers / city centers
- Fuel consumption of trucks altered by changed mission profiles: heavy-duty more long-haul with lower specific fuel consumption, medium-duty and light vehicles more city traffic and higher specific fuel consumption
- Overall vehicle kilometers travelled will (probably) increase

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[1] CO$_2$ emission reduction potential system-wise (for the entire transport sector)

Source: FEV

Vehicle miles travelled are expected to increase due to the positively affected competitive position and the decrease of down-time

USAGE – PILOT

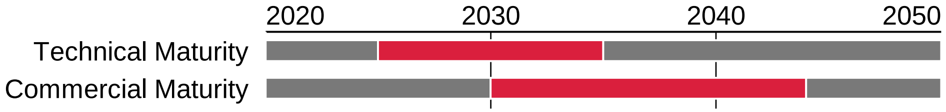
2030/40

Characteristics

- Full-time automated driving at all roadway and environmental conditions:
  - System performs all safety-critical functions
  - System monitors the roadway condition
- The driver is only required to maneuver the truck during specific operations (e.g. loading, unloading)
- Expected to be introduced on selected routes and highways first
- Technology installed increases costs:
  - Cameras, lidar and radar technology necessary
  - Increased computing power to process data gathered by sensors
  - Sensors and actuators to perform driving functions

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	2-5%
Relevance for long-haul	Medium
Relevance for regional-haul	Low



Key advantages

- Increase of productivity and ride comfort for the driver since the driver of can rest, thus increases mileage
- Decrease of down-time since safety can be enhanced
- Fewer congestion since transportation tasks can be shifted to night times more easily

Key challenges

- Technology needs to be developed further to ensure a safe operation in all situations
- Regulation needs to be adapted according to technology maturity
- Vehicles need to be equipped with significant amount of technology

Cross impacts and further comments

- Installed technology increases investment costs, however, if implemented with other automation measures, the cost could be partially leveraged
- Increase on-road transport's competitiveness:
  - Cost per km decreases
  - Ride comfort for drivers increases
  - Travelled kilometers might increase, thus mitigate fuel savings
- If fewer congestion can be achieved, this reduces fuel consumption
- Change of cabin design (living / working space) would be introduced

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Collaboration across shippers could lead to an important abatement in CO_2 emissions at relatively small costs

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USAGE – CARGO OPTIMIZATION (STEP 2)

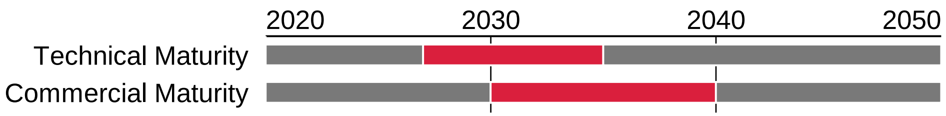
2030/40

Characteristics

- Implementation of measures allowing to increase cargos' average filling level:
  - Co-loading: regrouping of freight with similar shipment characteristics (e.g. departure point, destination) without regard to product's categories; implemented through common route planning and warehouse facilities sharing, between shippers / operators
  - Freight container modularization: all freight transport modes share the same interfaces and are able to use the same freight modules. Small freight modules that will typically be used for urban transport can be combined into bigger ones for long-distance transport and vice-versa

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	5-10%
Relevance for long-haul	Medium
Relevance for regional-haul	Medium



Key advantages

- Good CO_2 cost-benefit ratio and the potential to reduce the road traffic
- Positive effect on the entire commercial transportation sector

Key challenges

- Requires collaboration across shippers / operators
- Requires a high level of logistic management
- A common "modular system" for freight containers has to be regulated

Cross impacts and further comments

- Further decrease in CO_2 emissions could be achieved if implemented together with other logistics' measures (e.g. high capacity vehicle or hub and spoke model)
- Lower transportation costs per freight unit could shift an amount of goods from rail to road, determining a final increment in road traffic and emissions

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[1] CO_2 emission reduction potential system-wise (for the entire transport sector)

Sources: IEA, FEV

Logistics business claims increase in truck load, safety and infrastructure issues restrain implementation

USAGE – HIGH-CAPACITY VEHICLES

2030/40

Characteristics

- Larger trucks with heavier payload
- The fuel consumption increases with a slower rate in comparison to the increase of vehicle's weight / payload
- Unlikely to be applied to regional-haul vehicles
- High barriers on legal level due to infrastructural and safety issues (length and weight per axis):
  - Highway and bridge conditions, narrow curves, overtaking process
- Northern European countries are experienced into this practice:
  - In 1990, Finland limited trucks total weight to 60 tons
  - In 2013, Finland allowed 9 axles-, 76 tons-trucks on selected routes
  - In 2017, Sweden allowed 74 tons-trucks on selected routes

Key advantages

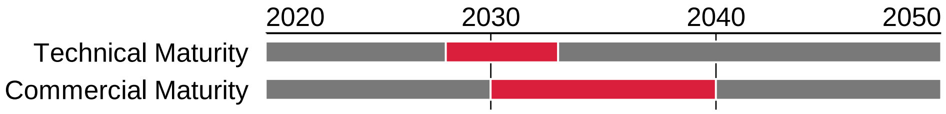
- Decrease in number of trucks needed to transport the same amount of freight; subsequently:
  - Less CO_2 emissions
  - Less traffic
- Positive business case especially for vast transportation distances with lack of alternatives to road transportation

Key challenges

- Regulation (e.g. vehicle length and max. payload allowance) needs to be modified
- Infrastructure (e.g. curves, small gas stations, parking areas)
- Large infrastructure maintenance and investments necessary
- Safety issues (overtaking) have to be solved

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	< 20%
Relevance for long-haul	High
Relevance for regional-haul	Low



Cross impacts and further comments

- Further decrease in CO_2 emissions could be achieved if implemented together with other logistics' measures (e.g. high capacity vehicle or hub and spoke model)
- A wide adoption of longer and bigger trucks, pushed by the legislation, could promote the shift to a "Hub and Spoke model"
- Lower transportation costs per freight unit could shift an amount of goods from rail to road, determining a final increment in road traffic and emissions

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Depending on various external factors fully automated driving may be realistic within the next 20-25 years – preliminary for selected routes

USAGE – FULLY AUTOMATED / DRIVERLESS TRUCKS

2040/50

Characteristics

- Full-time performance of all aspects of the driving task under all roadway and environmental conditions by automated driving system:
  - System is performing all safety-critical driving functions
  - System is monitoring all roadway conditions
- Step-by-step introduction expected:
  - Starting with specifically equipped roads, then roll-out to all sort of routes
- As no driver is required, also infrastructures have to be adapted in order to allow the truck to autonomously load, unload and refuel easily
- A considerable amount of technology (all type of hardware and smart / AI software) has to be implemented into the vehicle / roads

Key advantages

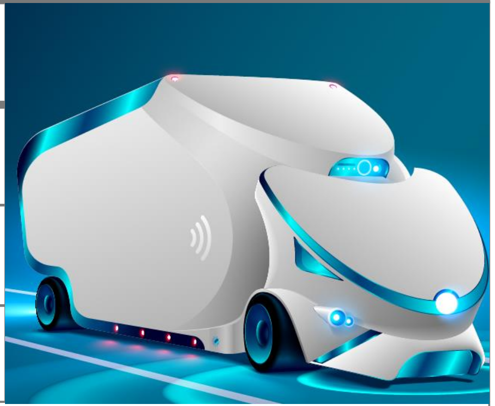
- Increase of productivity and ride efficiency
- Decrease of down-time since safety can be enhanced
- Fewer congestions since transportation tasks can be shifted to night times; no "rest" is required
- No driver's costs
- Fast operations

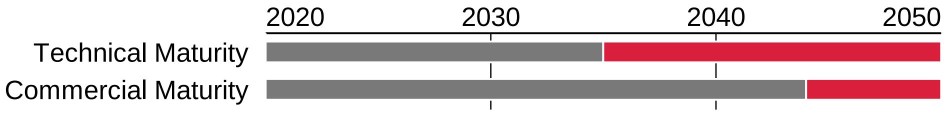
Key challenges

- Technology needs to be developed further to ensure a safe operation in all situations
- Regulation needs to be adapted according to technology maturity
- Vehicles need to be equipped with significant amount of technology
- Significant investments into infrastructure has to be done

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	2-5%
Relevance for long-haul	High
Relevance for regional-haul	Medium





Cross impacts and further comments

- Installed technology increases investment costs, however, if implemented with other automation measures, the cost could be partially amortized
- Could significantly promote a high level of logistics
- Positively affects competitive position of on-road transport:
  - Cost per km is expected to decrease
- If fewer congestions can be achieved, this reduces fuel consumption

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

The concept of physical internet, although hard to realize, must be the objective to pursue in order to push freight transportation to the next level

USAGE – CARGO OPTIMIZATION (STEP 3)

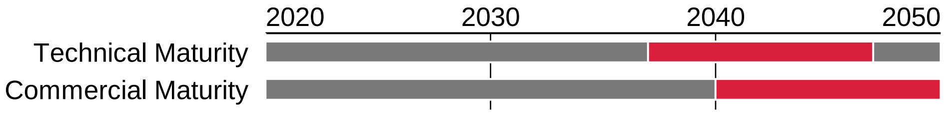
2040/50

Characteristics

- Implementation of advanced measures allowing to increase cargos' average filling level:
  - Physical internet: commercial vehicles, train, flights and ships connected to a shared platform allowing to deliver any good in the most efficient way

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	< 15%
Relevance for long-haul	High
Relevance for regional-haul	High



Key advantages

- Excellent CO_2 cost-benefit ratio and the potential to reduce the overall commercial traffic
- Positive effect on the entire commercial transportation sector
- Minimizes the total amount of kilometers required to ship any freight within all transports
- Delivery costs and time reduction
- Optimizes single trip length

Key challenges

- Requires collaboration across shippers
- Requires an extremely high level of logistic management
- Requires real-time tracking / status updates of all commercial vehicles
- Regulations may be required to monitor collaborations and to ensure that reduced costs of shipping are passed through to consumers

Cross impacts and further comments

- Further decrease in CO_2 emissions could be achieved if implemented together with automation measures
- Requires the implementation of a common "freight container modularization system" and a widely rolled-out "hub and spoke model"

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[1] CO_2 emission reduction potential system-wise (for the entire transport sector)

Sources: IEA, FEV

For long-haul HD applications the impact of hybridization measures is less important compared to that for regional-haul ones

2020/30

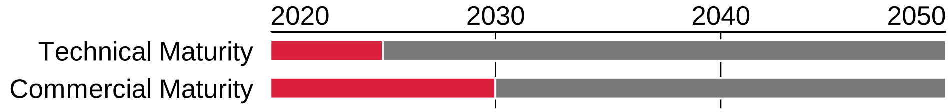
ELECTRIFICATION – POWERTRAIN ELECTRIFICATION (STEP 1)

Characteristics

- Implementation of first measures to hybridize the combustion engine (combined with electrified auxiliaries):
  - 48 V hybrid system
  - Boosting functionality
  - (Limited) ICE operating point shift
  - (Limited) recuperation
- CO_2 and other emission limits / local regulations and impact on TCO performance will drive electrification and hybridization degrees
- Highest potential in drive cycles with stop / start and acceleration / deceleration events, combined with predictive cruise control
- For long-haul HD applications business potential seems to be limited

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	1-3%
Relevance for long-haul	Low
Relevance for regional-haul	High



Key advantages

- Reduces overall fuel consumption through the optimization of ICE in transient phases
- Combined with predictive driving, further fuel economy potentials can be leveraged (e.g. sailing function with engine off)
- Increased low-end torque (support from e-motor)
- Potentially high degree of standard components

Key challenges

- Additional costs in comparison to pure ICE vehicle
- Overall potentials of 48 V system in HD applications limited (limitations in terms of power)
- No “pure electric drive” mode possible (limited power to 20-35 kW)
- Additional integration effort

Cross impacts and further comments

- Full potential of technology is highly related to other functions on the vehicle (such as predictive cruise control)
- 48 V system can have positive side-effects, e.g. electrically heated catalyst (positive impact on emissions due to reduced warm-up period)
- Load cycle shifts can reduce not only CO_2- but also NO_X-emission – with a potential (positive) impact on aftertreatment system costs
- Mentioned potentials require a system view / optimization

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Hotel load management with a battery auxiliary power unit or with a connection to the power grid avoids engine idling at places of rest

2020/30

ELECTRIFICATION – HOTEL LOAD MANAGEMENT

Characteristics

- Refers to the power load of convenience accessories for the usage of a truck with a sleeper cabin as a place of rest for the drivers
- Two possible solutions:
  - An auxiliary power unit (APU) used to support power demands not related to propulsion. Conventional APUs are diesel powered units; advanced APUs are mostly battery-powered, although fuel cells are being considered, too
  - Off-board power (shore power) using a plug to establish an electric connection between the grid and the truck during extended standstill periods

Key advantages

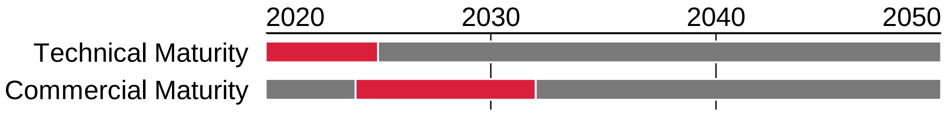
- Hotel load management:
  - No engine idle time during resting periods or extended standstill periods
- Can also offer significant pollutant emission benefits

Key challenges

- Hotel load management:
  - Development and integration
- The use of off-board power is highly dependent on the coverage of the infrastructure and the number of electrified parking spaces; furthermore, the vehicle's electrical architecture must accommodate the use of off-board AC power

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	1-2%
Relevance for long-haul	High
Relevance for regional-haul	Low



Cross impacts and further comments

- Infrastructure to be build-up for the plug solution could be connected with the anticipated investment in electric vehicle chargers at rest stops along motorways
- Penetration of e.g. battery APU is closely linked to legal boundaries (eco-credits, allowed rest time in cabin)

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

The implementation of e-drive functionality into long-haul HD trucks is strongly dependent on the quantity of inner city rides of such vehicles

FEV CONSULTING

ELECTRIFICATION – POWERTRAIN ELECTRIFICATION (STEP 2)

2030/40

Characteristics

- Implementation of first measures to (fully) hybridize the combustion engine (combined with electrified auxiliaries):
  - High voltage hybrid system, e.g. 350 V, 5 kWh battery, 100 kW e-motor
  - ICE operating point shift
  - Increased recuperation potential in comparison to 48 V system
  - Sailing functionality (engine-off)
- CO_2 and other emission limits / local regulations and impact on TCO performance will drive electrification and hybridization degrees
- Highest potential in drive cycles with stop / start and acceleration / deceleration events, combined with predictive cruise control
- Hence, for long-haul HD applications business potential seems to be not as large as for regional-haul vehicles

Key advantages

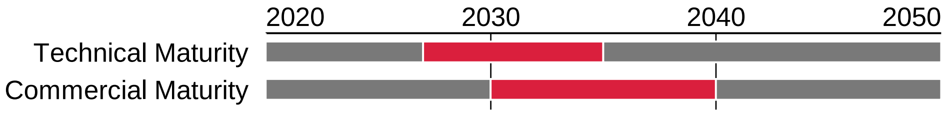
- Reduces overall fuel consumption through the optimization of ICE operation strategy in transient phases
- Combined with predictive driving, further fuel economy potentials can be leveraged (e.g. sailing function with engine off)

Key challenges

- Additional costs in comparison to pure ICE vehicle / 48 V system
- High voltage on-board with increased safety requirements
- Additional integration effort

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	2-8%
Relevance for long-haul	Medium
Relevance for regional-haul	High



Cross impacts and further comments

- Full potential of technology is highly related to other functions on the vehicle (such as predictive cruise control)
- Such measures increase their potential if implemented together with “Electrified roads” infrastructures

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Battery electric HD trucks are more likely to be adopted for regional-haul applications than for long-haul solutions

FEV CONSULTING

ELECTRIFICATION – BATTERY ELECTRIC TRUCK (GENERATION 1)

2030/40

Characteristics

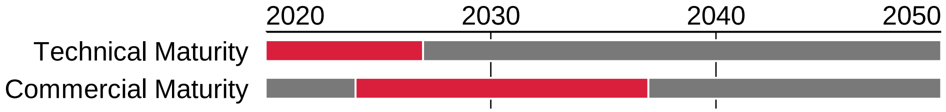
- Fully electric trucks for specific applications:
  - For long-haul HD applications business potential is limited (clear TCO based decision process – challenges in terms of battery weight / package / costs and energy capacity)
  - Regional-haul applications are more interesting due to city (area) entrances (also here: limited relevance assuming outer city logistic hubs)
- Until today, prototypes from leading CV manufacturers clearly indicate the usage as "urban" HD or MD mobility concepts (e.g. Daimler Urban eTruck)

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	100%
Relevance for long-haul	Low
Relevance for regional-haul	Medium

2

1



Key advantages

- No tank-to-wheel emissions
- Strong reduction of acoustic pollution during inner city rides

Key challenges

- Battery's packaging, weight, costs and charging time as well as usable lifespan
- Planned operations have to consider the battery status, infrastructural boundaries and the way of operating the vehicle
- Limited usage under extreme conditions (e.g. cold regions)
- Higher costs than ICE vehicle (dependent on system specs.)

Cross impacts and further comments

- Such measures increase their potential if implemented together with "Electrified roads" infrastructures
- The way the energy provided to the truck is generated, strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Hydrogen powered commercial vehicles have no pollutant and carbon emissions; today, infrastructure barely exists and product is expensive

2030/40

ELECTRIFICATION – FUEL CELL ELECTRIC TRUCK (GENERATION 1)

Characteristics

- In general, 2 concepts exist:
  - Small battery and large fuel cell (~300 kW)
  - Larger battery and smaller fuel cell (~200 kW)
- Trucks using hydrogen stored in a pressurized tank (~70MPa) and equipped with a fuel cell for on-board power generation
- Fuel cell powertrains recuperate braking energy and store it in the battery, which also reduces peak demand from the fuel cell during acceleration and enables optimization of operational efficiency
- Currently, several fuel cell trucks are announced (e.g. Hyundai in Switzerland) or already in usage (e.g. in US harbors, unit production)

Key advantages

- No tailpipe pollutant emissions
- Potential for zero well-to-wheel carbon emissions if hydrogen is produced from renewable power
- Smaller battery compared to battery electric vehicles
- Higher energy density in storage compared to battery electric vehicles

Key challenges

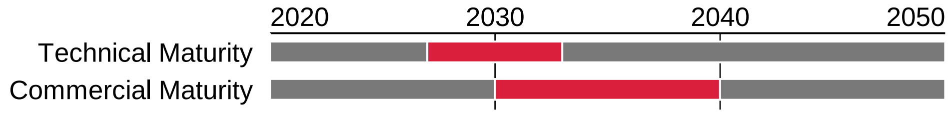
- Expensive refueling infrastructure
- Expensive vehicles due to low economies of scale and expensive materials, e.g. platinum
- Hydrogen production still (mostly) based on fossil methane
- Sustainable production route via electrolysis of renewable power is expensive

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	100%
Relevance for long-haul	Low
Relevance for regional-haul	Low

2

1



Cross impacts and further comments

- The way hydrogen is produced strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint
- Fuel cell powertrains benefit from technological advancement in both fuel cell and battery storage technologies

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Real benefits for HD applications come from recuperation in hilly areas, predictive drive systems and electrification of accessories

FEV CONSULTING

ELECTRIFICATION – POWERTRAIN ELECTRIFICATION (STEP 3)

2040/50

Characteristics

- Implementation of highly efficient hybrid powertrains on 800 V
- Functionalities identical to above mentioned points (powertrain electrification step 2) such as ICE operating point shift or recuperation
- Highest potential in drive cycles with stop / start and acceleration / deceleration events, combined with predictive cruise control
- Hence, for long-haul HD applications business potential seems to be not as large as for regional-haul vehicles
- In scenarios characterized by a major adoption of electrified road systems, a higher hybridization level will be introduced on trucks:
  - Electric engine covering all highway working conditions
  - Battery allowing full electric drive on small distances (e.g. between two main electrified roads)

Key advantages

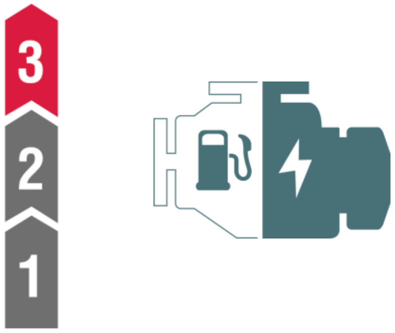
- Further reduction of overall fuel consumption through improved 800 V hybrid system

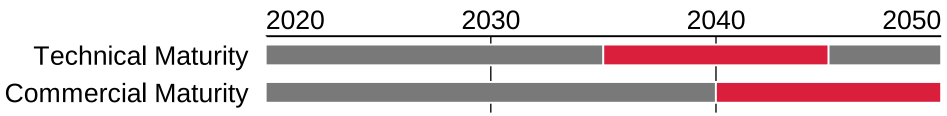
Key challenges

- Additional costs in comparison to pure ICE vehicle / previous hybrid versions (hence commercial attractiveness starting in 2040 timeframe)
- Additional R&D / integration / safety efforts

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	3-10%
Relevance for long-haul	High
Relevance for regional-haul	High





Cross impacts and further comments

- Full potential of technology is highly related to other functions on the vehicle (such as predictive cruise control)
- Such measures increase their potential if implemented together with electrified roads infrastructures

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Second generation of battery electric HD trucks will come with increased driving ranges at lower production costs

2040/50

ELECTRIFICATION – BATTERY ELECTRIC TRUCK (GENERATION 2)

Characteristics

- Fully electric trucks for specific applications:
  - For long-haul HD applications business potential is limited (clear TCO based decision process – challenges in terms of battery weight / package / costs and energy capacity)
  - Regional-haul applications are more interesting due to city (area) entrances (also here: limited relevance assuming outer city logistic hubs)
- In the 2040 timeframe, battery technology will have evolved significantly, increasing the "operational domain" of electrified trucks of gen. 2, e.g.:
  - Increased driving range due to higher energy densities
  - Lower weight, reduced package
  - Reduced costs

Key advantages

- No tank-to-wheel emissions
- Strong reduction of acoustic pollution during inner city rides

Key challenges

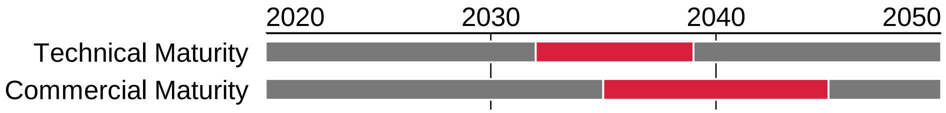
- Battery's packaging, weight, costs and charging time as well as usable lifespan
- Planned operations have to consider the battery status, infrastructural boundaries and the way of operating the vehicle
- Limited usage under extreme conditions (e.g. cold regions)
- (Still) higher costs than ICE vehicle (dependent on system specs.)

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	100%
Relevance for long-haul	Medium
Relevance for regional-haul	High

2

1



Cross impacts and further comments

- Such measures increase their potential if implemented together with "Electrified roads" infrastructures
- The way the energy provided to the truck is generated, strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Second generation of hydrogen powered commercial vehicles are commercially more attractive and come with increased efficiencies

2040/50

ELECTRIFICATION – FUEL CELL ELECTRIC TRUCK (GENERATION 2)

Characteristics

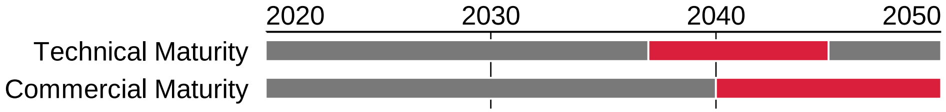
- In general, 2 concepts exist:
  - Small battery and large fuel cell (~300 kW)
  - Larger battery and smaller fuel cell (~200 kW)
- Trucks using hydrogen stored in a pressurized tank (~70MPa) and equipped with a fuel cell for on-board power generation
- Fuel cell powertrains recuperate braking energy and store it in the battery, which also reduces peak demand from the fuel cell during acceleration and enables optimization of operational efficiency
- Currently, several fuel cell trucks are announced (e.g. Nikola in the US market) or already in usage (e.g. in US harbors, unit production)
- In that second generation, fuel cell efficiency is further increased; costs are lowered due to a wider penetration (driven also by passenger car industry)

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	100%
Relevance for long-haul	Medium
Relevance for regional-haul	Medium

2

1



Key advantages

- No tailpipe pollutant emissions
- Potential for zero well-to-wheel carbon emissions if hydrogen is produced from renewable power
- Smaller battery compared to battery electric vehicles
- Higher energy density in storage compared to battery electric vehicles

Key challenges

- Expensive refueling infrastructure
- Expensive vehicles due to low economies of scale and expensive materials, e.g. platinum
- Unsustainable hydrogen production still predominant based on fossil methane
- Sustainable production route via electrolysis of renewable power is expensive

Cross impacts and further comments

- The way hydrogen is produced strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint
- Fuel cell powertrains benefit from technological advancement in both fuel cell and battery storage technologies

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

FEV expects overhead catenary vehicles to be limited to selected freight routes only

FEV CONSULTING

ELECTRIFICATION – CONDUCTIVE ROAD SYSTEMS

2040/50

Characteristics

- Overhead catenary:
  - Energy supply by overhead catenaries on dedicated routes / lanes only
- Charging rails:
  - Energy supply by rails in the asphalt on dedicated routes / lanes to every sort of equipped vehicle (e.g. including passenger cars)
- Current plans indicate an "electrification" of main routes in selected regions
- Main driver is to overcome the disadvantage of limited driving ranges for battery electric vehicles
- Supply trucks have to be connected via pantographs

Key advantages

Compared to diesel vehicle:

- Zero emissions when travelling under an overhead catenary line

Compared to battery electric vehicle:

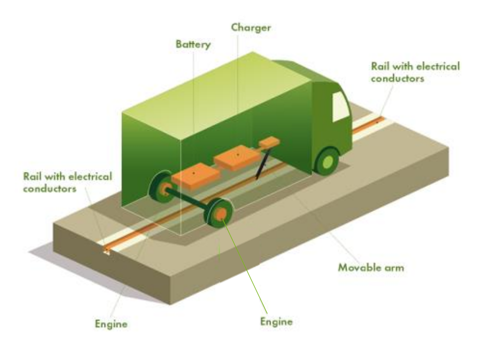
- Enables long-distance driving
- No down-time for recharging
- No energy losses due to on-board energy storage

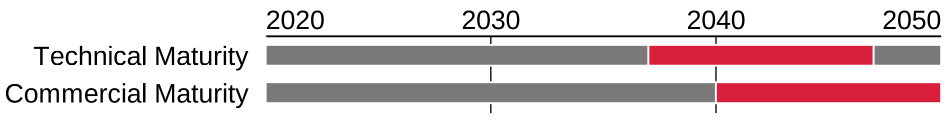
Key challenges

- Infrastructures require high investments
- Coverage of all freight routes with infrastructure unlikely
- Vehicle-to-infrastructure interface necessary or at least helpful
- Requires according space for installation (catenary); interference with other infrastructure to be considered

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	Driver for electric solutions
Relevance for long-haul	Medium
Relevance for regional-haul	Low





Cross impacts and further comments

- The way the energy provided to the truck is generated, strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint
- In contrary to overhead catenaries, charging rails offers further potentials in terms of business case / payback period (passenger cars usage, no limitation to HD trucks only)
- All vehicles using such infrastructures must be Plug-In hybrids (PHEVs), BEVs or FCEVs, as the electric motor should be dimensioned to fulfill all highway's conditions

[1] CO_2 emission reduction potential system-wise (for the entire transport sector)

Source: eRoadArlanda, FEV

Continuous charging on electrified roads offers great potentials but is challenged by significant infrastructural investments

ELECTRIFICATION – INDUCTIVE ROAD SYSTEMS

2040/50

Characteristics

- Energy supply by wireless charging through the road surface via magnetic induction:
  - Power supply station in surface creates magnetic field and induces power flow
  - Energy is transferred to truck by pick-up coil and provides energy to battery and / or engine
- Most solutions rely on fix charging spots
- Potentials are foreseen for regional applications, still major challenges exist (refer to below section)

Key advantages

Compared to diesel vehicle:

- Zero emissions when travelling on an electrified road

Compared to battery electric vehicle:

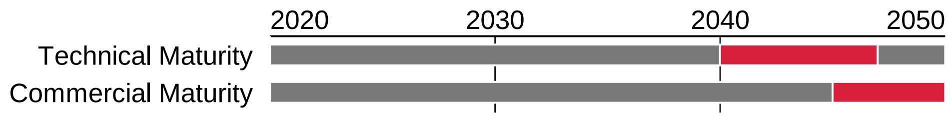
- Enables long-distance driving without use of large battery
- No down-time for recharging
- No energy losses due to on-board energy storage

Key challenges

- Infrastructure requires significant investments
- Coverage of all freight routes unlikely
- Standardized truck to infrastructure interface necessary
- Safety and security requirements of inductive energy flow

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	Driver for electric solutions
Relevance for long-haul	Low
Relevance for regional-haul	Medium



Cross impacts and further comments

- The way the energy provided to the truck is generated, strongly affects the well-to-wheel impact of such measures on the overall CO_2 fleet's footprint
- All vehicles using such infrastructures must be Plug-In hybrids (PHEVs), BEVs or FCEVs, as the electric motor should be dimensioned to fulfill all highway's conditions

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[1] CO_2 emission reduction potential system-wise (for the entire transport sector)

Source: FEV

Demand controlled auxiliaries move away from steady-state operations and help to increase fuel efficiency

EFFICIENCY INCREASE – DEMAND CONTROLLED AUXILIARIES

2020/30

Characteristics

- Depending on specific requirements / load point, demand controlled usage of auxiliaries (often implemented via electric actuators)
- Often, demand (electrified) auxiliaries come with a hybrid powertrain (e.g. combined with a 48 V mild hybrid)
- Variable / Electric pumps:
  - Mechanical decoupling, electric power steering and variable speed and displacement / electric coolant and oil pumps
  - No connection to the belt or chain drive required and thus higher flexibility for positioning
- Electric A/C compressor:
  - No connection to the belt or chain drive required; on-demand operation

Key advantages

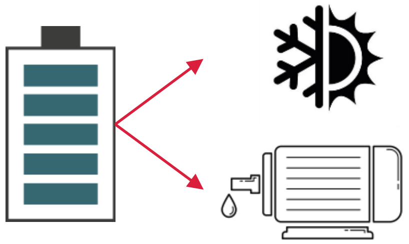
- Efficiency increase due to reduced losses
- Enables demand-based control independent from engine speed
- Electric A/C compressor:
  - Operation independent from engine speed
  - Free positioning

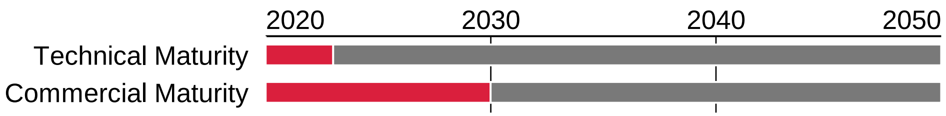
Key challenges

- Increased technology's costs
- (Partly) increased system complexity and weight
- Integration efforts

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	~2%
Relevance for long-haul	High
Relevance for regional-haul	High





Cross impacts and further comments

- Together with the increase of electrification level in trucks, a major adoption of electric auxiliaries is expected

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Reduced vehicle weight does allow higher payloads, hence increases operational efficiency; baseline CO_2 emissions can be reduced

FEV CONSULTING

EFFICIENCY INCREASE – LIGHTWEIGHT MEASURES (STEP 1)

2020/30

Characteristics

- Lightweight in commercial vehicles is mainly driven by freight potentials (increased payloads) and a positive impact on CO_2 emissions
- Also, further vehicle and powertrain measures which increase the weight (hybrid powertrain, additional aerodynamic elements) can be compensated
- Implementation of measures to reduce trucks' weight are (examples):
  - Use of aluminum for cabin's doors, floor, roof and wall
  - Hybrid aluminum-steel cabin body
  - Advanced steel body
  - Introduction of aluminum rims

Key advantages

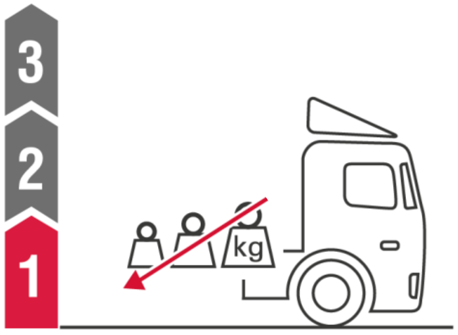
- Potential to increase the payload
- Potential to compensate for weight increase driven by other measures (see above, hybrid, etc.)
- Cabin, body:
  - No corrosion for aluminum
  - High strength steel is very rigid

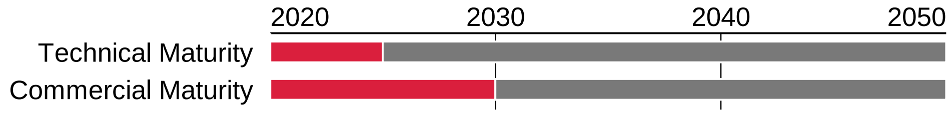
Key challenges

- Increased costs due to extensive usage of aluminum / new materials
- Increased manufacturing complexity (e.g. connections between aluminum and steel)

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	~1%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Cross impacts and further comments

- Changes in material within truck cabin come with high efforts in terms of product validation (safety / durability) for series applications
- Aluminum is less rigid, therefore connected parts and their corresponding stability needs to be checked carefully
- Integration effort, impact on manufacturing and material costs require a clear "benefit" analysis for lightweight measures
- Decision on lightweight measures must follow a "full system" view; different CO_2 measures (aero, weight, powertrain) compete with each other

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Improvement of aerodynamics can lead to benefits; as a first step, small improvements (e.g. additional fairings) are expected

EFFICIENCY INCREASE – AERODYNAMIC MEASURES (STEP 1)

2020/30

Characteristics

- Aerodynamic truck and trailer measurements are key technologies to meet future targets and fuel economy standards
- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~30% of fuel energy is lost in aerodynamic drag
- Implementation of first measures to reduce aerodynamic drag:
  - Cabin and wheel fairings
  - Rear facing cameras instead of side mirrors
  - Active grill shutter
  - Extenders to close the gap between tractor and trailer
  - Cabin's underbody covering
  - Cabin's tapered roof
  - Boat tails plates / extenders

Key advantages

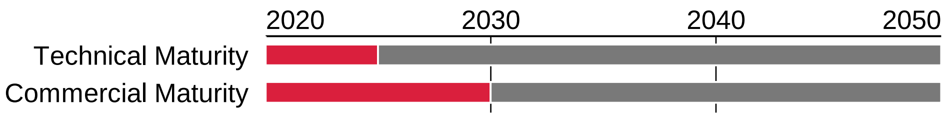
- Step 1 improvements are not investment-heavy (small additional or adapted components)
- Aerodynamic front, fairings and extenders:
  - Rather easy integration into existing tractor
- Active components:
  - Improved thermo-management and cooling with an active grill shutter

Key challenges

- Aerodynamic front, fairings and extenders:
  - Integration in brand design
- Rear facing cameras:
  - Regulation
  - Connection problems to the cameras are a safety risk
- Active components:
  - Durability

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	3-5%
Relevance for long-haul	High
Relevance for regional-haul	Low



Cross impacts and further comments

- Aerodynamic features are more important for long-haul than for vocational vehicles
- Decision on aerodynamic measures must follow a "full system" view; different CO_2 measures (aero, weight, powertrain) compete with each other

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Rolling friction reduction can be achieved with improved axles and tires

EFFICIENCY INCREASE – ROLLING RESISTANCE REDUCTION MEASURES (STEP 1)

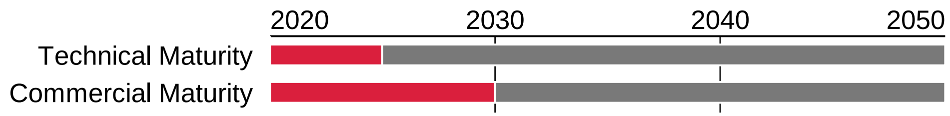
2020/30

Characteristics

- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~15% of fuel energy is lost in rolling friction
- Implementation of first measures to reduce rolling friction are, e.g.:
  - General axle efficiency improvements:
    - Efficiency improvements can be realized, e.g. through bearings, seals, weight and oil management
  - Overall tire improvements (considers shaved dual tires):
    - Includes adaptions to the material, architecture and design of the tires
  - Axle disconnect:
    - Use of live axle disconnect to change between 6x4 and 6x2

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	2-3%
Relevance for long-haul	Medium
Relevance for regional-haul	Low



Key advantages

- Overall reduction of rolling friction with a positive impact on CO_2
- Axle disconnect:
  - Reduced friction while maintaining performance

Key challenges

- Axle efficiency improvements:
  - R&D of enhanced solutions
  - Cost competitive pricing
- Overall tire improvements:
  - Limited improvement potential at considerable R&D efforts
  - Durability
- Axle disconnect:
  - Complex parts lead to a decrease in reliability

Cross impacts and further comments

- General axle improvements:
  - Fuel efficiency benefit is lower for vocational vehicles
- Overall tire improvements:
  - Slow progress compared to passenger cars due to low market volume
- Axle disconnect:
  - Fuel efficiency benefit for vocational vehicles is lower
- Decision on RR measures must follow a “full system” view; different CO_2 measures (aero, weight, powertrain) compete with each other

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Further engine improvements are expected until 2030; key measures are e.g. rightsizing or friction reduction (cranktrain optimization)

EFFICIENCY INCREASE – DIESEL ICE'S INTERNAL EFFICIENCY IMPROVEMENTS (STEP 1)

2020/30

Characteristics

- The brake thermal efficiency of today's heavy-duty engines is around 45%; with highly sophisticated measures, up to 60% are targeted (2040-2050)
- Implementation of first measures to increase ICE's efficiency (examples):
  - Cranktrain optimization:
    - Crankshaft offset (friction reduction)
    - Optimize main and con rod bearing diameter (friction reduction)
    - Reduced main bearing diameter (friction reduction)
  - Rightsizing (combination of downsizing and moderate downspeeding):
    - Enables engine to be customized for the application
    - Example: ~15% downsizing and ~3% or ~50 rpm downspeeding

Key advantages

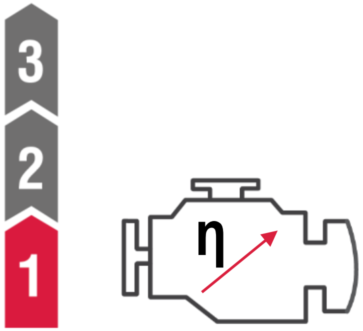
- Cranktrain optimization:
  - Reduced friction with positive impact on brake thermal efficiency
- Rightsizing:
  - Shift of operating points to engine map regimes with lower specific fuel consumption
  - Reduced mechanical friction losses

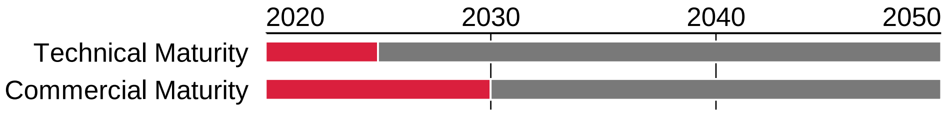
Key challenges

- Rightsizing:
  - Boosting system needs to be adapted
  - Engine hardware limits in mechanics and thermics
  - Possible negative impact on durability

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	4-5%
Relevance for long-haul	High
Relevance for regional-haul	High





Cross impacts and further comments

- Fuel efficiency benefits are realized for all heavy-duty vehicle applications
- Specialized engine oil additives may be required for the high contact pressures with increasing power densities and friction reduction strategies
- Rightsizing:
  - Influence on exhaust and boost system
  - Reinforced engine components to withstand higher mechanical stress
  - Potential negative impact on emissions
  - Higher driveline torque due to lower drive ratios

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

The optimization of the truck's weight will go on and is expected in a second step for the timeframe 2030/2040

2030/40

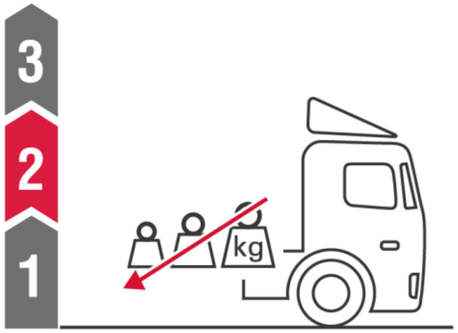
EFFICIENCY INCREASE – LIGHTWEIGHT MEASURES (STEP 2)

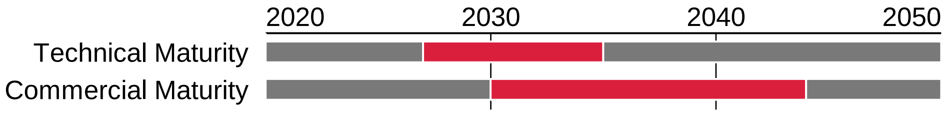
Characteristics

- Lightweight in commercial vehicles is mainly driven by freight potentials (increased payloads) and a positive impact on CO_2 emissions
- Also, further vehicle and powertrain measures which increase the weight (hybrid powertrain, additional aerodynamic elements) can be compensated
- Implementation of further measures to reduce trucks' weight (examples):
  - Advanced materials (e.g. magnesium, carbon) / 3D printed cabin parts
  - Advanced materials and monocoque frame for chassis
  - Advanced materials for efficient and light load body design
  - Steer-by-wire (for certain applications)
  - Brake-by-wire (for certain applications)
  - Glass Fiber Reinforced Plastics (GFRP) for suspensions and wheels

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	~2%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Key advantages

- Potential to increase the payload
- Potential to compensate for weight increase driven by other measures (see above, hybrid, etc.)

Key challenges

- Increased costs due to extensive usage of new materials
- Increased manufacturing complexity for advanced materials; comes with required investments into new production facilities

Cross impacts and further comments

- Changes in material within truck cabin come with high efforts in terms of product validation (safety / durability) for series applications
- Integration effort, impact on manufacturing and material costs require a clear "benefit" analysis for lightweight measures
- All "-by-wire" systems (e.g. brake-by-wire) require legal changes (not clearly discussed / foreseen as of today)
- Decision on lightweight measures must follow a "full system" view; different CO_2 measures (aero, weight, powertrain) compete with each other

---

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Also on the aerodynamic side a second step of improvements is foreseen, including (partly) new cabin designs

EFFICIENCY INCREASE – AERODYNAMIC MEASURES (STEP 2)

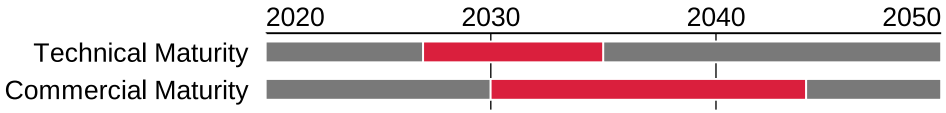
2030/40

Characteristics

- Aerodynamic truck and trailer measurements are key technologies to meet future targets and fuel economy standards
- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~30% of fuel energy are roughly lost in aerodynamic drag
- Implementation of further measures to reduce aerodynamic drag:
  - Cabin redesign (new body-in-white)
  - Adaptable ride height
  - Advanced aerodynamic sensing
  - Backward raked windshield
  - Teardrop shaped roof for load body / trailer
  - Active elements for load body / trailer
  - Underbody covering for load body / trailer

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	6-10%
Relevance for long-haul	High
Relevance for regional-haul	Low



Key advantages

- Significant CO_2 reduction potential in case of a new cabin design
- New cabin:
  - Potential for further alignment between markets
- Active chassis:
  - Adaption of the ground clearance to the driving situation at hand

Key challenges

- New cabin design:
  - High R&D cost, ~ € 500 million to € 1 billion
  - Combining aerodynamic design with brand identity
- Active chassis:
  - Durability and robustness

Cross impacts and further comments

- Aerodynamic features are more important for long-haul than for vocational vehicles
- Active chassis:
  - Interaction with active components, active bumpers and grill shutter in contest with active chassis
- Decision on aerodynamic measures must follow a “full system” view; different CO_2 measures (aero, weight, powertrain) compete with each other

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Further measures to reduce the rolling resistances are expected for the timeframe 2030/2040

EFFICIENCY INCREASE – ROLLING RESISTANCE REDUCTION MEASURES (STEP 2)

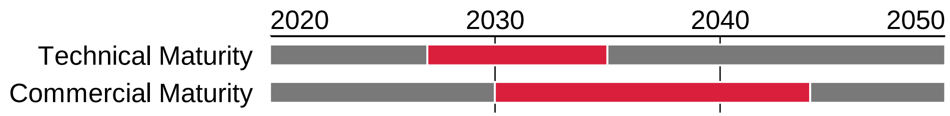
2030/40

Characteristics

- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~15% of fuel energy is lost in rolling friction
- Implementation of further measures to reduce rolling friction:
  - Improved tire pressure control system (sensor based)
  - Automated tire inflation system

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	3-4%
Relevance for long-haul	Medium
Relevance for regional-haul	Low



Key advantages

- Improved tire pressure control system (sensor based)
  - Sensor based solutions leads to more precise assessment of tire pressure
- Automated tire inflation system:
  - Reduced tire pressure loss
  - Reduced tire tear and wear

Key challenges

- Automated tire inflation system:
  - Durability concerns

Cross impacts and further comments

- Automated tire inflation system:
  - Possibly additional weight
  - Fuel efficiency improvement for vocational vehicles lower
- Decision on RR measures must follow a “full system” view; different CO_2 measures (aero, weight, powertrain) compete with each other

---

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Alternative combustion processes as Miller cycle help to reduce the fuel consumption and pollutant emissions in part load

EFFICIENCY INCREASE – DIESEL ICE’S INTERNAL EFFICIENCY IMPROVEMENTS (STEP 2)

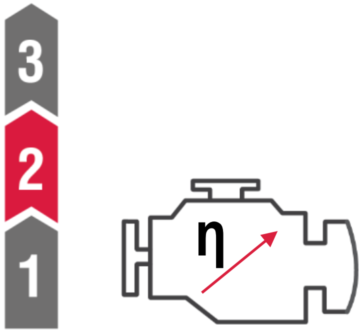
2030/40

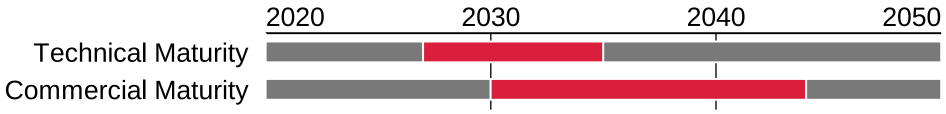
Characteristics

- The brake thermal efficiency of today’s heavy-duty engines is around 45%; with highly sophisticated measures, up to 60% are targeted (2040-2050)
- Implementation of further measures to increase ICE’s internal efficiency:
  - Increased PFP (up to 250 bar) and injection pressure (~3000 bar)
  - Miller cycle:
    - Intake valve closes before the piston reaches its bottom dead center thus lowering the effective compression ratio (CR) and allowing higher geometrical CR, thus higher thermodynamic efficiency
    - Requires a valve train variability and increased boost level
  - Further technologies (e.g. combustion rate shaping, variable compression ratio in niche applications)

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	6-8%
Relevance for long-haul	High
Relevance for regional-haul	High





Key advantages

- Increased peak firing pressures:
  - Potential for higher power output at constant displ.
  - Reduced exhaust enthalpy
- Increased injection pressure:
  - Potential for improved emissions with better thermal efficiency
- Miller cycle:
  - Increase of the thermal efficiency in part load

Key challenges

- Increased peak firing pressure:
  - Adaption of conrod, piston, bearings, liner, cylinder head and gaskets
  - Higher friction
- Increased injection pressure:
  - Minimal leakage to be ensured
- Miller cycle:
  - Increased boost level for constant load required

Cross impacts and further comments

- Specialized engine oil additives may be required for the high contact pressures with increasing power densities and friction reduction strategies
- Increased peak firing pressure:
  - Fuel efficiency benefits are lower for vocational vehicles
- Increased injection pressure:
  - First OEMs already apply 2,700 bar fuel injection pressure
- Miller cycle:
  - Alternative to variable compression ratio and also combination possible

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Turbocompound, organic Rankine cycle and thermoelectric generators recover waste heat and thus mitigate the vehicles demand for energy

EFFICIENCY INCREASE – WASTE HEAT RECOVERY SYSTEM

2030/40

Characteristics

- Turbocompound:
  - Waste energy recovered from exhaust through secondary turbine connected to crankshaft with fluid coupling and clutch
  - Alternative concepts: turbogenerator and electric turbocharger
- Organic rankine cycle:
  - Heat energy from tailpipe exhaust and/or exhaust gas recirculation used to evaporate and superheat a working fluid in a closed circuit which is expanded to generate mechanical power
- Thermoelectric generator:
  - Utilizes the Seebeck effect to generate electricity by using the heat flow from the hot exhaust side to the cold intake side

Key advantages

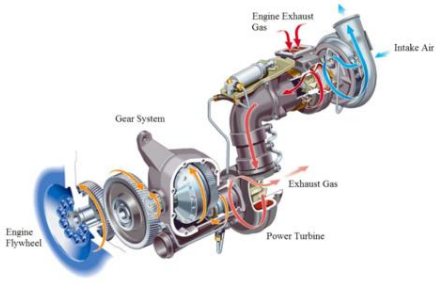
- Significant fuel economy benefits possible (depending on cycle)
- Turbocompound:
  - Higher maturity
  - Less complex system
  - Can be used to drive EGR
- Organic Rankine cycle and thermoelectric generator:
  - Usage of excess heat to generate electric power
  - Increases fuel efficiency

Key challenges

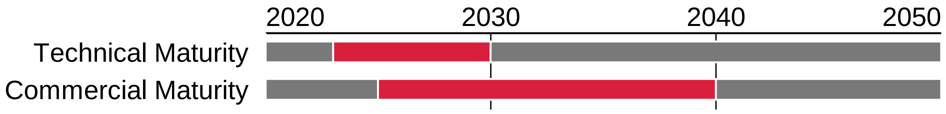
- High technology costs
- Turbocompound:
  - Lower temperature in aftertreatment system
- Organic rankine cycle:
  - Low maturity
  - Complex system and transient control
- Thermoelectric generator:
  - Very low maturity
  - Limited efficiency

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	1-5%
Relevance for long-haul	High
Relevance for regional-haul	Medium



Turbocompound



Cross impacts and further comments

- Organic Rankine Cycle:
  - Highly transient operation quite challenging
- Turbocompound:
  - Electric turbocharger can be used for both performance boost as well as waste heat recovery
- Highly-linked to the exhaust aftertreatment system
- Thermoelectric generator is expected to be adopted post 2030, together with an improved ORC (2nd generation)

[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

In the far future, further lightweight potentials will be achieved – in line with new cabin design (e.g. driverless truck cabin)

EFFICIENCY INCREASE – LIGHTWEIGHT MEASURES (STEP 3)

2040/50

Characteristics

- Lightweight in commercial vehicles is mainly driven by freight potentials (increased payloads) and a positive impact on CO_2 emissions
- Also, further vehicle and powertrain measures which increase the weight (hybrid powertrain, additional aerodynamic elements) can be compensated
- FEV expects the implementation of advanced measures to further reduce the trucks' weight through a wide use of innovative materials and designs
- Due to strong changes in cabin design, pushed by the introduction of driverless trucks, lightweight efforts will also be focused on other parts

Key advantages

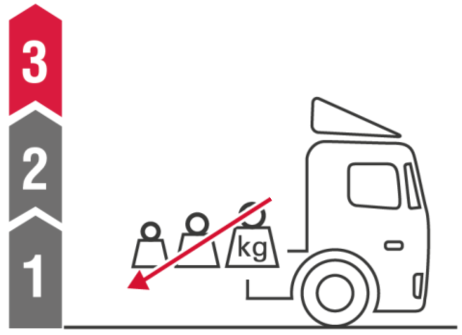
- Further reduction of CO_2 emissions due to another step of improved / lighter materials and an entirely new cabin design

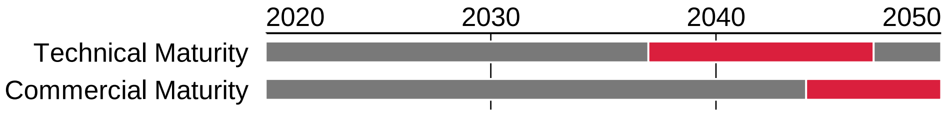
Key challenges

- Additional costs and implementation efforts are foreseen

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	~3%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Cross impacts and further comments

- Not yet assessable

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

By 2050, the truck will look totally different (e.g. driverless cabin) which will lead to another leap in terms aerodynamic drag reduction potential

EFFICIENCY INCREASE – AERODYNAMIC MEASURES (STEP 3)

2040/50

Characteristics

- Aerodynamic truck and trailer measurements are key technologies to meet future targets and fuel economy standards
- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~30% of fuel energy are roughly lost in aerodynamic drag
- FEV expects the implementation of advanced measures to further reduce aerodynamic drag; this comes e.g. with the introduction of innovative / new cabin designs (driverless cabin)

Key advantages

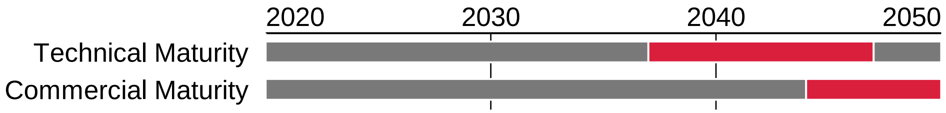
- Further reduction of CO_2 emissions due to another step of improved aerodynamics

Key challenges

- Additional costs and implementation efforts are foreseen

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	9-15%
Relevance for long-haul	High
Relevance for regional-haul	Low



Cross impacts and further comments

- Not yet assessable

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

In 2050, the reduction of rolling resistances is still foreseen to be considered within the area of axles and tires

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EFFICIENCY INCREASE – ROLLING RESISTANCE REDUCTION MEASURES (STEP 3)

2040/50

Characteristics

- In a steady-state operation point of a heavy-duty commercial vehicle on the highway, ~15% of fuel energy are roughly lost in rolling friction
- FEV expects the implementation of advanced measures to further reduce rolling resistances through wide use of innovative tires, low resistance bearings and new axle designs

Key advantages

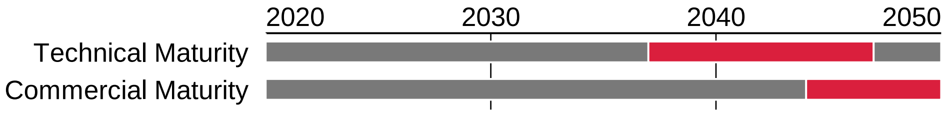
- Further reduction of CO_2 emissions due to lowered rolling resistances

Key challenges

- Additional costs and implementation efforts are foreseen

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	4-5%
Relevance for long-haul	Medium
Relevance for regional-haul	Low



Cross impacts and further comments

- Not yet assessable

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

FEV expects future ICEs to reach a brake thermal efficiency of nearly 60% (close to the theoretical maximum of the reference process)

EFFICIENCY INCREASE – DIESEL ICE'S INTERNAL EFFICIENCY IMPROVEMENTS (STEP 3)

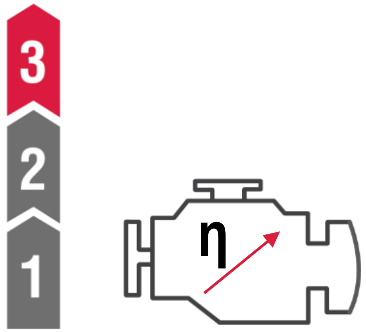
2040/50

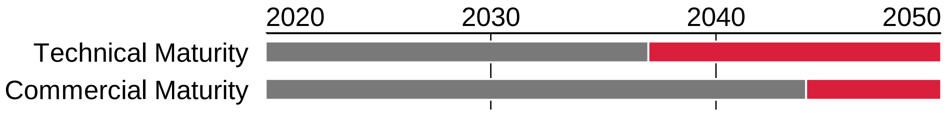
Characteristics

- The brake thermal efficiency of today's heavy-duty engines is around 45%; with highly sophisticated measures, up to 60% are targeted (2040-2050)
- 60% BTE is close to the theoretical maximum of the reference Seiliger process (depending on peak pressures and compression ratios)
- Considered future engine can't be specified in terms of expected technologies, only thermodynamic and combustion relevant boundaries are defined
- Also, alternative engine's concepts are in discussion for 2040+:
  - Opposed piston engine: two pistons move opposed to each other in a cylinder, within a two-stroke process (no cylinder head, no valve train)
  - Split cycle: separation of compression and expansion stroke into different cylinders

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	7-9%
Relevance for long-haul	High
Relevance for regional-haul	High





Key advantages

- Further reduction of CO_2 due to increased BTE in best-point operations
- Opposed piston engine:
  - Fewer heat losses
  - No complex cylinder head
  - Less weight
- Split cycle:
  - Reduced parasitic work
  - More energy from one cycle compared to a diesel cycle

Key challenges

- Increase of ICE's efficiency is linked to significant R&D efforts and costs – in an (increasingly) un-proportional way
- Opposed piston engine:
  - Higher emissions
  - Durability issues
  - New manufacturing facilities
- Split cycle:
  - Complex set-up, more parts
  - Packaging problem

Cross impacts and further comments

- Increased efficiencies towards the theoretical maximum of the reference process lead to significant requirements / cross effects (e.g. adaptation of materials, combustion system, boosting system)
- Such efficiency increase reduces the exhaust enthalpy; hence, related systems (e.g. Waste-Heat Recovery) are becoming less relevant
- Alternative engines are still in pre-development (only theoretical values)
- High costs for R&D and new manufacturing facilities need to be afforded in parallel to actual strong electrification trends

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[1] CO_2 emission reduction potential vehicle-wise

Source: FEV

Paraffinic fuels are drop-in capable and can be blended up to 100% while reducing pollutant emissions; production is still expensive

ENERGY CARRIER – PARAFFINIC FUELS

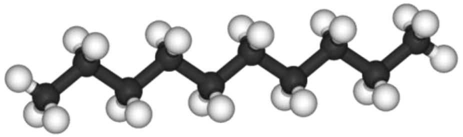
2020/30

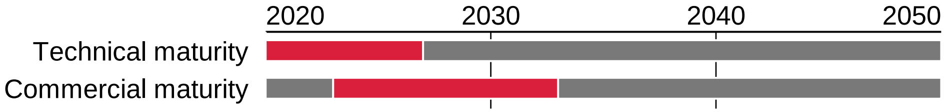
Characteristics

- Paraffinic fuels consist of C-H chains and have no oxygen content
  - Same maximum torque and power as fossil diesel
  - No cold start problems and good oxidation stability
- Produced from several biomass feedstocks and Power-to-Liquid:
  - Biomass feedstocks include vegetable oil, manure, plastics, other waste
  - Production from biomass using hydrotreatment, from Power-to-Liquid includes Fischer-Tropsch synthesis based on CO_2 captured from concentrated or ambient sources
- Standard defined in the EN15940
- Paraffinic fuels are also expected to be used in the aviation sector

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	80-97%
Relevance for long-haul	High
Relevance for regional-haul	High





Key advantages

- Drop-in fuel: blending of up to 100% without adaptions to infrastructure or vehicles
- Pollutant emissions can be reduced: HC, CO and particles; NO_x by re-calibration
- CO_2 emissions can be cut by ~ 5% thanks to a favorable C/H ratio, over EN 590 diesel
- Further CO_2 emission reduction possible with dedicated calibration

Key challenges

- Production to date is significantly more expensive than fossil fuels
- Not compliant with the EN590 due to a lower density
- CO_2 emission reduction from favorable C/H ratio can only be accounted to the OEMs if the regulation allows EN 15940 for certification

Cross impacts and further comments

- Pure usage expected beginning after 2040, blending in the whole timeframe
- Blending with fossil fuel and FAME is an option to increase the content of fuels from renewables, e.g. with a B33 consisting of 7 vol.-% FAME, 26 vol.-% paraffinic fuel and 67% fossil fuel

---

[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

Methanol is considered as a potential fuel in spark and compression ignition engines – limited adaptions of infrastructure and vehicles necessary

ENERGY CARRIER – METHANOL

2030/40

Characteristics

- Methanol is the simplest and shortest alcohol with the structure formula CH_3OH
- Methanol can be used in on-road transport in blends or purely and with a spark ignition, a compression ignition engine and a fuel cell (note: usage in a spark and compression ignition engine considered)
- Methanol blending of up to 20 vol.-% in gasoline does not require changes to the infrastructure and vehicles / powertrains
- Production of methanol from Power-to-Liquid is expected to start in the MENA region and be transported to Europe
- Methanol is expected to be used in the marine sector

Key advantages

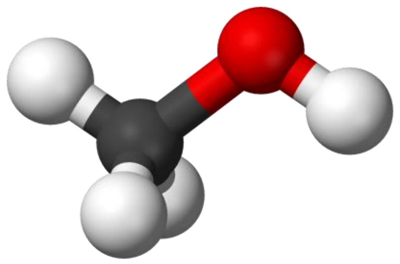
- Limited adaptions to vehicles and infrastructure at >20 vol.-% blend
- Production from Power-to-Liquid is cheaper than paraffins
- Methanol is already produced on a large scale for the chemical industry (45 bn kg per year)
- High thermal efficiency possible
- Bio-degradable
- Trials running, e.g. in China

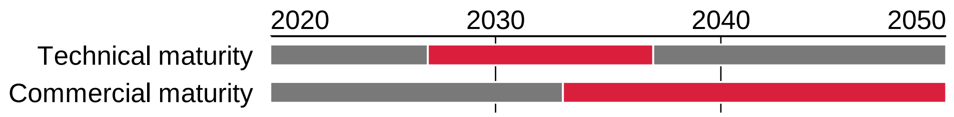
Key challenges

- Rather low energy density
- Development of according fuel standards
- Invisible flame may be an issue since detection of hazardous fire of could be delayed

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	75-97%
Relevance for long-haul	High
Relevance for regional-haul	High





Cross impacts and further comments

- Methanol is expected to be one building block of the future chemical and energy industry

---

[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

Long chain alcohols can be blended at up to 50% without adaptions to vehicles and infrastructure; production is still expensive

ENERGY CARRIER – LONG-CHAIN ALCOHOLS

2040/50

Characteristics

- Long chain alcohols describes the class of alcoholic compounds with chain lengths of seven to twelve, heptanol to dodecanol:
  - Handling up to 50 vol.-% blending is possible without adaptions to powertrains and infrastructure
  - > 50 vol.-% blending a more resistant fuel line and an adapted injection system is required
- Production can be established using fossils, biomass and Power-to-Liquid:
  - Mass production is already established in the chemical industry mostly based on fossil inputs
- Long chain alcohols are expected to be blended with paraffinic and fossil fuels

Key advantages

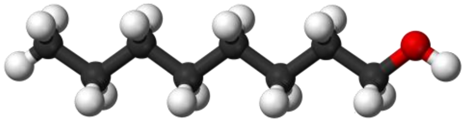
- Combustion efficiency can be increased by using a dedicated engine calibration
- Pollutant emissions can be reduced significantly, especially soot emissions but also CO and HC
- Particulate matter / NO_x trade-off eased, for octanol the trade-off disappears

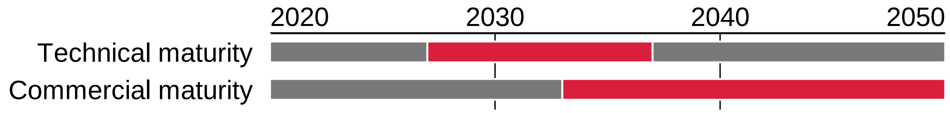
Key challenges

- To date high production costs, both from biomass and Power-to-Liquid:
  - More expensive than paraffins
- Some aspects of the production and usage are still in research phase

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	80-97%
Relevance for long-haul	Medium
Relevance for regional-haul	Medium





Cross impacts and further comments

- Combustion behavior and handling impacts in blends with components other than fossil fuel needs to be examined

[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

Ethanol has the advantage of being available, further supported by stakeholders; production is still expensive

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ENERGY CARRIER – ETHANOL

2040/50

Characteristics

- Ethanol can be used as a fuel in spark and compression ignition engines:
  - In spark ignition engines blends with up to 10 vol.-% ethanol do not require changes in the engine or infrastructure
  - High blend shares, e.g. E85 require updates to engines and infrastructure but already significant experience is available
  - In compression ignition engines, e.g. ED95 can be used with 95 vol.-% of ethanol
- Ethanol can be produced from a wide range of feedstocks, yet production processes are expected to be limited to Biomass-to-Liquid and Power-to-Liquid only in small scale, if any

Key advantages

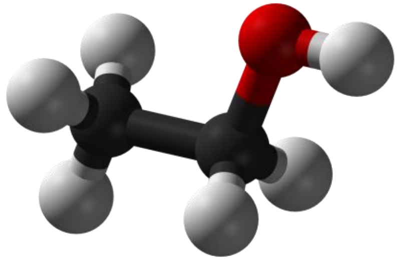
- Ethanol production from renewables is established
- High share of renewables can be introduced
- Support from selected OEM as Scania
- Support from industry stakeholders that produce Ethanol

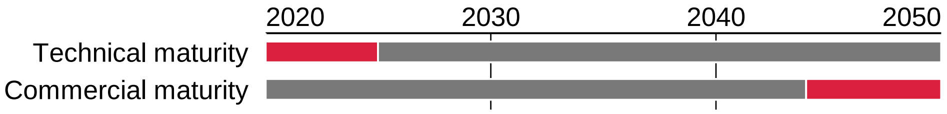
Key challenges

- Production is challenging:
  - Many potential feedstocks do not comply with the RED[2] II
  - Too expensive and limited in volume, if produced from cellulosic feedstock
  - Import from the USA based on corn expected to get more difficult in the future due to increasing domestic demand

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	70-97%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Cross impacts and further comments

- Technical maturity has already been proven for the usage of ethanol in spark ignition engines at all levels of blending up to pure usage
- Technical maturity of ED95 has already been proven in compression ignition engines, e.g. by Scania
- Commercial maturity is expected only in dedicated applications, within the discussed time horizon

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[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018; [2] Renewable Energy Directive

Source: FEV

Hydrogen can reduce CO_2 emissions significantly, especially when produced by electrolysis, yet there is a lack of fueling infrastructure

FEV CONSULTING

ENERGY CARRIER – HYDROGEN

2030/40

Characteristics

- Hydrogen can be used as a fuel in two ways of energy conversion:
  - Combustion engine in first usage
  - Fuel cell expected in the ramp-up of hydrogen, starting at low power applications and then developing towards higher power levels
- Hydrogen is the simplest, smallest and lightest element:
  - Due to these characteristics, there are high requirements for storage and transport systems
- Hydrogen production from steam-methane reforming is state of the art and electrolysis is one option for future production

Key advantages

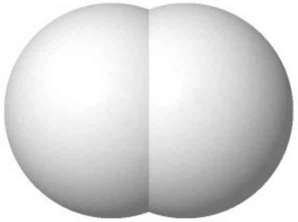
- No CO_2 emissions in a tank-to-wheel balance
- Pollutant emissions are:
  - Zero in a fuel cell application
  - Very low in a combustion engine application with a simple aftertreatment
- Electrolysis enables very low CO_2 emissions in a well-to-wheel balance, at low costs

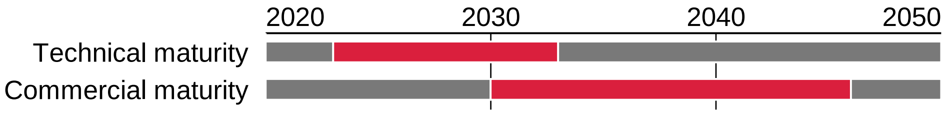
Key challenges

- Lack of fueling infrastructure
- High costs of the fuel cell system
  - Costs scale with the system power
- Pressure level of the fueling infrastructure not harmonized:
  - Busses require 350 bar predominantly
  - Passenger cars require 700 bar predominantly

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	30-97%
Relevance for long-haul	High
Relevance for regional-haul	Medium





Cross impacts and further comments

- The existing methane transport infrastructure can be used to transport hydrogen in blends

[1] For steam methane reforming and electrolysis with power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

Methane combustion can reduce the CO_2 emissions in the tank-to-wheel and with production from renewables also in the well-to-wheel balance

2020/30

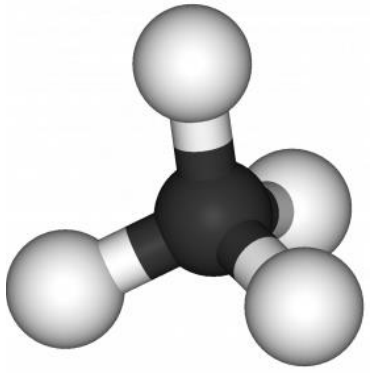
ENERGY CARRIER – METHANE

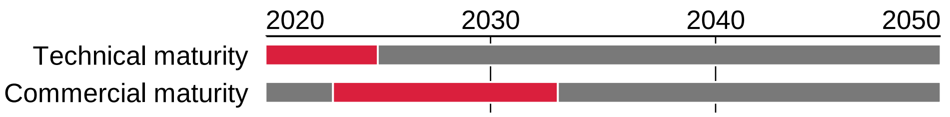
Characteristics

- Methane is the simplest paraffinic fuel with the molecular structure CH_4:
  - Compared to other hydrocarbon fuels, methane has the lowest C-to-H ratio, thus emitting the least carbon per energy content
- Methane can be produced from fossils, biomass and Power-to-Liquid
- Combustion in spark- and compression-ignition engines is possible

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	75-97%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Key advantages

- Production from biomass and Power-to-Liquid enables a high well-to-wheel CO_2 emission reduction
- Tank-to-wheel CO_2 emission reduction of 10-20% can be realized with all feedstocks, including fossil

Key challenges

- Lack of fueling infrastructure
- CNG has a low energy density
- LNG is expensive and needs sophisticated handling
- Expensive storage systems necessary to enable long-haul applications
- Methane slip in the whole value chain needs to be avoided

Cross impacts and further comments

- Commercial maturity is expected only in dedicated applications, until 2030

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[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

DME already has a fuel standard in the USA and is supported by selected OEMs; costs are still high and challenge a wider roll-out

FEV CONSULTING

ENERGY CARRIER – DME

2030/40

Characteristics

- Dimethylether (DME) is the shortest and simplest ether with two methyl groups
- DME can be produced from multiple carbon feedstocks, including coal, natural gas, oil, biomass and air
- Production processes include synthesis based on dehydration of methanol
- Usage of DME in a truck is considered an option in a dual-fuel engine with diesel:
  - Blending of DME and diesel is not considered to have a high market penetration, since all powertrain changes for a pure DME system are necessary, but only part of the CO_2 and pollutant emission reduction can be realized

Key advantages

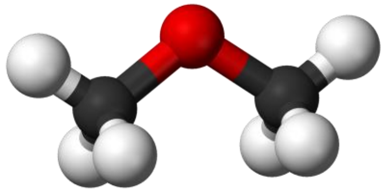
- Fuel standard already realized in the USA
- OEM support, especially from Volvo
- Combustion efficiency can be increased by up to 3%
- Pollutant emissions can be reduced significantly, especially soot and by re-calibration also NO_x

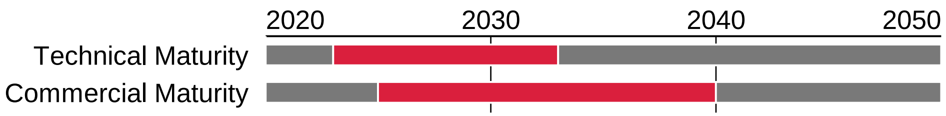
Key challenges

- Production costs are still not competitive
- Additional costs of the second storage and injection system
- Set-up of fuel standards in Europe
- Gaseous at ambient conditions:
  - Fuel pump, tank, injection system and combustion process need to be adapted

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	75-97%
Relevance for long-haul	Low
Relevance for regional-haul	Low





Cross impacts and further comments

- A production with methanol as an intermediate product would have the potential to produce DME and methanol in one synthesis location

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[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV

Electricity is one potential energy carrier also for the heavy-duty on-road transport, yet TCO is disadvantageous in most applications

2030/40

ENERGY CARRIER – ELECTRICITY

Characteristics

- Electricity is considered as an energy carrier if it is supplied from an external source to the vehicle
  - Plug-in vehicles can be both hybrid and battery electric vehicles
- Production of electricity will be considered based on the European mix
  - Development of electricity production processes determines the well-to-wheel savings
  - Increase of electricity production from renewables is required in Europe since the energy sector has a target of net zero greenhouse gas emissions by 2050 in the European Energy Roadmap

Key advantages

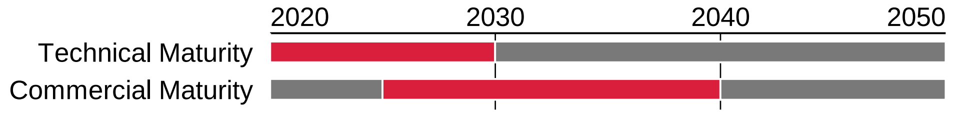
- Lower operating costs
- High energy efficiency from well-to-wheel point of view
- Less maintenance required compared to a diesel powertrain
- Excellent controllability of power conversion leads to synergies when deploying automated driving features

Key challenges

- Disadvantageous in TCO for most applications due to production costs of the battery:
  - TCO advantages only in use-cases with consistent and few kilometers driven between recharging as well as high amount of kilometers driven per day

Impact

	Quantitative assessment
CO_2 emissions reduction[1]	90-100%
Relevance for long-haul	Medium
Relevance for regional-haul	High



Cross impacts and further comments

- Commercial maturity will only be reached for specific applications:
  - Short and regional haul including the usage of heavy-duty trucks
- For long haul applications commercial maturity is not expected until 2050

[1] For typical biomass materials and power from renewables, assessed in well-to-wheel plus carbon sink balance in 2050 compared to fossil fuel in 2018

Source: FEV