Building a better working world

Strategic support to the Shift2Rail Joint Undertaking | S2R.19.OP.02

LOT 1 Strategy Advice

I.3 Work to support with a cost-benefit analysis the definition of migration paths for the implementation of S2R selected innovations on the European network

Final report

The better the question. The better the answer.
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List of Abbreviations

AB	Advisory Board
AMPI	Areas of Major Potential Improvement
ATO	Automatic Train Operations
CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CCS	Control command and signalling
CO2	Carbon dioxide
CH4	Methane
DEL	Deliverable
DRIMS	Dynamic Railway Information Management System
EY	Ernst & Young
HVAC	Heating, ventilation, air conditioning and cooling
Infra	Infrastructure
IP	Innovation Programme
IRR	Internal rate of return
JU	Joint Undertaking
KPI	Key performance indicator
LCC	Lifecycle Cost
Loco	Locomotive
N2O	Nitrous oxide
NPV	Net Present Value
O&M	Operations and maintenance
OPEX	Operating expenditures
Ops.	Operations
PAX	Passenger
pkm	Passenger-kilometre
R&I	Research & Innovation
RIMMS	Railway Integrated Measuring and Monitoring System
S2R	Shift2Rail
SPD	System platform demonstrators
TD	Technology demonstrators
tkm	Tonne-kilometre
WA	Work Area
WP	Work Package

Executive Summary

This report presents the results of the financial and socio-economic cost-benefit analysis for the deployment of the Shift2Rail JU (S2R) innovations in four illustrative scenario of typical rail segments.

The analysis covers the cost and benefits of four scenarios related to four segments of the rail sector: high speed, metro, regional passenger trains and freight transport.

The goal of this CBA is to assess the financial and societal impact of migration paths of innovations over a 30-year period. Migration paths are developed for each innovation, accounting for potential differences for specific use cases, herein after System Platform Demonstrators (SPDs). These paths determine the simulated implementation order and actual deployment timeframe of each technology innovation.

The **expected impact of the S2R innovations** include important customer services improvements, significant operational and maintenance costs reductions, and lower capital expenditure per passenger or tonne kilometre. These improvements will enable the rail sector to attract a larger demand for transport services and increase its revenue while generating important societal added value.

The results indicate that a **deployment of the S2R technologies is financially sustainable** and moderately profitable (no negative net revenue after the investment period, and positive IRR)[1].

Migration paths are a critical element of the deployment of the innovations. The assumptions taken in modelling the migrations include a rapid deployment of the technological improvements, as soon as they are available. A **sector-wide coordinated and rapid deployment** is essential to produce the expected benefits.

A **financing mechanism would be needed** for the initial years of investments in all cases, as the upfront CAPEX investment is not covered by the additional revenue. The modal shift is enabled by capacity gains, lower prices, and better services. It is projected to lag the investment period by a few years, thereby delaying additional revenue.

The impact of this investment is **expected to have significant spillover**. The socio-economic impact of the modal shift induced by the transformations are greater than the additional net revenue generation. The socio-economic impact is generated through modifying the external footprint of the transport sector (e.g., lower GHG emissions, greater safety, lower congestion levels), or economic value added (consumer and producer surpluses).

A baseline and an impact scenario have been considered for each SPDs based on the results of IMPACT-2 S2R CMF project. These scenarios include a baseline development of the sector over 30 years without the introduction of S2R innovations and considering a moderate progression of road electric vehicles (EV). The baseline (without S2R) is then matched to a scenario with S2R innovations roll-out.

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[1] Except for high speed and freight for which the investment is more profitable as they are projected to capture larger market shares.

IP1	IP2	IP3	IP4	IP5
IP 1 is focused on delivering a new generation of **passenger trains**, lighter and more energy- and cost-efficient, while at the same time providing a comfortable, safe and affordable travel experience for all passengers	IP 2 is focused on deploying **advanced communications systems** and enhancing traffic management (including predictive and adaptive operational control of train movements).	IP3 is focused on enhancing and upgrading the **rail network infrastructure** and optimizing its management and maintenance.	IP4 is focused on improving service quality for **rail users** and making multimodal travel easier. It develops interoperability standards for TSPs, solutions to ease ticket search and purchase, and journey tracking.	IP5 is focused on modernising and digitalising **freight rolling stock**.

Source: https://shift2rail.org/research-development/

Table 1: S2R innovation programmes in this CBA

The technologies developed in the five Innovation Programmes (IPs) are structured around 48 Technology Demonstrators (TDs). The difference between the S2R and noS2R scenarios is the roll out of all S2R innovations which leads to gains in capacity, operating and maintenance cost savings and changes in capital expenditure. The deployment of S2R also induces a transport modal shift, which leads to a higher number of passengers and tkm transported, and therefore higher revenue. Table 2 below shows the number of assets/capital that are used by market players in the set use cases (single representative lines within EU network, and not the entire network), which thus have to be equipped with S2R technologies.

	SPD1	SPD2	SPD3	SPD4		
	High Speed	Regional	Metro	Combined traffic trains	Single Wagon trains	Block trains
PAX trainsets	30	24	32	-	-	-
Locomotives	-	-	-	180	280	250
Wagons				420*18	750*17	560*13
Km of track*	300	70	21,5	600		
Software & processes	*Not a quantity*					

* *This includes all infrastructure along the lines.*

Table 2: Assets to be upgraded as part of S2R deployment in the selected use cases

A deployment timeline is developed for each asset type (fleet, infrastructure, command & control systems, IT solutions and processes). The deployment structure accounts for the market readiness of each technology, their dependency on the availability of other technologies, the total number of assets to migrate, and pace. Multiple versions of the migration paths have been considered by the study team. They were developed in consultation with an advisory board composed of industry stakeholders. The most cost-efficient path (rapid and coordinated migration) is presented in this study.

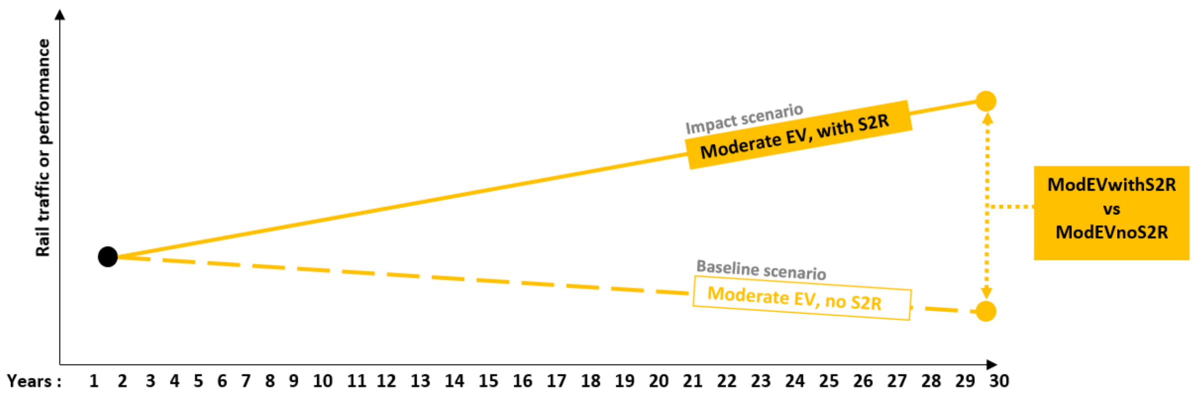


Figure 1: Illustrative example of the baseline and impact scenarios. Rail traffic denotes the number of pkm or tkm per year regardless of SPD.

The migration period is concentrated in the first half of the 30-year timeframe. The associated higher CAPEX leads to a negative cash flow for each market segments in multiple years. These episodes feature the investment cost required to finance the S2R innovations' deployement. The net chashflow turns positive for all segments after the initial investment period.

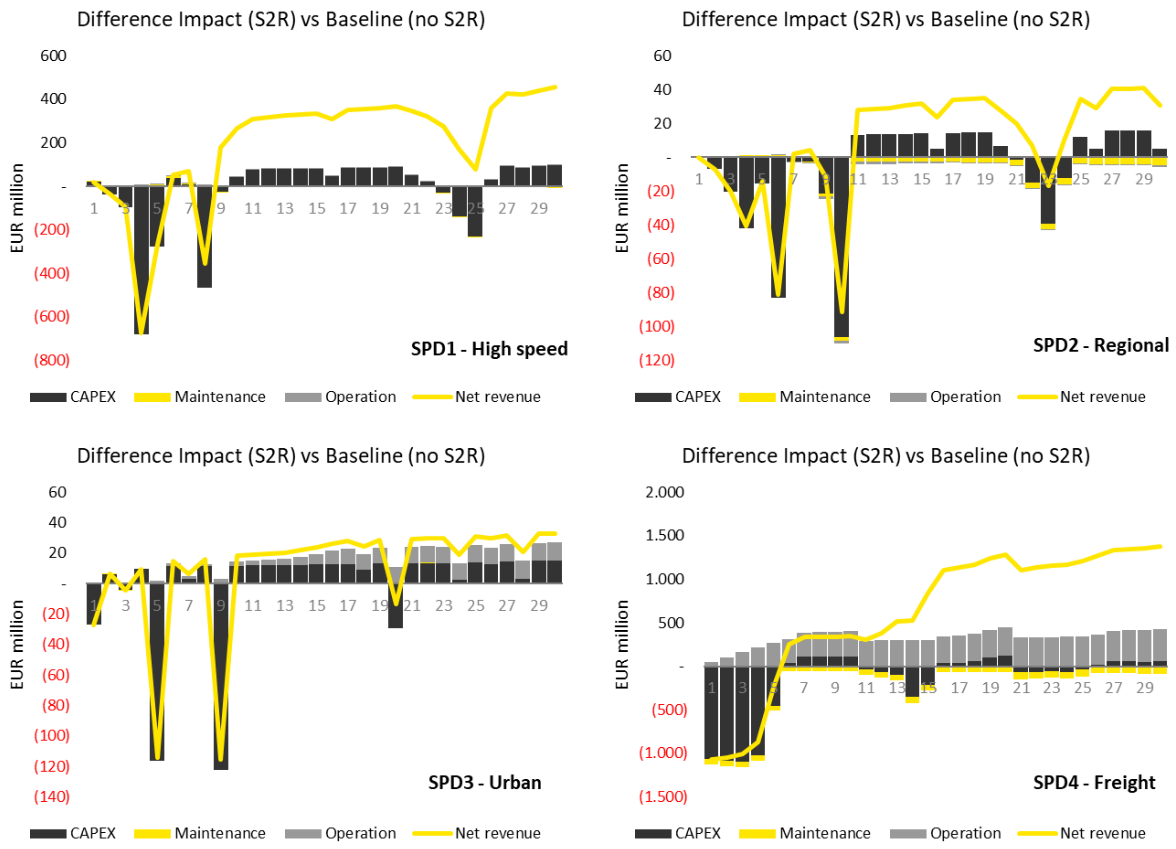


Figure 2: Differences between the baseline and impact scenario – overview

Revenue is projected to be higher in the impact scenario for the four markets, especially for high speed and freight. The net additional revenue (additional revenue minus additional costs), plotted in the charts, shows a significant multi-year drop in the investment period, at the beginning of the 30 years.

Maintenance costs are estimated to increase due to the larger fleet size, except in the urban case. However, the unit cost maintenance will be lower (per train or per line-km). In the passenger fleet (IP1), the relative reduction mostly happens for doors and brakes, and control systems for high-speed trains. New freight locomotives (TD5.1 and TD5.4)[2] are projected to have a higher maintenance cost due to their additional systems, but wagons would be cheaper to maintain (TD5.3). Switch and crossing systems maintenance are improved by TD3.1 and TD3.2, track maintenance is improved by TD3.2 and TD3.3.

Operational costs are reduced for urban and freight (aggregate values – shown as positive values in the cost bar charts). The OPEX per pkm pr tkm are reduced in all segments. These improvements come from the energy consumption (e.g. TD1.1, TD5.3, TD5.4) and labor costs (all TDs related to communication and digitalization).

CAPEX is greater in the impact scenario with a strong increase during the migration at the beginning of the period. The difference narrows down after the migration, with even a moderate negative difference for the regional and urban cases.

Fleet size is projected larger in the impact scenario in all cases, to address the higher demand for transport.

	SPD1	SPD2	SPD3	SPD4
Cumulative additional revenue	3 bln	249 mln	55 mln	7 bln
Investment cost (cumulative CAPEX diff.)	0.77 bln	166 mln	79 mln	4.3 bln
OPEX variation (cum OPEX diff)	+ 0,02 bln (More OPEX)	+ 9 mln (More OPEX)	-88 mln (Less expensive OPEX)	-4.6 bln (Less expensive OPEX)
Maintenance variation (cum maintenance diff.)	- 0,02 bln (Less OPEX)	+ 28 mln (More maintenance)	-1 mln (Less expensive maint.)	+ 1.1 bln (More maintenance)

Table 3: Financial summary, over 30 years (net present value, discounted @ 4%)

The CBA is built on two key metrics: the B/C ratio and the IRR:

- **cost-benefit ratio (B/C):** the total benefits (OPEX savings and/or additional revenue) over the total costs (increased CAPEX and OPEX).
- **internal rate of return (IRR)**: the rate return calculated on the additional cashflow in relation to the investment cost.

Each metric is calculated from real term costs and revenue, i.e., discounted at a 4% rate to obtain the Net Present Value (NPV) equivalent.

[2] See full list and description of TDs in annex.

	High Speed		Regional		Urban		Freight	
	B/C	IRR	B/C	IRR	B/C	IRR	B/C	IRR
Over 30 years	3,90	14%	1,23	6%	1,82	7%	2,18	10,7%
Over 20 years	2,38	12%	0,81	2%	0,67	0%	1,35	7,4%
Over 10 years	0,38	-22%	0,14	na	0,11	na	0,39	-16%

Note: discounted @4%. Some values appear as not applicable (na) when a large portion of the investment is yet to happen after the first 10 years.

Table 4: Main financial CBA results

General comments. The 30-year cost-benefit ratio (B/C) is >1 for all segments, indicating that financial benefits outweigh the costs. It is not the case at the 10-year horizon, when the investment period is often not completed, and the modal shift is not fully achieved and not yet delivering all expected benefits.

High speed analysis. The high-speed segment investment is associated to a strongly positive cost-benefit ratio, with benefits assessed at 3,90 and 2,38 times the costs, over 30 and 20 years respectively. This is mainly driven by a higher level of traffic generating more revenue, and a higher passenger ticket price compared to the baseline. Ticket prices will be reduced in both cases (future scenario with and without S2R impact), but less so in the scenario with S2R impact[3], thanks to the better service quality and customer experience. The net revenue (additional revenue minus all additional costs) from this investment do not stabilise in the positive before year 9 of the migration. The IRR is positive after 20 years (12%) and continues to improve after 30 years (14%).

Regional rail analysis. The network and fleet migration in the regional segment yield a 1.2 benefit to costs ratio across 30 years, with a 6% IRR. Revenue per passenger would decline (lower ticket prices). But higher traffic level should compensate for it. Operational costs and maintenance costs per passenger would decrease significantly.

Urban rail analysis. The deployment of S2R innovations in the urban rail segment would produce a benefit cost ratio of 1.8. The benefits for the urban segment come mostly from operational costs savings. Additional revenue alone is not sufficient to cover the investment costs. The revenue modelling assumption for urban rail is conservative. The cost-benefit ratio is very sensitive to ticket price projections. This is particularly the case for the urban context where small changes to a low unit price is impacting a larger number of tickets (see sensitivity analysis in Annex 4). Following the results of the modal shift evaluation model, this CBA includes a reduction in ticket prices for the urban SPD, which is one of the drivers of the modal shift. Maintaining the ticket price constant in the Impact scenario, with the same modal shift, would bring the B/C ratio from 1.82 to 2.84, and the IRR from 6.7% to 9.7%.

Freight analysis. Freight is projected to secure large market share gains thanks to the deployment of S2R innovations. This modal shift and efficiency gains leads to a 2.2 benefit cost ratio over 30 years, with a 10.7% IRR (1.4 B/C over 20 years, 7% IRR).

To account for diversity of the rail network across the EU and assess its potential impact on the overall results of this study, we apply an adjustment procedure on B/C ratios to consider differences in west south, east, and north Europe.

The adjusted B/C ratios are all lower after the adjustment, except for freight. The reduction is starker for the urban segment (SPD3) as the reduced revenue per passenger (lower ticket prices) is projected on a higher base traffic level than in the unadjusted case and this price

[3] Ticket pricing was retrieved directly from IMPACT-2's *Deliverable 3.3. Modal Shift Evaluation Model*

reduction is not compensated by the modal shift to the extend it is in SPD2. This leads to negative net additional revenue. Note that EU values are also discounted at 4%.

	SPD1		SPD2		SPD3		SPD4	
	EU	SPD	EU	SPD	EU	SPD	EU	SPD
10yrs, disc.	0,40	0,38	0,10	0,14	0,06	0,11	0,33	0,35
20yrs, disc.	2,44	2,38	0,62	0,81	0,33	0,67	1,82	1,41
30yrs, disc.	3,73	3,90	1,06	1,23	0,74	1,82	3,05	2,25

Note: EU: based on indicators adjusted to EU level. SPD: based on the SPD use case definitions in IMPACT1&2.

Table 5: EU level adjustments to cost-benefit ratios

The **societal cost-benefit analysis** of S2R technologies adds onto the financial cost-benefit analysis by providing a monetary valuation of the societal impact of the implementation of S2R technologies. The societal benefits from the S2R investments arise from the modal shift it induces. Traffic shifted to rail, from road or air, generally has a lower externality cost and generates aggregate economic benefits (especially if the transport costs are lower).

Externalities

- **Climate impact** - GHG emissions' savings from the impact of S2R.
- **Air pollution** - Savings in emissions of particulate matter.
- **Noise** - Lower decibels per person (for local communities).
- **Accidents** - Savings on preserved lives and treatment of injuries.
- **Infrastructure wear** - Possible savings on roads and airports which are more prone to wear - lower overall maintenance costs.
- **Congestion savings** - Benefit for the end consumer in terms of mobility level and time savings.
- **Wider Economic Benefits** (Metro only) - the spill-over effects to other markets (e.g. the labour market).

Economic Surpluses

- **Consumer surplus**
  Difference between the maximum amount the customer is estimated to be willing to pay for a trip minus the actual generalized cost for the trip.
- **Producer surplus**
  Difference between total revenue and total costs for the provider of services.

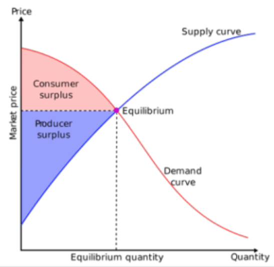


Figure 3: Domains of societal costs and benefits

Aggregate societal benefits are particularly significant for the high speed (SPD1) and the freight (SPD4) segments as they consider a much larger modal shifts' effect. Although lower, societal benefits for SPD2 and 3 are valued higher than the additional financial benefits generated in these segments.

	Benefit/Cost (30yrs, discounted)		Internal rate of return (30yrs)	
	Financial	Financial + Soc Ben	Financial	Financial + Soc Ben
SPD1	3,90	13,02	14,4%	31,6%
SPD2	1,23	4,61	5,8%	22,0%
SPD3	1,82	15,62	6,7%	34,3%
SPD4	2,18	3,14	10,7%	13,5%

Table 6: Cost-Benefit ration and IRR with societal benefits

Externalities represent a considerable benefit for all segments. Avoided greenhouse gas emissions combined with avoided air pollution make for the largest type of positive externality, followed by the added value of avoided accidents when shifting to rail transport. The total value of externalities is directly proportional to the modal shift induced in each segment. With a lower modal shift potential compared to other segments, urban rail is projected with lower environmental gains. However, investing there generates high economic surplus, and it is associated specific type of benefits related to the better connectivity inside metropolitan areas and positive spill overs (e.g., on the job market).

Economic surpluses represent the largest part of societal benefits. High-speed and freight modal shifts generate the highest modal shifts, and therefore the highest economic surpluses. Most of these surpluses come from the consumer side, as efficiency gains are translated to lower service prices. For urban in particular, the economic surplus is significantly larger than the additional financial revenue.

1 Objectives and Background

This Cost-Benefit Analysis (CBA) shows the financial impact of the implementation of the S2R technologies on the Infrastructure Managers (IM) and the Railway Undertakings (RU) in representative market segments. A baseline scenario (business as usual) is compared with an impact scenario (all S2R technologies implemented).

The financial CBA allows insights into:

- The consolidated profitability (general view).
- The financial sustainability.
- The cashflows set out on a timeline.

The CBA objective is to understand the financial and societal impact of migration paths for the S2R innovations. The financial CBA provides an overview of financial indicators, including: the Financial Net Present Value (NPV) the Internal Rate of Return (IRR), the total investment costs and additional revenue (nominal and discounted). The socio-economic CBA includes the valuation of Externalities and Economic surpluses.

The CBA tool created for this study is a flexible tool, allowing the user to analyse the impact of five S2R Innovation Programmes (IPs) for the scenarios designed around the four System Platform Demonstrators (SPDs), as well as modifying the deployment start date and the migration speed. The technologies developed in the five IPs are structured around 48 Technology Demonstrators (TDs), see annex for a list of TDs. The four SPDs are **High Speed**, **Metro**, and **Regional** passenger transport, and **Freight** transport.

IP 1	IP2	IP3	IP4	IP5
IP 1 is focused on delivering a new generation of **passenger trains**, lighter and more energy- and cost-efficient, while at the same time providing a comfortable, safe and affordable travel experience for all passengers	IP 2 is focused on deploying **advanced communications systems** and enhancing traffic management (including predictive and adaptive operational control of train movements).	IP3 is focused on enhancing and upgrading the **rail network infrastructure** and optimizing its management and maintenance.	IP4 is focused on improving service quality for **rail users** and making multimodal travel easier. It develops interoperability standards for TSPs, solutions to ease ticket search and purchase, and journey tracking.	IP5 is focused on modernising and digitalising **freight rolling stock**.

Source: https://shift2rail.org/research-development/

Table 7: S2R innovation programmes in this CBA

The CBA model is built around IMPACT-1 and IMPACT-2 research results. Notably, it relies on the high speed, metro, regional and freight use cases and underlying scenarios developed in previous research activities. Two sets of reports will often be cited in this report:

- **The KPI model.** See IMPACT-2 deliverable D4.3 *Reviewed quantitative KPI model*[4] as well as IMPACT-1 deliverable D3.3 *Use Cases for SPDs*[5]. The KPI model data are used to define the four market segments (fleet size and network characteristics), to infer revenue figures (from payload and frequency indicators) and assess costs.

[4] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-2
[5] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-1

- **The modal shift evaluation model.** See IMPACT-2 deliverable D3.3 Modal shift evaluation model. The modal shift evaluation model is used to infer traffic variations and subsequent revenue changes.

Mode	SPD1 – High speed	SPD2 – Regional	SPD3 – Urban	SPD4 - Freight
Definition	Max. 300 km/h	Max 160 km/h	Max 80 km/h	Max 120 km/h
Network specifications	300 km of track, 30 high speed trains, 45k trips per year	70 km of track, 24 regional trains, 61k trips per year	21.5 km of track, 32 metro, 342k trips per year	600 km of track, three types of traffic (block, combined, and single wagon), 710 locomotives, 1730 wagons, 57k trips per year

Note: See the KPI model documentation for more characteristics of the four use cases.

Table 8: Market segments in this CBA

The CBA model provides a monetary estimate of the savings and revenue increases (benefits) and additional expenditures (costs) of the implementation of the S2R technologies. It is based on a generic 30-years annual cashflow model of fleet and infrastructure management. It considers three main types of costs: capital expenditures maintenance and operation expenditures. Revenue is calculated based on traffic forecasts elaborated in use cases definitions and modal shift analysis. They are obtained by multiplying ticket prices by passenger trips, or tonne-km price by freight volume traffic. Migration paths are developed for each innovation, accounting for potential differences across market segments. These paths determine the implementation order and timeframe of each technology innovation. These paths are translated into the time, costs, and impacts.

The remainder of this report is structured as follows:

- Section 0 outlines the **migration paths of S2R innovations** for each asset type.
- Section 2 summarises the main inputs and the key results of the **financial CBA.**
- Section 3 expands the analysis with the **socio-economic CBA results.**
- Section 4 presents the overall results and provides **conclusions**.

Migration paths

This section presents the migration path for the technology and process innovations whose costs and benefits are assessed in this report. Each innovation is illustrated and described in a Technological Demonstrator (TD), and TDs are grouped in Innovation Programmes (IPs).

1.1 Innovation Programmes overview

A detailed presentation of the IPs is available in *Annex 6: Overview of Innovation Programmes*. This section presents an overview of IPs and summarise dependencies or conditions for TD deployment.

- **IP 1 is focused on delivering a new generation of passenger trains**, lighter and more energy- and cost-efficient, while at the same time providing a comfortable, safe and affordable travel experience for all passengers. It is organised around eight TDs.
- **IP 2 is focused on deploying advanced communications systems and enhancing traffic management** (including predictive and adaptive operational control of train movements). Shift2Rail activities will support the rapid and widespread deployment of advanced traffic management and control systems by providing improved functionalities and standardised interfaces based on common operational concepts, easing migration from legacy systems, lowering overall costs, and adapting them to the needs of different rail segments as well as a multimodal smart mobility system. It is organised around 11 TDs.
- **IP3 is focused on enhancing and upgrading the rail network infrastructure** and optimizing its management and maintenance. It is organised around 11 TDs.
- **IP4 is focused on improving service quality for rail users** and making multimodal travel easier. It develops interoperability standards for TSPS, solutions to ease ticket search and purchase, and journey tracking. It is organised around 6 TDs
- **IP5 is focused on modernising and digitalising freight rolling stock**. It is structured around 5 TDs

Building on an analysis dependency, this subsection presents an overview of the **deployment timeline** selected for each SPD to form the **migration paths** for different asset categories. Table 9 below shows the number of assets/capital that are used by market players in the set use cases (single representative lines within EU network, and not the entire network), which thus have to be equipped with S2R technologies.

	SPD1	SPD2	SPD3	SPD4		
	High Speed	Regional	Metro	Combined traffic trains	Single Wagon trains	Block trains
PAX trains	30	24	32	-	-	-
Locomotives	-	-	-	180	280	250
Wagons				420*18	750*17	560*13
Km of track*	300	70	21,5	600		
Software & processes	*Not a quantity*					

** This includes all infrastructure along the lines.*

Table 9: Assets to be upgraded as part of S2R deployment in the selected use cases

Migration paths are constructed from the combination of the market readiness of the different technologies, the dependencies across technologies, and the number of assets (trains, wagons, track…) to upgrade. The TD **deployment type** might be a linear progression, a ramp-up (convex curve), or a batch deployment at certain time intervals.

The migration path structures are user-defined and can be changed as the tool is used in the future and can therefore reflect the state of the deployment. For the purposes of this study and to allow for a default option, a rapid and coordinated deployment scenario was constructed. This scenario was built based on information obtained from consultation (interviews and emails) with IP representatives on:

- The impact of a TD within an IP on the assets, making a distinction between track and fleet, where fleet was further broken down by passenger train and locomotives and wagons for freight trains;
- The time needed for implementing the relevant TD on the assets;
- The possibility for retrofitting;
- The sequence of the roll-out of the TDs within an IP on a timeline.

A distinction was made for :

- TDs that can be implemented at the same time, but it is not a requirement to achieve the benefits of the relevant TDs and;
- TDs where there is a high interdependency to achieve the relevant benefits

Deployment narrative in IP1. Deploying TDs of IP1 implies retrofitting or purchasing new passenger trains. However, TD3, 4, 6 (car body, running gear, and doors) cannot be retrofitted on existing trains. Retrofitting of the traction system, the control system, or the HVAC in 2022 does not make sense if new train purchases should be scheduled in 2026 to deploy the non-retrofittable technologies. Therefore, we opted for modelling the deployment of IP1 through the purchase of new trains. We also selected a batch deployment approach for the migration of IP1, to emulate the management of a small to medium fleet upgrade. See section 1.2 for the full migration path of passenger trains.

Deployment narrative in IP2. The deployment of IP2 innovations requires the upgrade of the **passenger trains and freight locomotives**: upgrade of onboard command and communication systems for TDs on *Communication System*, *Automatic Train Operation (ATO), Moving Block Train Integrity*, *Virtual Coupling*, *and Cyber Security*. The upgrade of the **infrastructure** is also required for *Communication System*, *Automatic Train Operation (ATO), Moving Block, Safe Train Positioning, and for IP2 TD9: Traffic Management System*, *Smart radio-connected all-in-all wayside objects*, and *Cyber Security*. Finally, freight wagons will be migrated for *Train Integrity*, *Virtual Coupling* and *Cyber Security*.

New processes will also need to be implemented for TD2.6 and 2.7: *New laboratory test framework*, and *Standardised engineering and operational rules*.

Deployment narrative in IP3. The deployment of IP3.3 is influenced entirely by the market readiness level (and investment strategy of relevant stakeholders). Hence, TD3.2 and TD3.4 (new generation tracks and switch & crossing system tracks) are expected to be introduced in 10 years. This will replace the optimized version of tracks and switches & crossing systems (TD3.1 and 3.3). The deployment of TDs 3.9 and 3.11 can start after 2 years and all others can start immediately.

Deployment narrative in IP4. The deployment of all TDs can technically start immediately. However, the benefits of 3 and 4 will be delayed, due to interdependencies, by 5 years. This is due to TDs 4.1,4.2 & 4.5 which will be deployed after 2 years (due to dependency on TD4.6) and take 2 years to finish.

Deployment narrative in IP5. Deploying TDs of IP5 involves retrofitting or purchasing new locomotives and wagons. However, TD5.2 & 5.5 (Digital Transport Management & Business analytics and implementation strategies) cannot be retrofitted on existing trains.

Alternative scenarios assumptions. The most notable mode that is expected to evolve rapidly and undergo a similarly rapid migration is the road transport. The metric used for this evolution is, similarly to the IMPACT-2's Deliverable 3.3, the percentage of electric vehicles in operation. For the alternative scenario therefore, an assumption was retrieved from IMPACT-2's model which consists of 50% of road vehicles being EVs by the end of S2R migration.

The price of new fleet and components. The prices of individual components were taken directly from the KPI Model constructed by the IMPACT-2. The prices are of new components as well as same components but with new features (which then results in two values: baseline price and S2R price of item). How this is translated to CAPEX is depicted in Section 2.4.1.

1.2 Migration path of high-speed, regional, and urban segments

This section combines the TD level information (market readiness, dependencies, and deployment types) to structure the migration path of the fleet, track side and onboard ccs, infrastructure and process & IT solutions of high speed, regional, and urban (SPD1, 2, 3) rail market segments.

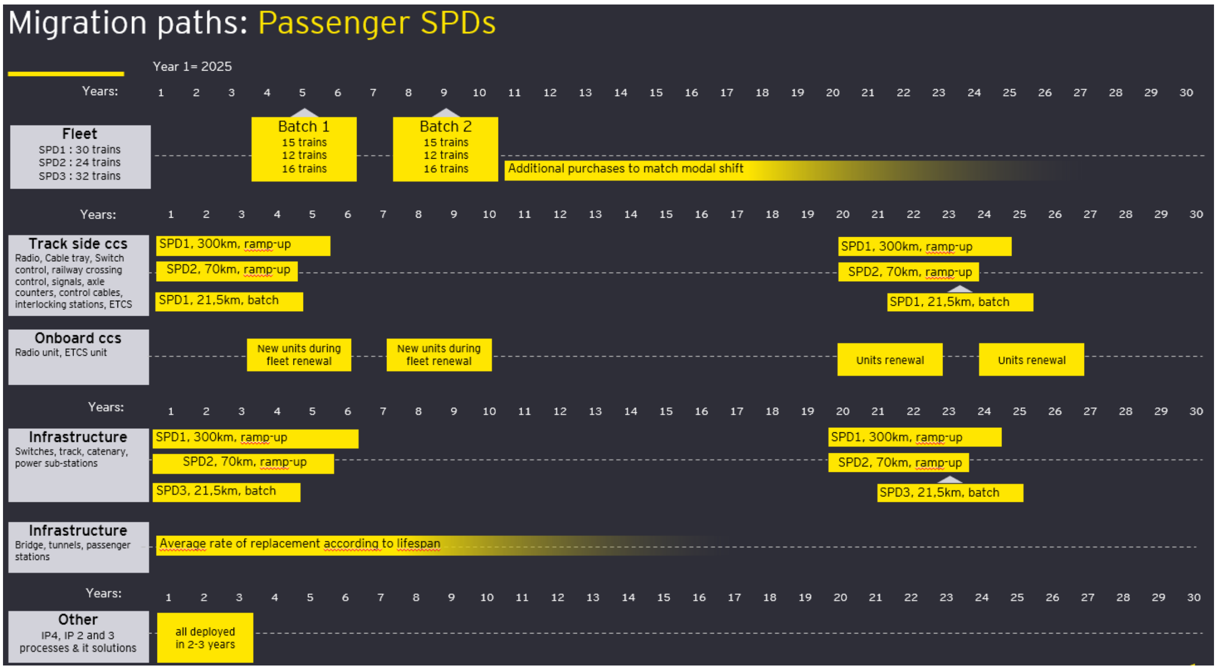


Figure 4: passenger trains migration path

Passenger trains are expected to be impacted by 20 different TDs, from IP1, IP2, and IP3. Most TDs will be available for deployment at the start of the analysis period. A subset of TDs will be made available after 5 to 7 years, especially within IP 1. Given that some of these late TDs cannot be retrofitted, we model the deployment through a purchase plan of new trains, with the first batch scheduled at year 5, and the second one in year 9. 50% of the fleet is upgraded in each batch. TD2.8 is retrofitted or deployed on new CCS units around year 20.

Fleet to migrate:

- SPD1: 30 passenger trains
- SPD2: 24 passenger trains
- SPD3: 32 passenger trains

Network size to migrate:

- SPD1: 300 km of track
- SPD2: 70 km of track

- SPD3: 21,5 km of track
- SPD4: 600 km

Note that while km's of tracks are used as the main unit of deployment, this migration plan also includes assets such as radio towers, bridges, tunnels, switches, and other infrastructure equipment. Their costs are converted in euro per km of track in the model.

Tracks and related infrastructure components will benefit from 21 TDs.

1.3 Migration path of the freight segment

This section combines the TD level information (market readiness, dependencies, and deployment types) to structure the migration path of the fleet, track side and onboard ccs, infrastructure and process & IT solutions of the freight rail segment (SPD4).

Figure 5: freight migration path

Freight locomotives are expected to be impacted by 14 different TDs. Most TDs will be available for deployment at the start of the analysis period. Some TDs will not be commercially available at the start of the analysis period and deployed during the first upgrade wave. This is the case for all TDs apart from TD 2.8 (Virtual Coupling) which is expected to be technologically viable only after 9 years from the start of the analysis period. This corresponds to the end of the EU Rail Joint Undertaking cycle.

Freight wagons are expected to be impacted by 9 different TDs. Similarly, to other asset types, most TDs will be available for deployment at the start of the analysis period.

Assets to migrate:

- 180 combined traffic locomotives
- 280 single loaded wagon traffic locomotives
- 250 block train locomotives
- 600 km of track
- 420 combined traffic wagons
- 750 single load wagons
- 560 block train wagons

2 Financial CBA

The financial part of the CBA provides monetary estimates of the savings and revenue increases (benefits) and additional expenditures (costs) of the implementation of the S2R technologies. It is based on a generic 30-years annual cashflow model of fleet and infrastructure management. It considers three main types of costs: capital expenditures maintenance and operation expenditures. Revenue is calculated based on traffic forecasts elaborated in use cases definitions and modal shift analysis. They are obtained by multiplying ticket prices and passenger traffic, or km-tonne price and freight volume.

This section presents the general input to the CBA, then it documents the projected changes in costs and revenue, then it develops the analysis of the main results. See next chapter for the socio-economic part of the cost-benefit analysis.

2.1 General input

The general input to the CBA calculations includes:

- Market segment definition
- Inflation assumption
- Traffic projections in baseline and impact scenario

The analysis is performed for **four market segments**: high-speed, regional, urban and freight. Each segment is analysed on an illustrative line, with representative parameters and features. The main parameters are as follows:

	SPD1	SPD2	SPD3	SPD4		
	High Speed	Regional	Metro	Combined traffic trains	Single Wagon trains	Block trains
PAX trains	30	24	32	-	-	-
Locomotives	-	-	-	180	280	250
Wagons				420*18	750*17	560*13
Km of track*	300	70	21,5	600		
Software & processes	*Not a quantity*					
Passenger per trip	*326,4*	*92,4*	*630*			
Ton transported per trip				*572*	*432*	*499*

Source: Reviewed quantitative KPI model

Table 10: Types and number of assets to be migrated

See IMPACT-2 deliverable D4.3 *Reviewed quantitative KPI model*[6] as well as IMPACT-1 deliverable D3.3 *Use Cases for SPDs*[7] for a full list of parameters and data points used to structure the high-speed, regional, urban, and freight use cases, their operation and maintenance costs, and their capital expenditure costs.

Price inflation is set at 1,25% annual in both the baseline and impact scenarios.

The **CBA is built around two scenarios**: a baseline scenario (noS2R) and an impact scenario (with S2R). The difference between the S2R and noS2R scenarios is the roll out of all S2R innovations which leads to gains in capacity, operating and maintenance cost savings, changes in capital expenditure. The deployment of S2R also leads to a modal shift, which leads to a higher number of trips (more passengers and tkm transported), and therefore higher revenue. The extend of the modal shift induced by S2R depends on the degree of

[6] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-2
[7] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-1

electrification of road transport, represented here by a Moderate Electric Vehicle progression (ModEV) scenario. The two main assumptions of the moderate EV scenario are a 50% penetration of electric vehicles, and the peak hour average travel cost for EVs is 40% of conventional vehicles. These values were derived from EV forecasting literature.

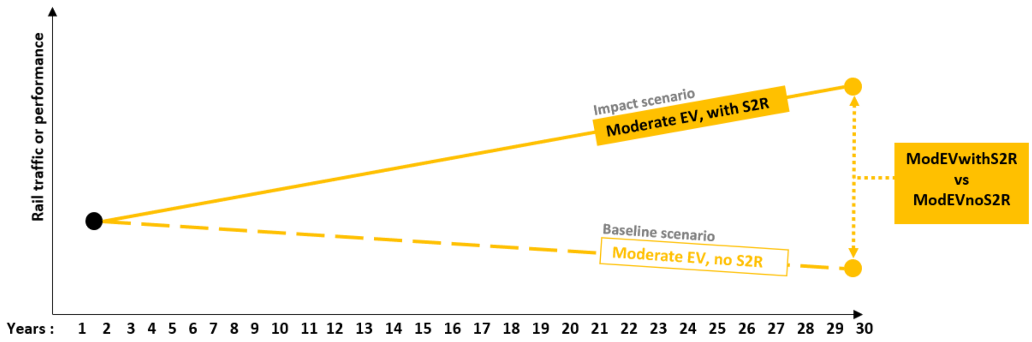


Figure 6: Illustrative example of the baseline and impact scenarios. Rail traffic denotes the number of pkm or tkm per year regardless of SPD.

The analysis is focused on the differences between the impact scenario and the baseline, i.e. ModEVwithS2R vs ModEVnoS2R.

2.2 Scenarios

High speed (SPD1)

Baseline scenario. Initial conditions for the high-speed line are made of 14.7 million passengers per year, transported by a fleet of 30 trains, through 45 thousand trips. In the business-as-usual conditions of the baseline scenario, the number of trips is expected to decline to 43 thousand trips after 30 years, driven down by a demand reduction of 603 thousand annual passengers. Ticket prices are also expected to decline, from 47 euros to 38 euros after 30 years (before inflation).

Impact scenario. Assumptions for the impact scenario include a 29.7% growth of annual trips after 30 years, driven by an additional 3.5 million passengers per year, and served by 9 additional trains in the fleet. Ticket prices also contract, but less so than in the baseline scenario; from 47 to 43 euros (before inflation), thanks to better services and customer experience. The rate of change in ticket prices in all SPDs is tied to the deployment rate according to the constructed migration path. The reduction in prices follows the deployment rate with a user-defined delay period (default is 5 years) to reflect the nominal rigidity of prices. Additionally, a condition is applied for meeting a certain minimum rate of deployment for the price reduction to incur since benefits of a partial deployment within some of the IPs are marginal. E.g., in the IP1, once the migration completion level reaches 50%, only then the reduction in prices is induced (again, delayed by a period of 5 years). Additionally, the ticket projections prices were taken directly from the previous work of IMPACT-2 (Deliverable 3.3) as will be shown further.

Regional (SPD2)

Baseline scenario. The regional baseline counts 5.7 million passengers per year, with a fleet of 24 trains delivering 61 thousand annual trips. The number of trips is expected to drop by a 30% by the end of the period, with a modal share grabbed by road transport and electric vehicles. Ticket prices are assumed to remain constant, at an average of 6.9 euros (before inflation).

Impact scenario. With the deployment of better customer services, and a slight average ticket prices reduction (from 6.9 to 6.3), the number of annual trips is assumed to grow by 30 thousand annual units after 30 years, adding 2 million passengers annually. The fleet size would need to grow by 50%.

Urban (SPD3)

Baseline scenario. The first year of the urban baseline features 215 million passengers transported per year, with a fleet of 24 trains performing a total of 342 thousand trips per year. Under business-as-usual conditions, the number of passengers transported per year is projected to drop by 4 million. And the price which starts at 1,68 would reach 1,69 after 30 years (before inflation).

Impact scenario. The conservative assumption retained for the impact scenario is a 1,7% growth of passengers transported annually, at the end of the period (i.e. 3.5 million more passengers). The ticket prices are projected to decrease from 1,68 from 1,65 euros (before inflation). Only one additional train would be required in the fleet.

Freight (SPD4)

Baseline scenario. The rail freight baseline starts with a 51.4 billion tkm activity level spread across single wagon, block, and combined traffic trains. After 30 years, the baseline scenario assumes an additional 400 million tkm per year. The fleet is made of 710 locomotives, 420 combined traffic wagons, 750 single wagon traffic wagons, and 560 block train wagons. The price per tkm is 0,1112 euros.

Impact scenario. With the deployment of S2R innovations, the activity level is projected at 64.8 billion tkm per year. This additional demand is driven by better services and an assumed 10% price reduction, from 0,1112 euros to 0,1001 euros per tkm (before inflation). The important increase in transport demand would require the fleet to expand with an addition 186 locomotives and 450 wagons.

The technical, performance, and cost assumptions in the baseline and impact scenario of each segment are obtained from the KPI model.

2.3 Projected changes in revenue and costs

2.3.1 Projected changes in revenue

In the CBA model, changes in revenue are driven by:

- Changes in **number of tickets** sold (SPD 1, 2, and 3) or **tkm** (SPD4), which are driven by the increase in attractiveness of service and supported by increase in capacity (of train and tracks). These improvements stem from a higher punctuality and reliability, and payload improvements. This is captured by the modal shift assumptions underpinning each scenario.
- Changes in **ticket prices** (SPD 1, 2, and 3) or **tkm** prices, which are driven by the supply/demand analysis performed in the modal shift model (IMPACT 2 DEL3.3) and reflected in the CBA model. Ticket prices and prices per tkm are gradually adjusted to their post migration equilibrium projection in tandem with the overall migration progress.

Revenue arising from tickets sold and freight charges are a function of the number of passengers and tkm transported, as well as ticket prices and freight transport charges.

Revenue = tickets (pax/trip) X ticket price

Revenue = tkm X tkm price

The increases in passengers and tkm were derived using the parameters of the KPI model[8] (since the remaining of the CBA is built on these parameters). In the IMPACT-2 KPI model there are 4 relevant subsystems (unreliability and capacity subsystems for passenger SPDs and freight respectively). The parameters used in these calculations by IMPACT-2 were based on a thorough literature review. The KPI model also contains projections on the possible improvements in these domains.

Estimation of number of tickets or tkm

Pax trips in baseline scenario = pax trips derived from the KPI model

Pax trip in the S2R scenario = pax trips from the KPI model, adjusted to new modal share

Data on prices

The price changes as a result of S2R were analysed and projected in research performed by IMPACT-2[9]. The ticket prices are projected to decline in all impact scenario (before inflation), as a result of operational savings passed down to consumers. The high-speed segment however preserve a higher price in the impact scenario thanks to improvement in consumer services and experience.

The price movements assumed for each SPD are shown in Table 11.

Prices of tickets or tkm transported		SPD1	SPD2	SPD3	SPD4
Year 1 - Baseline	€/pax or €/tkm	47	6,9	1,68	0,1112
Year 30 - Baseline future -	€/pax or €/tkm	28	6,9	1,69	0,1112
Year 30 - S2R impact scenario	€/pax or €/tkm	43	6,3	1,65	0,1001*

Source: Impact-2 D3.3 Modal Shift evaluation model
Note: (*) 10% assumed price reduction is larger than the IMPACT2 projections.

Table 11 - Price movements projected for each SPD

Estimating additional revenue

The ticket prices shown in Table 11 are used to calculate differences in revenue by multiplying with the number of tickets sold (or tkm).

Revenue is calculated at the aggregate level, for the whole context in each SPD. The changes in prices and in traffic are gradually introduced, according to the overall migration progress. To factor in the gradual implementation of the IPs along their migration paths, we construct an approximate breakdown of IP contributions to the modal shift (see *Annex 1: IP contribution to modal shift*). The relative IP contribution is then multiplied by the index of migration progress achieved within each IP. A lag is introduced between the capital expenditure realisation and the corresponding modal shift, to account for the time it takes for the innovations to be deliver its benefits. This lag is 5 years for passenger trains, and 10 years for freight trains investments. In addition, it should be noted, that net revenue is partly

[8] IMPACT-2 (2021) KPI Model
[9] IMPACT-2 (2021) *Deliverable 3.3 - Modal Shift Evaluation model*

driven by subsidies. Notably, the subsidies will not affect the gross revenue but will rather affect the CAPEX and thus result in a higher net revenue in the model.

Finally, the Infrastructure Manager revenue are calculated by applying Track Access Charge (TAC) on the annual traffic projection.

SPD1	SPD2	SPD3	SPD4		
High Speed	Regional	Metro	Combined traffic trains	Single Wagon trains	Block trains
10,0	2,0	3,5	8,0	7,5	7,0

Table 12: Track Access Charge assumptions (EUR/train-km)

2.3.2 Projected changes in costs

We consider two main types of costs in both scenarios: capital expenditures, maintenance costs, and operational costs. For the four market segments, we rely in the detailed cost structure laid out in the report on "Subsystem structure and sublevel KPIs" (Deliverable D4.2 of IMPACT-1)[10]. The main cost sections are as follows:

Capital Expenditure (CAPEX)

- ***Fleet CAPEX.*** Train and wagons costs.
- ***CCS CAPEX.*** radio, cable tray, switch controls, crossing controls, signals, axle counters control cable, interlocking stations, ETCs (onboard and landside units).
- ***Infrastructure CAPEX.*** Switches, tracks, catenary, power substations, bridges, tunnels, passenger stations.

Operation Expenditure (OPEX)

- **Operational costs.** Cost of operating the fleet (labour, energy, track access charges).
- ***Maintenance costs.*** Cost of maintaining the network infrastructure and the fleet. These typically include labour costs, material for repairs, fuel, energy.

Cost modelling assumptions

In the baseline scenario, annual capital expenditure is modelled based on the average asset renewal rate, according to their lifespan (e.g., with a 30 years lifespan the annual fleet CAPEX is 1/30th of the CAPEX of the whole fleet). In the impact scenario, the CAPEX is accelerated at the beginning of the period, to deploy the S2R innovations. This assumption is not used for yard CAPEX in the freight segment, for which the spending rate is kept at the same pace in both scenario (i.e gradual yard upgrades). S2R technologies have an impact on the cost of new assets (e.g., new trains, new ETS units, new switches). The CBA uses the cost data reported in the life cycle calculations of the KPI model.

The resulting CAPEX evolution in the impact scenario is illustrated in Figure 7.

[10] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-1

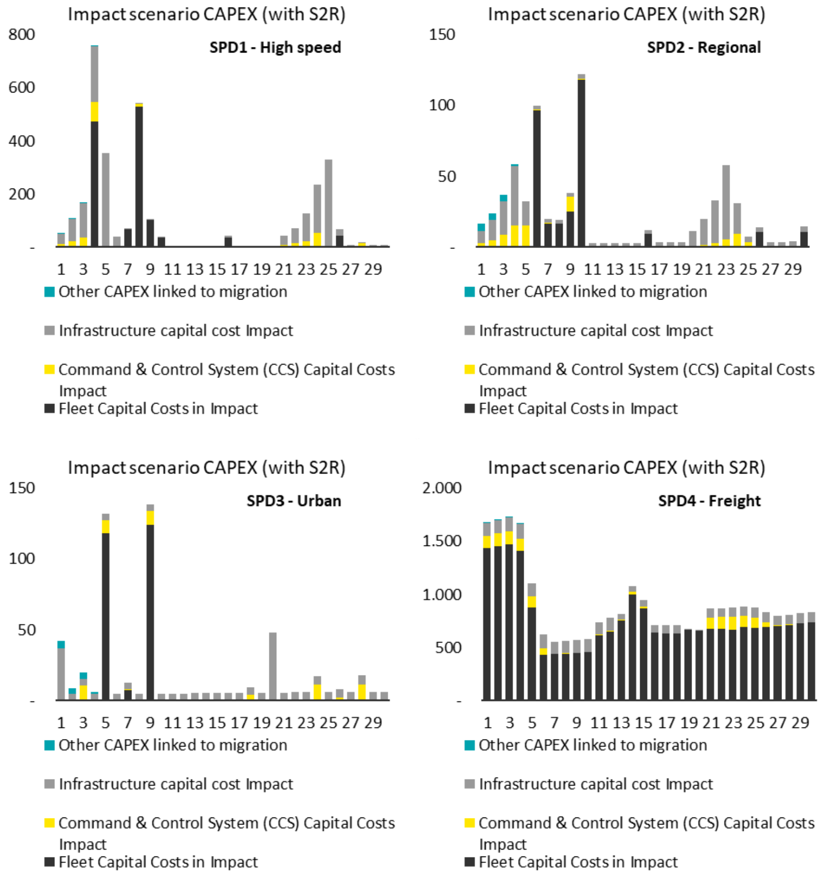


Figure 7: CAPEX cost modeling in impact scenarios (EUR million)

2.4 Financial analysis

This section presents the financial CBA results. After an overview of the differences between the baseline and S2R scenario, key metrics and headline results are presented. Then an analysis of the results is outlined with policy implications.

2.4.1 Differences between baseline and S2R scenario

The migration period is concentrated in the first half of the 30-year timeframe (see chapter 3). The associated higher CAPEX leads to a negative cash flow for each market segments (i.e. SPDs) in multiple years. These episodes feature the investment cost required to finance the S2R innovations' deployement. A punctual subsidy could offset the negative cashflow years. Or a financing mechanism could support the deployment years as the net chashflow turns positive for all segments after the initial investment period. Rolling stock and infrastructure investments are eligible for funding under different EU funds, and various national mechanisms. A 10% to 15% CAPEX subsidy would improve the financial cost-benefit ratio (see CAPEX sensitivy anlayis is annex 4).

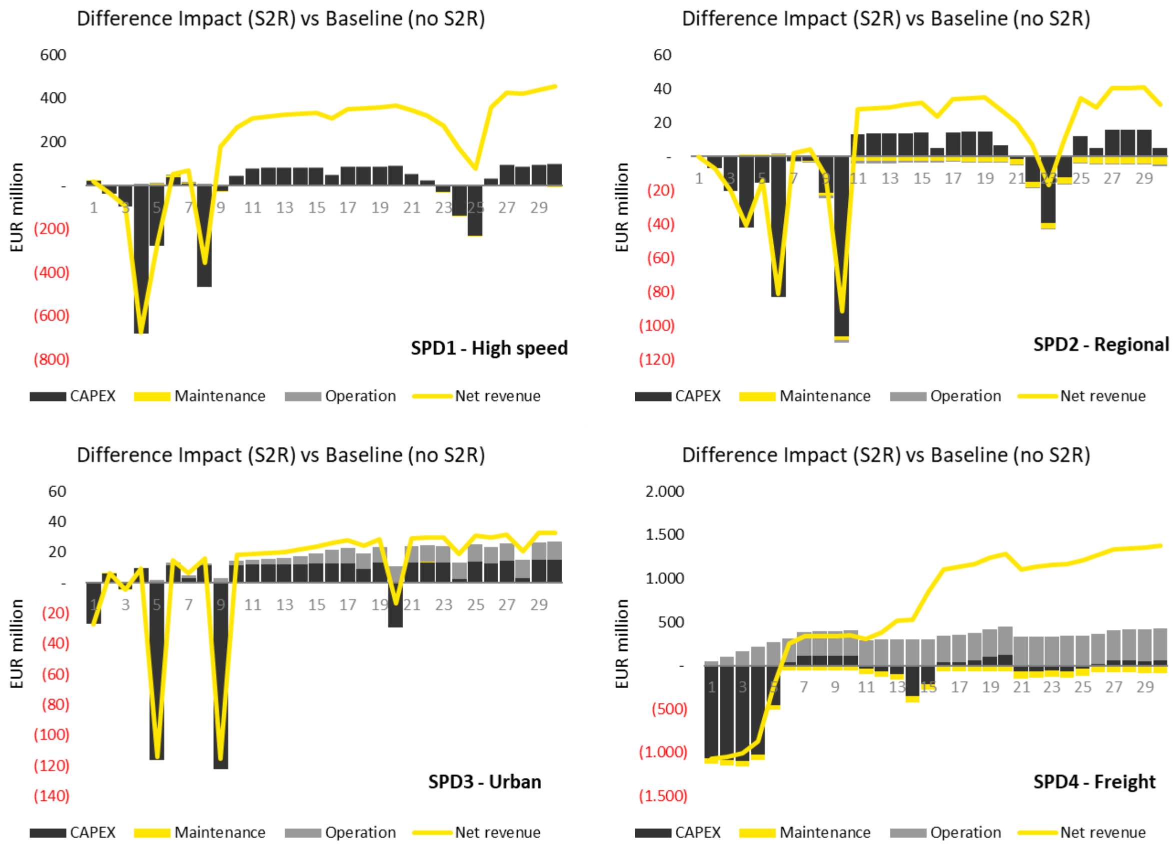


Figure 8: Differences between the baseline and impact scenario – overview (graphs are displayed individually in Annex 7)

Figure 10 presents a detailed overview of financial values.

Revenue is projected to be higher in the impact scenario for the four markets, especially for high speed and freight. The net additional revenue (additional revenue minus additional costs), plotted in the charts, shows a significant multi-year drop in the investment period, at the beginning of the 30 years.

Maintenance costs are estimated to increase due to the larger fleet size, except in the urban case. However, the unit cost maintenance will be lower (per train or per line-km). In the passenger fleet (IP1), the relative reduction mostly happens for doors and bakes, and control systems for high-speed trains. New freight locomotives (TD5.1 and TD5.4) are projected to have a higher maintenance cost due to their additional systems, but wagons would be cheaper to maintain (TD5.3). Switch and crossing systems maintenance are improved by TD3.1 qnd TD3.2, track maintenance is improved by TD3.2, TD3.3, and

Operational costs are reduced for urban and freight (aggregate values – shown as positive values in the cost bar charts). The OPEX per pkm pr tkm are reduced in all segments. These improvements come from the energy consumption (TD1.1, TD TD5.3, TD5.4) and labour costs (all TDs related to communication and digitalization).

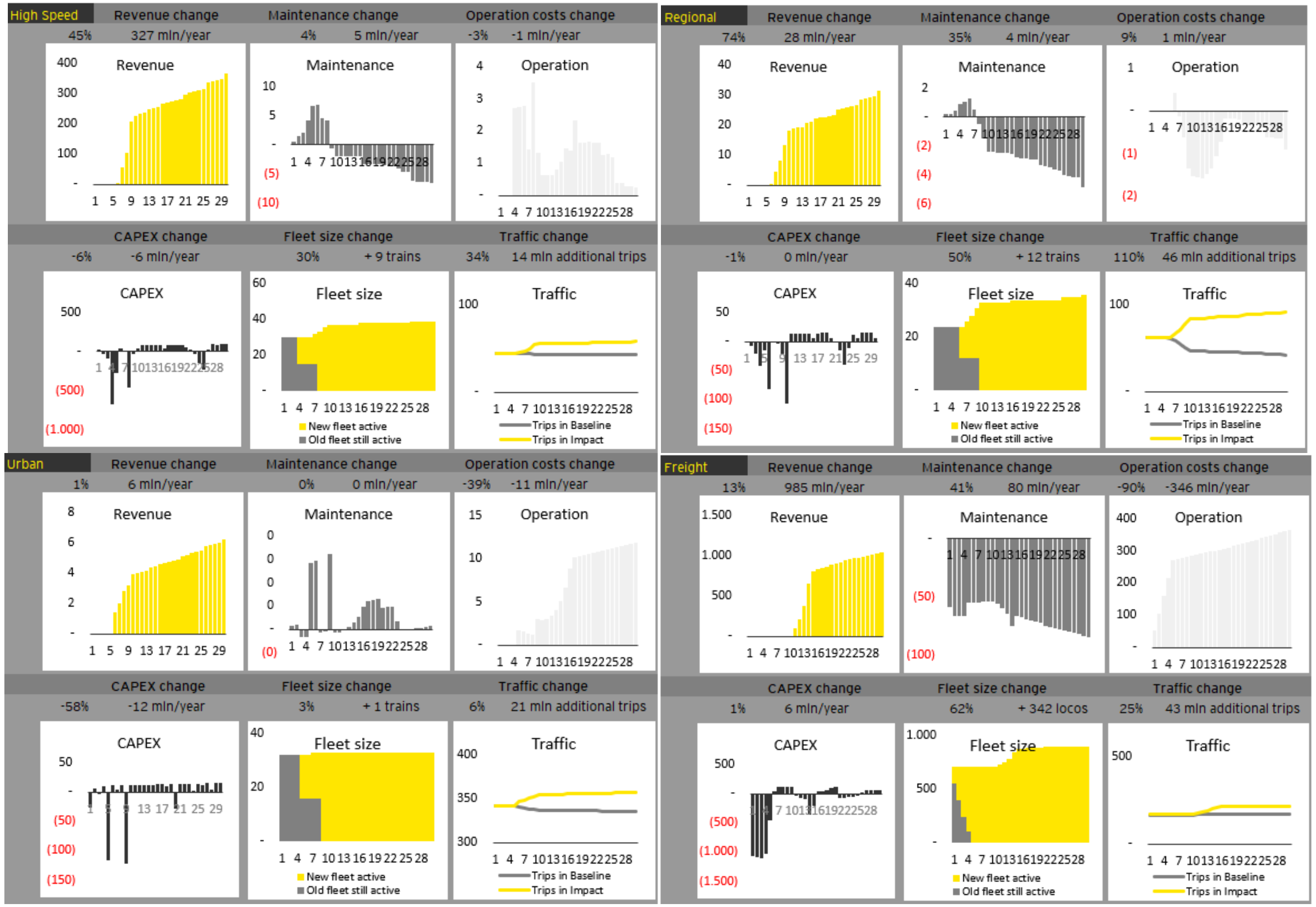
CAPEX is greater in the impact scenario with a strong increase of the expenditure rate during the migration phase, at the beginning of the period. The difference narrows down after the migration, with even a moderate negative CAPEX cost difference for the regional and urban cases (i.e., lower CAPEX on average after S2R technologies adoption). CAPEX therefore reflects the difference of incurred costs between natural fleet renewal rate and the S2R renewal rate. Hence it ties to migration by taking the ratio between the two migration rates (natural vs S2R, in trains acquired per year) multiplied by the cost of new fleet acquired. The relative capex will therefore change according to how rapid the migration is. The closer the migration gets to the natural renewal rate the closer the CAPEX will get to the cost of additional components only (for non-retrofittable technologies).

Fleet size is projected larger in the impact scenario in all cases, to address the higher demand for transport.

	SPD1	SPD2	SPD3	SPD4
Cumulative additional revenue	3 bln	249 mln	55 mln	7 bln
Investment cost (cumulative CAPEX diff.)	0.77 bln	166 mln	79 mln	4.3 bln
OPEX variation (cum OPEX diff)	+ 0,02 bln (More OPEX)	+ 9 mln (More OPEX)	-88 mln (Less expensive OPEX)	-4.6 bln (Less expensive OPEX)
Maintenance variation (cum maintenance diff.)	- 0,02 bln (Less OPEX)	+ 28 mln (More maintenance)	-1 mln (Less expensive maint.)	+ 1.1 bln (More maintenance)

Figure 9: Financial summary, over 30 years (net present value, discounted @ 4%)

While the unit costs in operation and maintenance are improved by the S2R innovations, the total changes presented in Figure 9 and the annual figures in Figure 10 might show an increased OPEX and maintenance costs when the projected fleet is expanded to address the additional demand (SPD1,2,4).



Note: Graphs represent Impact (S2R) vs Baseline (noS2R) scenario differences. Negative values in the graphs indicate "More costs" in the impact scenario. % Changes based on last 10 years.

Figure 10: Differences between the baseline and impact scenarios – detailed view. Individual charts can be found in Annex 7.

2.4.2 Main financial CBA results

The CBA is built on two key metrics: the B/C ratio and the IRR:

- **Cost-benefit ratio (B/C):** the total benefits (OPEX savings and/or additional revenue) over the total costs (increased CAPEX and OPEX).
- **internal rate of return (IRR):** the rate return calculated on the additional cashflow in relation to the investment cost.

Each metric is calculated from real term costs and revenue, i.e., discounted at a 4% rate to obtain the Net Present Value (NPV) equivalent.

	High Speed		Regional		Urban		Freight	
	B/C	IRR	B/C	IRR	B/C	IRR	B/C	IRR
Over 30 years	3,90	14%	1,23	6%	1,82	7%	2,18	10,7%
Over 20 years	2,38	12%	0,81	2%	0,67	0%	1,35	7,4%
Over 10 years	0,38	-22%	0,14	na	0,11	na	0,39	-16%

Note: discounted @4%. Some values appear as not applicable (na) when a large portion of the investment is yet to happen after the first 10 years.

Figure 11: Main financial CBA results

General comments. The 30-year cost-benefit ratio (B/C) is >1 for all segments, indicating that financial benefits outweigh the costs. It is not the case at the 10-year horizon, when the investment period is often not completed, and the modal shift is not fully achieved and not yet delivering all expected benefits.

High speed analysis. The high-speed segment investment is associated to a strongly positive cost-benefit ratio, with benefits assessed at 3,90 and 2,38 times the costs, over 30 and 20 years respectively. This is mainly driven by a higher level of traffic generating more revenue, and a higher passenger ticket price compared to the baseline. Ticket prices will be reduced in both cases, but less so in the impact scenario, thanks the better service quality and customer experience. The net revenue (additional revenue minus all additional costs) from this investment do not stabilise in the positive before year 9 of the migration. The IRR is positive after 20 years (12%) and continues to improve after 30 years (14%).

Regional rail analysis. The network and fleet migration in the regional segment yield a 1.2 benefit to costs ratio across 30 years, with a 6% IRR. Revenue per passenger would decline (lower ticket prices). But higher traffic level should compensate for it. Operational costs and maintenance costs per passenger would decrease significantly.

Urban rail analysis. The deployment of S2R innovations in the urban rail segment would produce a benefit cost ratio of 1.8. The benefits for the urban segment come mostly from operational costs savings. Additional revenue alone is not sufficient to cover the investment costs. The revenue modelling assumption for urban rail is conservative. The cost-benefit ratio is very sensitive to ticket price projections. This is particularly the case for the urban context where small changes to a low unit price is impact a larger number of tickets (see sensitivity analysis in Annex 4). Following the results of the modal shift evaluation model, this CBA includes a reduction in ticket prices for the urban SPD, which is one of the drivers of the modal shift. Maintaining the ticket price constant in the Impact scenario, with the same modal shift, would bring the B/C ratio from 1.82 to 2.84, and the IRR from 6.7% to 9.7%.

Freight analysis. Freight is projected to secure large market share gains thanks to the deployment of S2R innovations. This modal shift and efficiency gains to a 2.2 benefits cost ratio over 30 years, with a 10.7% IRR (1.4 B/C over 20 years, 7%IRR).

	High Speed	Regional	Urban	Freight
Impact vs Baseline, per unit (tkm or pkm)				
CAPEX	-26%	-47%	-59%	-19%
OPEX	-24%	-42%	-41%	-92%
Maintenance	-19%	-29%	-4%	13%
Revenue	14%	-8%	-2%	-10%

Note: based on last 10 years of the 30-year analysis period.

Table 13: changes per pkm or tkm

EU level adjustments. The potential for modal shift and the cost of maintaining and operating rolling stock and the infrastructure might vary across different EU member states. To account for diversity of the rail network across the EU and assess its potential impact on the overall results of this study, we apply an adjustment procedure on B/C ratios to consider differences in west south, east, and north Europe. See *Annex 2: EU level correction factors* for a detailed presentation of the procedure and underlying assumptions.

The adjusted B/C ratios are all lower after the adjustment, except for freight (Table 14). The reduction is starker for the urban segment (SPD3) as the reduced revenue per passenger (lower ticket prices) is projected on a higher base traffic level than in the unadjusted case and this price reduction is not compensated by the modal shift to the extend it is in SPD2. This leads to negative net additional revenue. EU values are also discounted at 4%.

	SPD1		SPD2		SPD3		SPD4	
	EU	SPD	EU	SPD	EU	SPD	EU	SPD
10yrs, disc.	0,40	0,38	0,10	0,14	0,06	0,11	0,33	0,35
20yrs, disc.	2,44	2,38	0,62	0,81	0,33	0,67	1,82	1,41
30yrs, disc.	3,73	3,90	1,06	1,23	0,74	1,82	3,05	2,25

Note: EU: based on indicators adjusted to EU level. Discounted at 4%. SPD: based on the SPD use case definitions in IMPACT1&2.

Table 14: EU level adjustments to financial cost-benefit ratios

The adjustment considers:

- An adjusted OPEX, maintenance and revenue projects across south, east, north and east Europe (based on purchasing power parity). CAPEX values are kept unchanged.
- The total rail transport market size in each of the 4 EU MS groups.
- A slightly lower modal share increases in south and east EU than in the north and west.
- More details on this adjustment are available in *Annex 2: EU level correction factors*.

Note that the adjustment procedure projects pkm or tn-km metrics to the whole EU rail market, which affects the cost-benefit ratio even without adjustments.

Heterogenous progress would lead to lower benefits. Another important factor that might impact the results of this study is the speed of technology adoption. Different levels of deployment progress across Europe would lead to different balances of costs and benefits across different regions and affect the overall cost-benefit ratio.

Cost overruns would drive the cost-benefit ratio down. This study did not factor any cost overrun[11]. The cost data was obtained from the KPI model. Cost overruns might drive down

[11] Marina Cavalieri, Rossana Cristaudo & Calogero Guccio (2019) Tales on the dark side of the transport infrastructure provision: a systematic literature review of the determinants of cost overruns, Transport Reviews, 39:6, 774-794, DOI: 10.1080/01441647.2019.1636895

the cost-benefits ratio by raising overall costs and delaying benefits accrual. For a simple illustration of this issue, we stress test the main results by increasing the CAPEX values by 15%. The results can be consulted in Annex 4: Sensitivity analysis.

But unit costs might come down in the future and improve the results. Economies of scale and technological improvement often drive manufacturing costs down, especially on the time scale of relevant to this study (ex: batteries, solar panels)[12]. Therefore, we also provide the results with a 15% CAPEX reduction in Annex 4: Sensitivity analysis.

[12] Nemet, G.F. Improving the crystal ball. Nat Energy 6, 860–861 (2021). https://doi.org/10.1038/s41560-021-00903-9

3 Socio-economic CBA

The socio-economic cost-benefit analysis of S2R technologies adds onto the financial cost-benefit analysis by providing a monetary valuation of the societal impact. Benefits from the S2R investments derives significantly from the induced modal shift. Traffic shifted to rail, from road or air, generally has a lower externality cost and generates aggregate economic benefits (especially if it transport costs is lower).

In line with the IMPACT-2[13] methodology (Deliverable 2.3 - Societal Benefits) by, the societal cost-benefit areas included in this exercise are shown in Figure 12. See *Annex 3: Externalities and economic surpluses* for a detailed overview of externalities and surpluses considered.

Externalities

- **Climate impact** - GHG emissions' savings from the impact of S2R.
- **Air pollution** - Savings in emissions of particulate matter.
- **Noise** - Lower decibels per person (for local communities).
- **Accidents** - Savings on preserved lives and treatment of injuries.
- **Infrastructure wear** - Possible savings on roads and airports which are more prone to wear - lower overall maintenance costs.
- **Congestion savings** - Benefit for the end consumer in terms of mobility level and time savings.
- **Wider Economic Benefits** (Metro only) - the spill-over effects to other markets (e.g. the labour market).

Economic Surpluses

- **Consumer surplus**
  Difference between the maximum amount the customer is estimated to be willing to pay for a trip minus the actual generalized cost for the trip.
- **Producer surplus**
  Difference between total revenue and total costs for the provider of services.

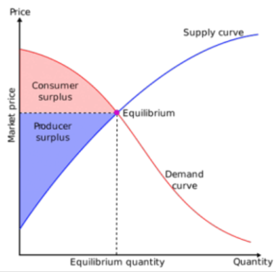


Figure 12: Domains of societal costs and benefits

The total societal benefits are added to the net financial revenue (Figure 13) and used to recalculate the IRR and B/C ratios.

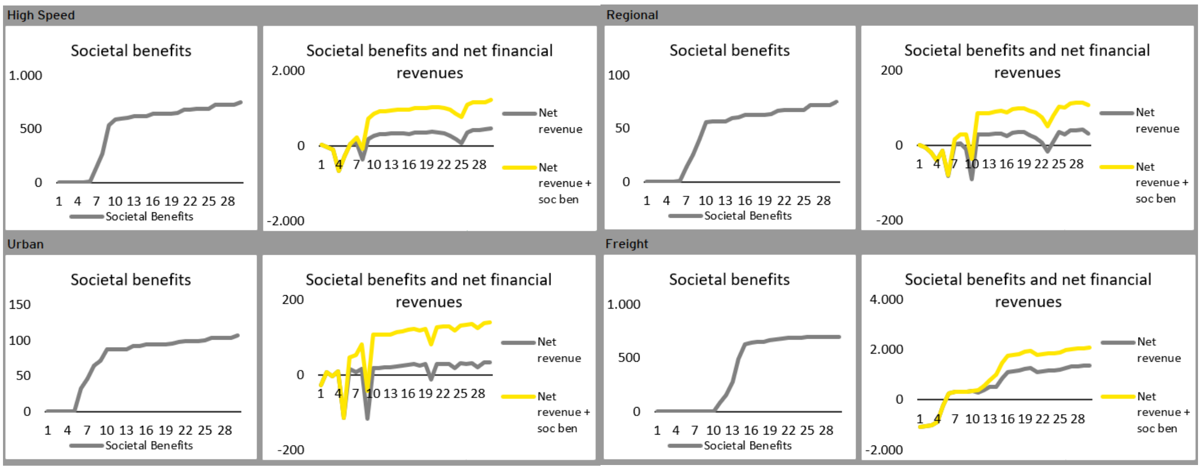


Figure 13: Total societal benefits and impact on net revenue (revenue - all expenses in EUR million)[14]

[13] IMPACT-2
[14] If net revenue goes below zero, this represents higher annual expenses than annual revenues of the S2R scenario compared to the future projection without S2R - which is evident during the migration phase due to the costs of acquiring new fleets.

Aggregate societal benefits are particularly significant for the high speed (SPD1) and the freight (SPD4) segments as these are the ones with the largest modal shift's effect. Although lower, societal benefits for SPD2 and 3 are valued higher than the additional financial revenue generated in these segments.

	High Speed	Regional	Urban	Freight
Cumulative total societal benefits	7.139	684	1.093	5.138
Of which externalities	*823*	*272*	*139*	*2.045*
Of which economic surpluses	*7.139*	*684*	*1.093*	*3.093*

Note: EUR million, net present value, discounted @ 4%. These values are the annual total societal benefits obtained after full completion of the migration. Before full completion, the analysis includes only a fraction of these values, proportional to the migration completion progress.

Table 15: NPV of societal benefits over 30 years

Externalities generate considerable benefits in all segments. Avoided greenhouse gas emissions combined to avoided air pollution make for the largest type of positive externality, followed by the added value of avoided accidents when shifting to rail transport. The total value of externalities is directly proportional to the modal shift induced in each segment. With a lower modal shift potential compared to other segments, urban rail is projected with lower environmental gains. However, investing in urban rail generates high economic surplus, and it is associated to a specific type of socio-economic benefit related to the better connectivity inside metropolitan areas and positive spill overs (e.g., on the job market).

Economic surpluses represent the largest part of societal benefits. High-speed and freight segments are projected with the highest modal shifts, and therefore the highest economic surplus. Most of these surpluses comes from the consumer side, as efficiency gains are translated into lower service prices. For urban in particular, the economic surplus is significantly larger than the additional financial revenue.

	High Speed			Regional			Urban			Freight		
	B/C	B/C+	IRR	B/C	B/C+	IRR	B/C	B/C+	IRR	B/C	B/C+	IRR
Over 30 years	3,90	13,0	14%	1,23	4,61	6%	1,82	15,6	7%	2,18	3,14	10,7 %
Over 20 years	2,38	8,18	12%	0,81	3,14	2%	0,67	6,54	0%	1,35	1,86	7,4%
Over 10 years	0,38	1,28	-22%	0,14	0,55	na	0,11	0,11	na	0,39	0,39	-16%

B/C: Financial benefit cost ratio, B/C+: financial and societal benefit cost ratio, IRR: financial internal rate of return.

Table 16: Cost-benefit ration and IRR with societal benefits

When combined to the financial cashflow analysis, societal benefits significantly improves the returns of the S2R investment across all segments.

4 Overall CBA results and conclusions

This report presents the results of the financial and socio-economic cost-benefit analysis for the deployment of S2R innovations in four illustrative scenario of typical rail segments.

The **expected impact of the S2R innovations** include important customer service improvements, significant operational and maintenance costs reductions, and lower capital expenditure per passenger or tonne kilometre. These improvements will enable the rail sector to attract a larger demand for transport services and increase its revenue while generating important societal added value. Multiple versions of the migration paths have been considered by the study team. They were developed in consultation with an advisory board composed of industry stakeholders. The most cost-efficient path (rapid and coordinated migration) is presented in this study.

The results indicate that a **deployment of the S2R technologies is financially sustainable** and moderately profitable (no negative net revenue after the investment period and positive IRR)[15].

Migration paths are a critical element of the deployment of the innovations. The assumptions made in modelling the migration path include a rapid deployment of the technological improvements, as soon they are available. A **sector-wide coordinated and rapid deployment** is essential to produce the expected benefits.

In all cases, a **financing solution would be needed** at the beginning, as the upfront CAPEX investment is not covered by any additional revenue. The modal shift is enabled by capacity gains, lower prices, and better services. It is projected to lag the investment period by a few years, thereby delaying additional revenue.

The impact of this investment is **expected to have a significant spill over**. The socio-economic impact of the modal shift induced by the transformations are greater than the additional net revenue generated. The socio-economic impact is generated through modifying the external footprint of the transport sector (e.g., lower GHG emissions, greater safety, lower congestion levels), or economic value added (consumer and producer surpluses).

	High Speed			Regional			Urban			Freight		
	B/C	B/C+	IRR	B/C	B/C+	IRR	B/C	B/C+	IRR	B/C	B/C+	IRR
Over 30 years	3,90	13,0	14%	1,23	4,61	6%	1,82	15,6	7%	2,18	3,14	10,7 %
Over 20 years	2,38	8,18	12%	0,81	3,14	2%	0,67	6,54	0%	1,35	1,86	7,4%
Over 10 years	0,38	1,28	-22%	0,14	0,55	na	0,11	0,11	na	0,39	0,39	-16%

B/C: Financial benefit cost ratio, B/C+: financial and societal benefit cost ratio, IRR: financial internal rate of return.

Figure 14: overall CBA results

High speed analysis. The investment in the high-speed segment is associated to a strongly positive cost benefit ratio, with benefits assessed at 3,90 and 2,38 times the costs, over 30 and 20 years respectively. This is mainly driven by a higher level of traffic, and a higher passenger ticket price compared to the baseline. Ticket prices will be reduced in both cases (with and without S2R), but less so in the impact (S2R) scenario, thanks to better service quality and customer experience. The net revenue (additional revenue minus all additional

[15] Except for high speed and freight for which the investment is more profitable as they are projected to capture larger market shares.

costs) from this investment does not stabilise in the positive before year 9 of the migration. The IRR is positive after 20 years (12%) and continues to improve after 30 years (14%).

Regional rail analysis. The network and fleet migration in the regional segment yield a 1.2 benefit to costs ratio across 30 years, with a 6% IRR. Revenue per passenger would decline (lower ticket prices). But higher traffic level should compensate for it. Operational costs and maintenance costs per passenger would decrease significantly.

Urban rail analysis. The deployment of S2R innovations in the urban rail segment would produce a benefit cost ratio of 1.8. The benefits for the urban segment come mostly from operational costs savings. Additional revenue alone is not sufficient to cover the investment costs. The revenue modelling assumption for urban rail is conservative. The cost-benefit ratio is very sensitive to ticket price projections. This is particularly the case for the urban context where small changes to a low unit price impacts a larger number of tickets (see sensitivity analysis in Annex 4). Following the results of the modal shift evaluation model, this CBA includes a reduction in ticket prices for the urban SPD, which is one of the drivers of the modal shift. Maintaining the ticket price constant in the Impact scenario, with the same modal shift, would bring the B/C ratio from 1.82 to 2.84, and the IRR from 6.7% to 9.7%.

Freight analysis. Freight is projected to gain additional market shares thanks to the deployment of S2R innovations. This modal shift and related efficiency gains result in a 2.2 benefits cost ratio over 30 years, with a 10.7% IRR (1.4 B/C over 20 years, 7% IRR).

RU/IM. The migration is beneficial for both the infrastructure manager and the railway undertaking. The internal rate of return is greater for the RU in the high-speed and the freight segments which is where the largest revenue increases are expected. The balance between the two stakeholder is highly depended on track access charges (TAC) assumptions. TAC was assumed identical in the baseline and the impact scenario.

High Speed

Cost benefit ratio (B/C)	Nominal	Discounted
Over 30 years	9,48	3,90
Over 20 years	4,61	2,38
Over 10 years	0,43	0,38
Over 30 years + soc ben	31,27	13,02
Over 20 years + soc ben	15,85	8,18
Over 10 years + soc ben	1,48	1,28

Over 30 years, benefits are 3,9 times the costs, and amount to a 14,4% IRR.

Internal rate of return (IRR)	Aggregated	RU	IM
IRR 30yrs	14,4%	20,5%	7,4%
IRR 20yrs	12,1%	18,8%	6,7%
IRR 10yrs	-22%	-11,0%	-11,0%
IRR 30yrs + soc ben	31,6%	/	/

Regional

Cost benefit ratio (B/C)	Nominal	Discounted
Over 30 years	2,08	1,23
Over 20 years	1,20	0,81
Over 10 years	0,15	0,14
Over 30 years + soc ben	7,68	4,61
Over 20 years + soc ben	4,64	3,14
Over 10 years + soc ben	0,59	0,55

Over 30 years, benefits are 1,23 times the costs, and amount to a 5,8% IRR.

Internal rate of return (IRR)	Aggregated	RU	IM
IRR 30yrs	5,8%	3,2%	9,6%
IRR 20yrs	1,7%	-3,5%	9,1%
IRR 10yrs	na	-5,1%	-5,1%
IRR 30yrs + soc ben	22,0%	/	/

Urban

Cost benefit ratio (B/C)	Nominal	Discounted
Over 30 years	15,11	1,82
Over 20 years	1,05	0,67
Over 10 years	0,12	0,11
Over 30 years + soc ben	123,03	15,62
Over 20 years + soc ben	9,95	6,54
Over 10 years + soc ben	1,52	1,39

Over 30 years, benefits are 1,82 times the costs, and amount to a 6,7% IRR.

Internal rate of return (IRR)	Aggregated	RU	IM
IRR 30yrs	6,7%	6,8%	5,5%
IRR 20yrs	0,4%	2,2%	na
IRR 10yrs	na	-3,6%	-3,6%
IRR 30yrs + soc ben	34,3%	/	/

Freight

Cost benefit ratio (B/C)	Nominal	Discounted
Over 30 years	3,70	2,18
Over 20 years	1,99	1,35
Over 10 years	0,46	0,39
Over 30 years + soc ben	5,44	3,14
Over 20 years + soc ben	2,82	1,86
Over 10 years + soc ben	0,46	0,39

Over 30 years, benefits are 2,18 times the costs, and amount to a 10,7% IRR.

Internal rate of return (IRR)	Aggregated	RU	IM
IRR 30yrs	10,7%	43,8%	12,2%
IRR 20yrs	7,4%	43,7%	9,5%
IRR 10yrs	-16%	na	na
IRR 30yrs + soc ben	13,5%	/	/

Figure 15: Detailed overall CBA results[16]

[16] The figure shows aggregated results for the entire sector, as well as the ones split between IMs and RUs. The split was derived from different revenue streams and cost streams. Each item from both categories was either assigned to RU or IM depending on the ownership (e.g. track access charges to IM and ticket prices to RUs).

Uncertainty and caveats. Estimates of costs and benefits in this study are built on the results of other reports and assumptions that jointly contribute to a level of uncertainty around the CBA results. For example, changes in the modal shift, delayed availability of new technologies, and modified deployment timelines are factors that would significantly affect the results. The results were also found to be sensitive ticket prices and to potential variation in planned CAPEX. Challenges are likely to arise for a coordinated EU deployment, which might affect the timing and costs benefit projections. The micro (company) level cost-benefit would also differ from this aggregate estimate and vary from on company to another.

The main studies and sets of assumptions underpinning this CBA are:

- Those of the **KPI Model.** See IMPACT-2 deliverable D4.3 *Reviewed quantitative KPI model*[17] as well as IMPACT-1 deliverable D3.3 *Use Cases for SPDs*[18]. The KPI model assumptions and data points are used to define the four market segments (fleet size and network characteristics). We further assume some revenue figures from payload and frequency indicators. All cost assumptions from the KPI model are also re-used for this CBA. Operating costs not covered by the KPI model where not considered in this analysis (e.g., labour costs not related to rolling stock, ticketing costs)
- Those of the **Modal Shift evaluation model**. See IMPACT-2 deliverable D3.3 Modal shift evaluation model. The modal shift evaluation model is used to infer traffic variations and subsequent revenue changes, with some slight deviations documented in Annex 5 of this report. The findings of this report and D3.3 should be taken as rough estimates of the effects of implementing S2R and road technologies in a scenario similar to the existing situation. As a result, it does not reflect a comprehensive sensitivity study of many macroeconomic and other variables affecting scenarios 10 years or longer in the future (e.g., energy prices, road congestion…), nor the COVID-19 pandemic, which is discussed further below.
- Additional assumptions: Economic surpluses were obtained from the IMPACT-2 study on socio-economic impacts[19] and scaled up or down accorded to the estimated level of traffic. The surpluses, moreover, strongly depend on the general growth assumptions (standard of living, income distribution, GDP, etc.)

COVID-19. Since these models that CBA is based on (and whose results strongly depends on) were constructed ahead of the COVID-19 pandemic, the CBA itself does not reflect possible projection adaptations that COVID-19 has introduced. There are clear indications that the COVID pandemic has produced a considerable financial burden on the rail market players. The passenger traffic was strongly impacted. However, rail freight in particular has shown resilience in the environment of strong supply chain issues in other modes. This will be the base for future political prioritisation of rail freight sector by decision-makers. Moreover, during the pandemic the public awareness of environmental impact of their travels and goods has significantly increased, which puts rail at the forefront as the most environmentally sustainable in most applications[20]. This concludes that the following years may be financially difficult for the rail industry as the recovery could be slow, however over the coming years and decades, the public support and political prioritisation will likely induce the modal shifts and KPIs that we are seeing in the mentioned models constructed by IMPACT-2. This means that this CBA would retain its relevance over the long run.

[17] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-2
[18] https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=IMPACT-1
[19] IMPACT-1 (2021) Socio-Economic Impact Assessment and Baseline Assessment, Deliverable 2.3
[20] Doppelbauer, J (2021) Post-pandemic recovery of rail transportation. [Available at: https://europa.eu/newsroom/events/post-pandemic-recovery-rail-transportation_en]

Annex 1: IP contribution to modal shift

Weighting scheme used to scale societal benefits according to the migration progress.

SPD#	IP relative contribution to modal shift (sum=100%)	Rationale
SPD1 High Speed	IP: 15%, IP2: 35%, IP3: 10%, IP4: 40%, IP5: 0%	The changes in customer experiences (IP4) are expected to contribute most to the modal shift to high-speed lines. Advanced traffic management and control systems to be developed through IP2 will allow for some efficiency gains and improve the service offering. Performance and capacity improvements derived from IP1 and IP3 will allow for an increase in traffic to a type of segment which already run at maximum capacity in large knots and some highly utilized lines (mainly in France).
SPD2 Regional	IP1: 17.5%, IP2: 35%, IP3: 10%, IP4: 37.5%, IP5: 0%	The changes in customer experiences (IP4) are expected to contribute most the modal shift to regional lines as well. Advanced traffic management and control systems to be developed through IP2 will allow for some efficiency gains and improve the service offering. Performance and capacity improvements derived from IP1, IP2 and slightly IP3 will allow for an increase in traffic in regions that already run at maximum capacity (mainly in large knots and some highly utilized lines). Reliability, capacity derived from the coms and management system and info upgrades of IP2 and IP3 will benefit most the regional segment. Customer experience and analytics should contribute slightly less (IP4). And IP1 improvements will mostly benefits operators and not significantly contribute to attract more passengers.
SPD3 Urban	IP1: 10%, IP2: 30%, IP3: 30%, IP4: 30%, IP5: 0%	Future stations in IP3, capacity and reliability improvements from IP2 and IP3, as well as customer experience should equally contribute to the shift in the urban segment. IP1 should also contribute slightly with increasing the number of seats per train.
SPD4 Freight	IP1: 0%, IP2: 15%, IP3: 10%, IP4: 0%, IP5: 75%	Moving block, ATO and traffic management system of IP2 and condition-based maintenance of IP3 are expected to contribute to the capacity and punctuality increase and competitiveness of freight transport. But most of the modal shift is expected to come from the service and cost competitiveness gains obtained from IP5.

Source: own analysis and expert consultations.

Table 17 - IP Contributions to the modal shift figures[21]

[21] This IP mapping of contributions is a result of a qualitative analysis that was conducted together with IMPACT-2 experts. Most of the reasoning discussed is shown in the table and most of the percentages are the averages of different experts' opinions

Annex 2: EU level correction factors

To account for diversity of the rail network across the EU, we apply an adjustment procedure to account for differences in west south, east, and north Europe.

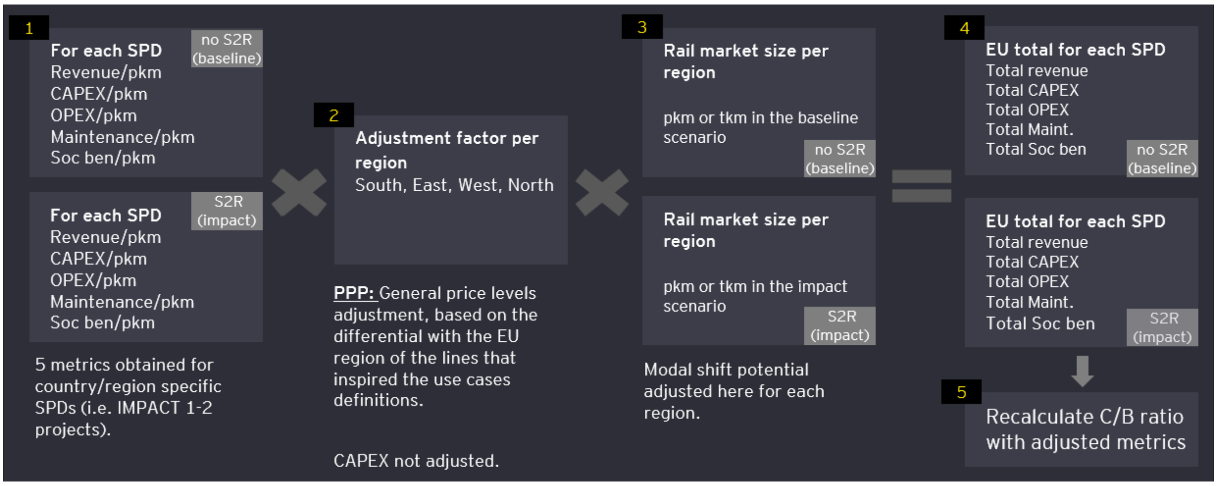


Figure 16: EU level adjustment process

Step 1: Revenue, CAPEX, OPEX, Maintenance and Societal Benefits per tkm or passenger-km are extracted from the main analysis, for each market segment.

Step 2: For each market segment, an assessment is made regarding the potential regional (west, east, north, west[22]) differences of Revenue, OPEX, Maintenance and societal benefits per unit. That assessment is based on purchasing power parity levels (see Table 18 for adjustment factors and rationales). The CAPEX level is kept the same throughout Europe, as the supplying industry is well integrated. Revenue is adjusted mechanically, without considerations for partial equilibrium effects.

Step 3: The total transport market in the baseline (PAX or tkm per year) is obtained by processing MS[23] [24] or EU level[25] data. The baseline market projection (percentage change) is kept unchanged. In the impact scenario, a more modest modal share increase potential in south and east Europe is considered, as well as a more optimistic modal share increase for western and northern Europe.

Step 4: The indicators from step one is then multiplied by the adjustment factor of step 2 and scaled at EU level with the regional market size from step 3, for both the baseline and the impact scenario.

Step 5: The evolution of the difference (impact vs baseline) in total Revenue, OPEX, Maintenance and Societal Benefits is then used to calculate the adjusted cost-benefit ratio.

[22] Subregions definition from standard UN classification https://upload.wikimedia.org/wikipedia/commons/thumb/7/7a/Europe_subregion_map_UN_geoscheme.svg/1280px-Europe_subregion_map_UN_geoscheme.svg.png
[23] Total EU rail pkm allocated to regional and urban segments with 60%/40% split of data from https://ec.europa.eu/eurostat/databrowser/view/ttr00015/default/table?lang=en
[24] Rail freight data from https://ec.europa.eu/eurostat/databrowser/view/RAIL_GO_TOTAL__custom_1444943/default/table?lang=en
[25] For high speed Geographical breakdown assumed same as regional and urban passenger transport. Total data from https://www.statista.com/statistics/279576/high-speed-rail-transport-in-eu-27/

	SPD1	SPD2	SPD3	SPD4
West	100% SPD1 is based on a Western line (French)	100% SPD2 based on a Western line (German).	100% SPD3 based on a Western line (Austrian).	85% Western EU ppp is about 15% lower than Northern ppp.
East	50% Eastern EU ppp is about 35% lower than Western ppp	50% Eastern EU ppp is about 35% lower than Western ppp	50% Eastern EU ppp is about 35% lower than Western ppp	40% Eastern EU ppp is about 60% lower than Northern ppp
South	70% South EU ppp is about 20% lower than Western ppp.	70% South EU ppp is about 20% lower than Western ppp	70% South EU ppp is about 20% lower than Western ppp	60% South EU ppp is about 40% lower than Norther ppp.
North	120% North EU ppp is about 20% higher than Western ppp.	120% North EU ppp is about 20% higher than Western ppp.	120% North EU ppp is about 20% higher than Western ppp.	100% SPD4 is based on a Northern line (Sweden-Germany)

Table 18: EU level adjustment factors[26]

Underlying assumptions. The regions shown above were constructed based on the split shown in Figure 17. The 60-40 split between regional and metro was included based on the consultation with IMPACT-2 experts.

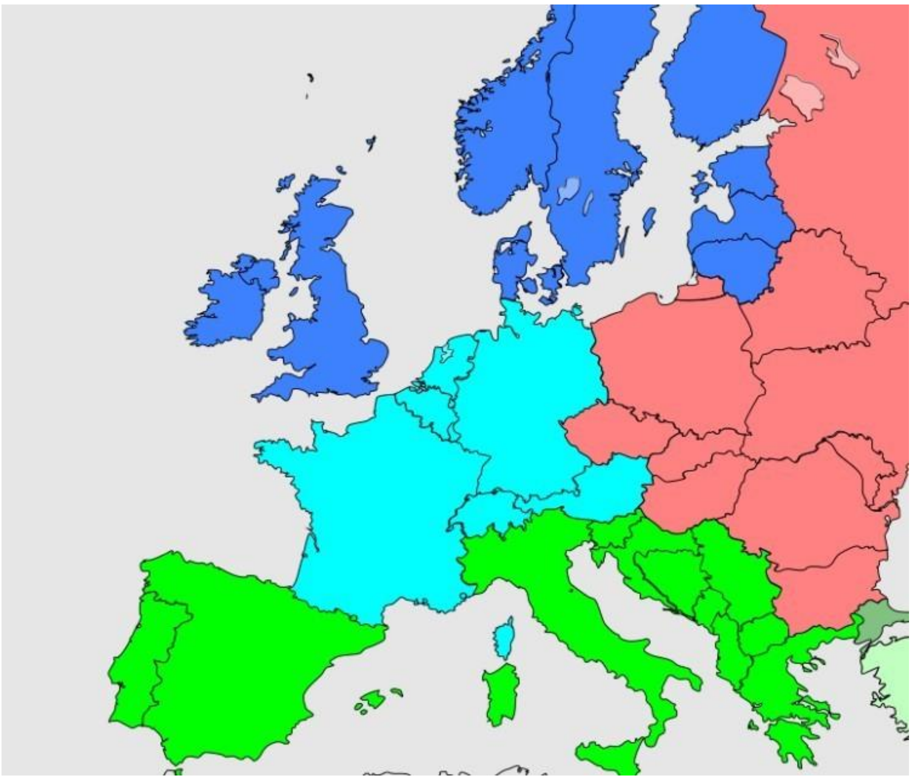


Figure 17 - The considered regions (North, South, East, West) are shown in colour coding

[26] Purchasing Power Parity (PPP) data source: https://ec.europa.eu/eurostat/databrowser/view/tec00120/default/table?lang=en

Annex 3: Externalities and economic surpluses

A3.1 Externalities

Externalities are referred to as "the effect of production or consumption of goods and services imposing costs or benefits on third-parties which are not reflected in the prices charged for the goods and services being provided"[27]. The significant externalities that will be considered are shown in Figure 12 and will be expanded upon in this section. in the context of transport, six types of externalities are considered: climate, air pollution, noise, accidents, infrastructure wear, time savings linked to road congestion.

Climate Impact. Due to the fact that the effects of climate change are global, long-term and have risk patterns that are difficult to anticipate, identifying the costs associated with these effects is rather complex. Transport results in emissions of CO_2, N_2O and CH_4 (methane), all of which are greenhouse gases contributing to climate change. Therefore, the climate costs of transport need to be included[28].

Air Pollution. The emission of air pollutants can lead to different types of damages. Most relevant and probably best analysed are the health effects due to air pollutants. However, other damages such as building and material damages, crop losses and biodiversity losses are also relevant.

- **Health effects**. The inhalation of air pollutants such as particles (PM_{10}, $PM_{2.5}$) and nitrogen oxides (NO_x) leads to a higher risk of respiratory and cardiovascular diseases. These negative health effects lead to medical treatment costs, production loss at work (due to illness) and, in some cases, even to death.
- **Crop losses**. Ozone as a secondary air pollutant (mainly caused by the emission of NO_x and VOC) and other acidic air pollutants (e.g., SO_2, NO_x) can damage agricultural crops. As a result, an increased concentration of ozone and other substances can lead to lower crop yields (e.g., for wheat).
- **Material and building damage**. Air pollutants can mainly lead to two types of damage to buildings and other materials: a) pollution of building surfaces through particles and dust; b) damage of building facades and materials due to corrosion processes, caused by acidic substances (e.g., nitrogen oxides NO_x or sulphur oxide SO_2).
- **Biodiversity loss**. Air pollutants can lead to damage to ecosystems. The most important damages are the acidification of soil, precipitation and water (e.g., by NO_x, SO_2) and the eutrophication of ecosystems (e.g., by NO_x, NH_3). Damages to ecosystems can lead to a decrease in biodiversity (flora & fauna) [28].

Noise Pollution. Traffic noise is generally experienced as a disutility and is accompanied by significant costs. Noise emissions from traffic pose a growing environmental problem due to the combination of a trend towards greater urbanisation and an increase in traffic volumes. Whilst the increase in traffic volume results in higher noise levels, the increase in urbanisation results in a higher number of people experiencing disutility due to noise. As a result, the costs of traffic noise are expected to grow in the future despite potential noise-reducing improvements in vehicles, tyres and roads[28].

Accidents. Accidents occur in all forms of traffic and result in substantial costs, consisting of two types of components: material costs (e.g., damages to vehicles, administrative costs

[27] OECD (2021) *Glossary Of Industrial Organisation Economics and Competition Law* https://www.oecd.org/regreform/sectors/2376087.pdf
[28] European Commission (2019) *EU Handbook on External Costs of Transport* https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1

and medical costs) and immaterial costs (e.g., shorter lifetimes, suffering, pain and sorrow). The EU Handbook on External Costs of Transport has laid out monetary value of each life, light injury and serious injury alike that occurs and modelled this as EUR per pkm for each transport mode. This is thus taken as the most adequate source[28].

Infrastructure wear. The cost of infrastructure wear is not covered in the EU Handbook on External Costs of Transport, although it is covered in the socio-economic Impact of the Transport Sector by the Swedish Transport Administration[29]. It is defined as deterioration of infrastructure and is directly related to maintenance costs. There is a non-negligible difference between modes in their footprint on the general infrastructure that is maintained with public funds[29].

Congestion. Congestion is a condition where vehicles are delayed when travelling. In particular, a congestion cost arises when an additional vehicle reduces the speed of the other vehicles of the flow and hence increases travel time. Road congestion cost can be defined on the basis of a speed-flow relationship in a given context, for example at an urban or inter-urban level[30].

Wider Economic Benefits. These are effects for consumers and / or producers in secondary markets, for example labour market, inputs markets and subcontractors, competing markets (products that are substitutes) etc. Normally this type of effect is negligible, but in markets that are not functioning well (i.e., when there is a market failures) the wider economic benefits become non-negligible. Indirect effects that are negligible if one looks at the net effect from a socio-economic point of view can, however, give rise to regional redistribution of resources and benefits[29].

A3.2 Economic Surpluses

Economic surplus is an economically relevant category of societal benefits. The two related quantities are:

Consumer Surplus. Consumer surplus is taken as the difference between what a consumer of the service is willing to pay minus the costs paid for ticket or car travel. If a consumer is willing to pay more for a unit of a good than the current asking price, they are getting more benefit from the purchased product than they would if the price was their maximum willingness to pay. They are receiving the same benefit (i.e., the good), with a smaller cost as they are spending less than they would if they were charged their maximum willingness to pay[31]. This, rather than being calculated, is taken from the IMPACT-2's model.

Producer Surplus. Producer surplus, on the other hand is the difference between total revenue and total cost for the provider of the service. Producer surplus is usually used to measure the economic welfare obtained by the manufacturer in the market supply. When the supply price is constant, the producer welfare depends on the market price. Otherwise, the figures acquired from IMPACT-2 (D2.3) are used as a steady-state value and scaled according to the KPI use cases (to be elaborated in the next section).

A.3.3 Calculation approach

[29] Swedish Transport Administration (2020) *ASEK - Guidelines for cost-benefit analysis in the transport sector* https://www.trafikverket.se/for-dig-i-branschen/Planera-och-utreda/Planerings--och-analysmetoder/Samhallsekonomisk-analys-och-trafikanalys/asek-analysmetod-och-samhallsekonomiska-kalkylvarden/ (retrieved from IMPACT-2)

[30] Externality descriptions taken from European Commission (2019) *EU Handbook on External Costs of Transport* https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1

[31] Daniel T. Slesnick (2008) *The New Palgrave Dictionary of Economics* https://doi.org/10.1057/978-1-349-95121-5_626-2

The high-level methodology of determining the rates of accrual of societal benefits' revenue through time consists of 3 steps, as shown in Figure 3. The steps are iterative for all SPDs as they include different IP mappings and different migration paths (see further).

- **Step 1: Extraction of relevant data and valuation of societal benefits.** This includes data from IMPACT-2 deliverable 2.3 – Societal Benefits (methodology), IMPACT-2 Deliverable 3.3 Modal shift evaluation model (building upon the modal shift results), the EU Handbook on External Costs of Transport (for the quantification of externalities per pkm or tkm), and various other studies and sources (mostly for the quantification of externalities per pkm or tkm for different modes).
- **Step 2: Mapping IP Contributions to modal shift.** Assessment of the contribution of different IPs to the modal shift in each SPD
- **Step 3: integration with migration paths.** Scaling up of societal benefits across time according to migration progress within each IP and each SPD.

Step 1: Extraction of relevant data and valuation of societal benefits

The results of the modal shift evaluation model are the main input data for the CBA model, alongside the results of D2.3. The modal shifts (in % of modal share) for each SPD are taken from D3.3. Since externalities are valued in either passenger-kilometre (pkm) or tonne-kilometre (tkm), the nominal values of pkm and tkm that shifted need to be extracted from the differences in modal shares following the approach outlined in Figure 18. This approach is structured across 5 steps. The traffic estimates are then multiplied by the externality prices from the EU handbook for each type of externality and summed up with consumer and producer surpluses.

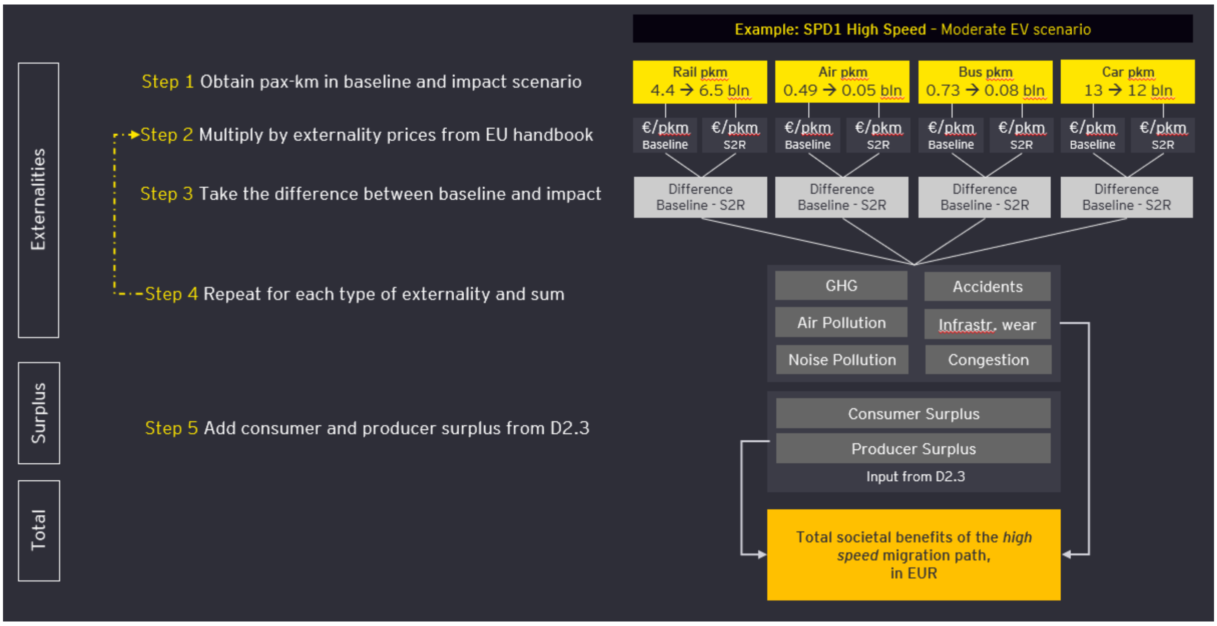


Figure 18: approach to value societal benefits

Data used for scaling of benefits between use cases

The data extracted from D3.3 needs to be made comparable to the underpinning contexts of the CBA (for each SPD). As mentioned in the previous chapter, the use cases on which the modal shift evaluation model was based on are different than the ones used in the KPI model and thus the CBA model that is building upon it. Hence, an adaptation of the overall number of pkms and tkms is required.

Hence, the use cases that were used are different and, in order to acquire the right value of pkm or tkm shifted from other modes to rail mode shares from the IMPACT-2 report are used and applied to a new value of overall pkm or tkm in all modes used in the KPI model. This is done by multiplying the journey length by the overall number of passengers or tonnes of goods transported in a year, which can be derived from KPI model's parameters.

Moreover, in the Modal Shift Evaluation Model there are different scenarios that aim to project the future of transport modes and model the impact of S2R compared to these. Due to the rate of change in road transport and the complexity of other modes like air and maritime, road transport was the only one altered through time according to the penetration of EVs and AVs. Following the discussion in the model and presentation of data, as well as the discussion with experts from IMPACT-2, Moderate EV scenario values were taken as the most relevant ones, which is defined by EV penetration of 50% for all road transport[32].

Step 2: IP Contributions to modal shift

To gradually recognise societal benefits form S2R innovations, it is necessary to link them to the migration paths. The approach used in this case is a mapping of IP contributions to the modal shift. The exact rationale behind the weights of different IP contributions for each SPD is shown in *Source: own analysis and expert consultations.*

Table 17, Annex 1: IP contribution to modal shift.

Step 3: integration with migration paths

The index of migration progression developed in step 2 is used to gradually scale up the societal benefits obtained in step 1. The accrual of societal benefits therefore ties to a percentage completion of each IP at any given point multiplied by its weight of contribution to modal shift. This is then further delayed similarly to the recognition of financial benefits: which means applying a user-defined period (default is 5 years). Additionally, a condition is applied for meeting a certain minimum rate of deployment for the benefit to incur. E.g., in the IP1, once the completion level reaches 50%, only then the emergence of benefits is induced (again, delayed by a user-defined period)[33].

[32] IMPACT-2 (2021) *D3.3 Modal Choice Evaluation model*
[33] Each of the quotas for the rate of deployment was decided in agreement with the IMPACT-2 experts.

Annex 4: Sensitivity analysis

This annex tests some of the hypothesis underpinning the main results.

	SPD1	SPD2	SPD3	SPD4
Main results	3.90	1.23	1.82	2.18
CAPEX +15% increase	2.74	0,92	1.06	1.49
CAPEX -15%	6.79	1.88	6.41	4.07
OPEX & Maintenance +15%	2.57	1.00	0,84	1.94
OPEX & Maintenance -15%	4.48	1.57	2.86	2.48
Higher prices (+5% in Impact)	4,47	1.36	5.75	2.74
Lower prices (-5% in Impact)	3,33	1.10	0.52	1.62
IP weighting for modal shift				
More weight on IP1 (+6%) 6% / -2% / -2% / -2%/ 0%	3,72	1.19	1.83	na
More weight on IP2 (+6%) -2%/ 6% / -2% / -2%/ -2%	3.77	1.06	1.52	2.17
More weight on IP3 (+6%) -2%/ -2% / 6% / -2%/ -2%	3.78	1.06	1.54	2.17
More weight on IP4 (+6%) -2%/ -2% / -2% / +6%/ -2%	3.81	1.07	1.54	2.19
More weight on IP5 (+6%) 0%/ -2% / -2% / -2%/ +6%	na	na	na	2.19

Table 19: Sensitivity analysis – B/C Ratio

The sensitivity analysis of IP weighting in the migration progress index used to introduce the modal shift is performed by skimming 2% to each IP and adding them on the weight of a selected IP.

CAPEX and OPEX sensitivity are assessed by providing an interval of + and - 15%.

Annex 5: Calculating traffic figures from the KPI model

The number of passengers per year, or tkm per year, in the impact scenario (S2R) are obtained in three steps:

1. rail market size estimation in KPI model,
2. total transport market estimation,
3. derive new market size for rail with the new modal share (from IMPACT-2 D3.3)

STEP 1: baseline rail market size in KPI model. Below is an excerpt of the parameters used in the KPI model[34] and the calculations conducted for the purposes of this study below (in grey). These figures relate the baseline traffic level (i.e., before the modal shift).

Parameter	Unit	Source	SPD1	SPD2	SPD3	Single waggon trains	Block trains	Combined traffic trains	Calculations
	Parameters from the KPI Model								
km/journey	(km)	FINE1	300	70	21.5	600	600	600	a
km/year	(km / year)	IMPACT-2 WP4	450,000	180,000	230,000	120000	140000	190000	b
load factor	(-)	SPD4: D5.4.2, Page 10 SPD1-3: IMPACT-2 WP4	64%	42%	70%	50%	40%	60%	c
track capacity	(trains/h)	IMPACT-2 WP4	6	5	12	80	80	80	d
Payload_Max	(t)	SPD4: D5.4.2, Page 10 SPD1-3: IMPACT-2 WP4	-	-	-	1143	1081	832	e
Payload	(t)	SPD4: D5.4.2, Page 10 SPD1-3: IMPACT-2 WP4	380	142	200	571.5	432.2	499.2	f
Passenger Weight	(kg)	defined	80	80	75	-	-	-	g
load factor	(-)	SPD4: D5.4.2, Page 10 SPD1-3: IMPACT-2 WP4	64%	42%	70%	50%	40%	60%	h
train capacity	(#)	IMPACT-2 WP4	510	220	900	-	-	-	i
fleet adquisition	(trains)	IMPACT-1 WL	30	24	32	280	250	180	j
Pax transported per trip	(pax/trip)		326.4	92.4	630				c*i
train-km per year	(train-km/year)		13,500,000	4,320,000	7,360,000	33,600,000	35,000,000	34,200,000	b*j
trips per year	(trips/year)		45,000	61,714	342,326	56,000	58,333	57,000	a/(b*j)
pax/year	**(pax/year)**		**14,688,000**	**5,702,400**	**215,665,116**				**(b*j)*(c*i)/a**
tkm per year	**(tkm/year)**					**19,202,400,000**	**15,127,000,000**	**17,072,640,000**	**f*(b*j)**

Table 20 - KPI model parameters and the corresponding calculations[35]

The tkm per year in the KPI model (i.e., the scope of the CBA model) is obtained as follows **payload*trains*km per year.** Note that the payload variable includes the payload factor, applied on the max payload. For single wagon freight trains, this yields 572 ton*280 trains *120000 km per year= 19 202 400 000 tkm per year.

The PAX per year in the KPI model is obtained as follows: **km per year*trains*load factor*train capacity / km per journey**. For high-speed trains, this yield: 450 000 km *30 trains *64% load *510 capacity / 300km-journey = 14 688 000 pax/year (i.e., tickets per year).

STEP 2: total transport market estimate. The resulting tkm and pax figures were divided by the modal share of rail in the baseline scenario in the results of D3.3 Modal Shift Evaluation Model. This then gives the overall number of passengers and tkm's across all transport modes using KPI parameters.

STEP 3: rail market share after modal shift. The transport market size was then multiplied by the new modal share breakdowns, to obtain the number of pax and tkm after the S2R implementation. The modal shift values were obtained from the Moderate EV scenario

[34] "Subsystem structure and sublevel KPIs" (Deliverable D4.2 of IMPACT-1)
[35] The excerpt is present in the CBA Model in the "InputsFromIMPACT" tab. (The values are rounded in the report, yet in the CBA model they are taken directly from the IMPACT-2's model and thus remain accurate)

projections in the results of the modal shift evaluation report (IMPACT-2 D3.3) and further adjusted based on the generalise the results as follows:

For reference, the initial input figures used for modal shifts are shown in Table 21..

Number of tickets or tkm sold		SPD1	SPD2	SPD3	SPD4
Baseline					
Modal Share of rail	%	23,62%	18,18%	30,30%	20,72%
Sold tickets / service units of tkm in rail	pax or tkm	14.688.000	5.702.400	215.665.116	51.402.040.000
Tickets / service units sold across all modes	pax or tkm	62.171.430	31.363.200	711.766.067	248.070.923.405
Moderate EV without S2R					
Modal share of rail	%	22,65%	12,41%	29,71%	20,93%
Sold tickets / service units of tkm	pax or tkm	14.084.423	3.890.666	211.464.110	51.928.011.422
Moderate EV with S2R					
Modal share of rail	%	35,00%	22,51%	30,63%	31,46%
Sold tickets / service units of tkm	pax or tkm	21.760.001	7.058.312	218.046.125	78.030.997.753

Source: modal shares obtained from the modal shift evaluation model (IMPACT-2 D3.3)

Table 21: Rail modal shares calculations from the D3.3 - Modal Shift Evaluation model

The resulting traffic projections in the baseline scenario feature a decline in all market segments except for freight (stagnation). The decline is for SPD1 and SPD2. Traffic levels are increased in all impact scenario projections, except for the urban segment (SPD3).

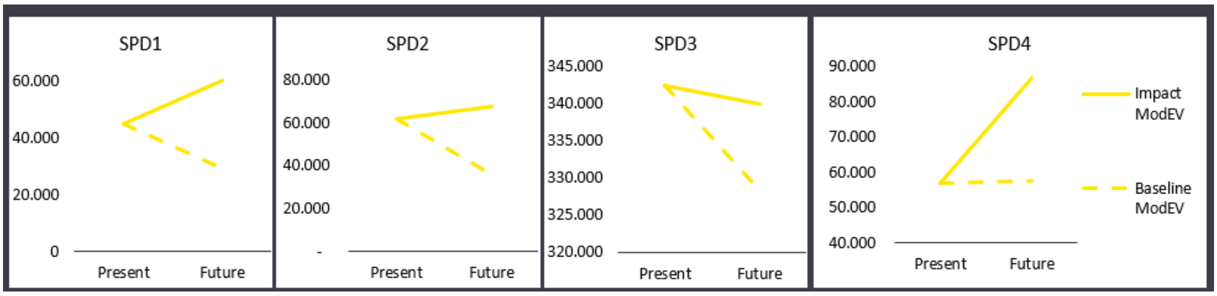


Figure 19: Rail traffic (in pkm) in the baseline and impact scenarios

The projections are then slightly amended to fit the generic context of this study, as follows.

For high-speed, we use a slightly more conservative estimate of market gains and lower ticket price declines. Instead of **22.6% vs 35%** modal share at the end of the period, we use **22.6% vs 28.8%.** The ticket price drop in the baseline is reduced by 50% compared to the IMPACT projection (9.5 euros reduction instead of 19 euro reduction per ticket).

For regional rail, we use a more optimist projection in passenger trips per year (48.6% increase over 30 years instead of 34.2% increase). Hence, instead of **12.4% vs 22.5%** modal share at the end of the period, we use **12.4% vs 25.8%.**

For urban rail, we also use a more optimist projection by assuming a lower decline of the baseline scenario and slightly better performance in the impact scenario, leading to a 6.4% traffic difference in baseline vs impact instead of 4.9%. Hence, instead of **29.7% vs 30.6%** modal share at the end of the period, we use **29.7% vs 31.1%**

For freight more modest difference between the baseline and impact scenario (i.e., less pessimistic projections without S2R). We assume a 26% tkm volume increase instead of a 52% increase. Hence, instead of **20.9% vs 31.4%** modal share at the end of the period, we use **20.7% vs 26.1%.** A price 10% tkm price reduction assumption is also adopted.

Annex 6: Overview of Innovation Programmes

This section presents the technology and process innovations whose costs and benefits are assessed in this report. For each IP, the **TDs are briefly presented** with a high-level introduction to their expected impact in terms of financial costs and benefits. The subsections then summarise **dependencies** or conditions for TD deployment.

<u>IP 1: future generation of passenger trains</u>

IP 1 is focused on delivering a new generation of passenger trains, lighter and more energy- and cost-efficient, while at the same time providing a comfortable, safe and affordable travel experience for all passengers. It is organised around eight TDs[36]:

TD 1.1 - Traction system. It will develop new traction components and subsystems, for Metro, Regional train and High-Speed Trains. <u>Expected impact</u>: Through higher reliability, it will reduce maintenance costs but also slightly increase the capital costs of passenger fleets.

TD 1.2 - Train control and monitoring system (TCMS). A new-generation TCMS will allow bottlenecks caused by physically coupled trains to be overcome. The new drive-by-data concept for train control, along with wireless information transmission, aims to make new control functions possible. <u>Expected impact</u>: It will slightly reduce the capital and maintenance costs of high-speed trains. The main impacts are unlocking functionalities developed in other TDs.

TD 1.3 - The new generation of car body. Lightweight materials will lead to significantly lighter vehicles. <u>Expected impact:</u> more passengers within the same axle load constraints (higher revenue), use less energy (lower operating costs) and have a reduced impact on rail infrastructure (lower maintenance costs).

TD 1.4 - Running gear. It will develop innovative combinations of new architectural concepts, new actuators in new lighter materials. <u>Expected impact:</u> new functionalities, and significantly improved performance levels with the possibility of vibration energy recovery.

TD 1.5 - New braking systems. They will allow higher brake rates and lower noise emissions will. <u>Expected impact</u>: higher mass and volume in bogies, leading to higher line capacity (increased revenue).

TD 1.6 - Innovative doors. New lightweight composite structures could be made to react faster at existing safety and reliability levels. <u>Expected impact</u>: reducing platform dwell times and increasing overall line capacity, and better consumer experience (increased revenue), lower energy consumption (lower operating costs).

TD 1.7 - Train modularity in use. New modular concepts for train interiors that allow operators to adapt the vehicle layout to the actual usage conditions, and will improve passenger flows, thus optimising both the capacity of the vehicle and dwell times. <u>Expected impact:</u> Increased capacity (increased revenue).

TD 1.8 - Heating, Ventilation, Air conditioning and Cooling (HVAC) systems. It will help limiting the climatic impact from these systems within rail vehicles. <u>Expected impact:</u> No clear financial impact.

[36] Source for the description of TDs: https://shift2rail.org/research-development/ip1/

Dependencies and market readiness in IP1. There are no technical dependencies across TDs in IP1. All solutions can be implemented in parallel as they refer to different train sub-systems. However, TD1.3, 1.4, 1.5, 1.6 are expected to come to market later than TD1.1,1.2,1.7,1.8, around 2026-27.

IP 2: communication, traffic management and control systems

IP 2 is focused on deploying advanced communications systems and enhancing traffic management (including predictive and adaptive operational control of train movements). Shift2Rail activities will support the rapid and widespread deployment of advanced traffic management and control systems by providing improved functionalities and standardised interfaces based on common operational concepts, easing migration from legacy systems, lowering overall costs, and adapting them to the needs of different rail segments as well as a multimodal smart mobility system. It is organised around 11 TDs[37]:

TD 2.1 - Communication System. It aims to overcome the shortcomings in the current European Train Control System (ETCS) and Communications-Based Train Control (CBTC) and deliver an adaptable train-to-ground communications system usable for train control applications in all market segments, using packet switching/IP technologies (GPRS, EDGE, LTE, Satellite, Wi-Fi, etc.). The system will enable easy migration from existing systems (e.g., GSM-R), provide enhanced throughput, safety and security functionalities to support the current and future needs of signalling systems, and be resilient to interference and open to developments in radio technology. Backwards compatibility with ERTMS will be ensured. Expected impact: increased capacity, speed (quality of service), safety and security.

TD 2.2 - Automatic Train Operation (ATO). The aim is to develop and validate a standard ATO up to GoA3/4 over ETCS, where applicable, for all railway market segments (mainline/high speed, urban/suburban, regional and freight lines). Expected impact: increased capacity and safety.

TD 2.3 - Moving Block. It aims to improve line capacity by decoupling the signalling from the physical infrastructure, and removing the constraints imposed by trackside train detection, thereby allowing more trains on a given main line, especially for high-density passenger services. Expected impact: increased capacity, speed (quality of service) and safety.

TD 2.4 - Safe Train Positioning. It aims to develop a fail-safe, multi-sensor train positioning system (applying Global Navigation Satellite Systems (GNSS) technology to the current ERTMS/ETCS core and possible introducing an add-on for fulfilling the scope). It will enable the use of other new technologies (e.g., inertial sensors) or sensors (e.g., accelerometers, odometer sensors), to boost the quality of train localisation and integrity information, while also reducing overall costs, in particular by enabling a significant reduction in all trackside conventional train detection systems (balises, track circuits and axle counters). Expected impact: increased capacity, speed (quality of service) and safety, reduction of costs.

TD 2.5 - Train Integrity. It aims to specify and prototype an innovative on-board train integrity solution, capable of autonomous train-tail localisation, wireless communication between the tail and the front cab, safe detection (SIL4) of train interruption and autonomous power supply functionality without the deployment of any fixed trackside equipment. This functionality will be developed for those market segments (e.g., freight and low traffic lines) lacking such a function. Expected impact: increased safety and reduction of costs.

[37] https://shift2rail.org/research-development/ip2/

TD 2.6 - New laboratory test framework. The development of a new framework comprises simulation tools and testing procedures for carrying out open test architecture with clear operational rules and simple certification of test results. It aims to minimise on-site testing by performing full laboratory test processes. The test framework will also allow remote connection of different components/subsystems located in various testing labs. Expected impact: reduction of costs, increased capacity in marshalling yards (due to testing grounds no longer being required).

TD 2.7 - Standardised engineering and operational rules. It aims to contribute to the creation of an open standard interface and a functional ETCS description model, all based on formal methods. It will ease verification and authorisation processes, eventually leading to improved interoperability, while reducing the need for extensive field tests in future. Expected impact: reduction of costs and reduction of administrative burden for market entries and innovative solutions.

TD 2.8 - Virtual Coupling. It aims to enable 'virtually coupled trains' to operate much closer to one another (within their absolute braking distance) and dynamically modify their own composition on the move (virtual coupling/uncoupling of train convoys). Expected impact: significantly increased capacity and speed (quality of service).

TD 2.9 - Traffic Management System. It aims to improve traffic management operations with automated processes for data integration and exchange with other rail business services. The backbone of the new architecture will be a scalable, interoperable and standardised communication structure applicable within an integrated rail services management system. These features will be combined with new business service applications to allow for predictive and dynamic traffic management. It will use and integrate real-time status and performance data from the network and from the train, using on-board train integrity solutions and network object control functions, supported by wireless network communication. Expected impact: : increased attractiveness of service through higher punctuality, increased capacity, reduced operational expenditures.

TD 2.10 - Smart radio-connected all-in-all wayside objects. This TD aims to develop autonomous, complete, intelligent, self-sufficient smart equipment ('boxes') able to connect not only with control centres (e.g., interlocking) or other wayside objects and communicating devices in the area (by radio or satellite), but also, for instance, with on-board units. Such intelligent objects — knowing and communicating their status conditions — would not only provide opportunities in terms of cost reduction and asset management improvement, but also set out new means of railway network information management and control. Expected impact: increased attractiveness of service through higher speeds and punctuality, reduced operational expenditures.

TD 2.11 - Cyber Security. It aims to achieve the optimal level of protection against any significant threat to the signalling and telecom systems in the most economical way (e.g., protection from cyber-attacks and advanced persistent threats coming from outside). Expected impact: Reduced cyber risks - no direct impact on cash flow.

Dependencies and market readiness in IP2. Multiple dependencies are identified within IP2, for instance the need for the communication infrastructure and tools to be available for block-train or virtual coupling systems.

TD2.8 Virtual coupling is expected to become market ready later in the study period, around 2031.

IP 3: infrastructure

IP3 is focused on enhancing and upgrading the rail network infrastructure and optimizing its management and maintenance. It is organised around 11 TDs[38]:

TD3.1 - Enhanced Switch & Crossing System is to improve the operational performance of existing Switch & Crossing (S&C) designs by delivering new S&C subsystems with improved RAMS, LCCs, sensing and monitoring capabilities, self-adjustment, noise and vibration performance, interoperability, and modularity. Expected impact: increased capacity and quality of service (safety & speed), reduction of operational expenditures.

TD3.2 – Next Generation Switch & Crossing System intends to produce radical, creative system solutions that deliver new techniques for guiding trains to cross tracks with the goal of improving capacity while lowering maintenance costs, traffic disruptions, and LCCs. Expected impact: increased capacity and quality of service (safety & speed), reduction of operational expenditures.

TD 3.3 - Optimised Track System will examine how new solutions in the form of goods, processes, and procedures might achieve improved levels of dependability, sustainability, capacity, and LCC savings by challenging track construction assumptions now inherent in track design. The goal is to provide medium-term solutions, which necessitates that the solutions be compatible with existing solutions and regulations. Expected impact: increased capacity and quality of service (safety & speed), reduction of operational and capital expenditures for new infrastructure.

TD 3.4 – Next-Generation Track System intends to significantly improve the track system, with a time frame of 40 years beyond the current state of the art. This suggests that significant improvements in performance should be prioritized. The TD process will follow a tightly connected chain, beginning with analyzing the railway's long-term needs and feasible ways to achieve them. Expected impact: increased capacity, and quality of service (safety & speed).

TD 3.5 – Proactive Bridge and Tunnel Assessment, Repair, and Upgrade project's major goal is to enhance inspection procedures and repair processes in order to minimize costs, improve quality, and, if possible, extend the service life of bridges and tunnels. Furthermore, noise and vibration reduction are prioritized goals. Expected impact: reduced maintenance costs and operational costs.

TD 3.6 – Dynamic Railway Information Management System (DRIMS) aims to create an innovative system for managing, processing, and analyzing railway data. This TD's operations will be closely linked to the other two TDs in the area of data collection and administration. The purpose of DRIMS is to collect data from the Railway Integrated Measuring and Monitoring System (RIMMS – TD 3.7) and offer high-quality input to Intelligent Asset Management Strategies (IAMS – TD 3.8). Expected impact: more targeted investments and lower risk investments.

The goal of **TD 3.7 - Railway Integrated Measuring and Monitoring System (RIMMS)** is to provide non-intrusive and completely integrated tools and methodologies for obtaining information on the present status of assets. To that purpose, the TD will concentrate on collecting asset status data in collaboration with TD3.1 through TD3.5. Expected impact: more targeted investments and lower risk investments, higher quality of service (information to the customer).

The vision of **TD 3.8 - Intelligent Asset Management Strategies (IAMS)** is a holistic, whole-system approach to asset management that uses data collected and processed by TD3.6 and

[38] https://shift2rail.org/research-development/ip3/

TD3.7. This includes incorporating long-term strategies into the day-to-day maintenance and other maintenance tasks. Expected impact: more targeted investments and lower risk investments.

The **TD 3.9 – Smart Power Supply** project's overall goal is to establish a railway power grid as part of a larger integrated and communicating system. Expected impact: lower exposure to global energy price volatility, higher quality of service (less pollution, higher speeds and lower noise levels).

TD 3.10 – Smart Metering for Railway Distributed Energy Resource Management System aims to create a precise map of energy flows throughout the railway system, which will serve as the foundation for any energy management strategy. Expected impact: more targeted investments and lower risk investments, lower energy cost (OPEX).

TD 3.11 - Future Stations project's main ambition is to improve the station's consumer experience. The TD is organized around four core functional demands: two demands address capacity and security in large stations, one demand addresses small station design with the goal of lowering whole-life costs and standardizing design, where practicable, and the final demand addresses accessibility[39]. Expected impact: improved quality of service (customer experience)

Dependencies in IP3. There are no interdependencies. All solutions can be implemented in parallel, as they refer to different train subsystems. TD3.2 and 3.4 (new generation (switch controls and tracks) however will be implemented after an amortization period of TD3.1 and 3.3 which will optimize the current version of these assets.

IP 4: Technical framework, Customer experience applications and Multimodal travel services.

IP4 is focused on significantly improving service quality for rail users and making multimodal travel easier. It develops interoperability standards for TSPS, solutions to ease ticket search and purchase, and journey tracking. It is organised around 6 TDs[40]:

TD4.1 - Interoperability Framework aims to make multimodal travel easier in a diversified setting with several modes of transportation. The world of transportation service providers requires flexibility; it advances at its own speed and employs a variety of data types and interfaces. At the semantic level, interoperability creates formal and explicit representations of the transportation domain in an open, standard, machine-readable language that computers can exchange automatically. Expected impact: increased quality and thus attractiveness of service.

TD4.2 – Travel Shopping intends to provide a comprehensive shopping application enabler that includes all modes of transportation, all operators, and all geographies, and produces a list of customer-relevant trip offers that are guaranteed available for booking, purchase, and ticketing. The IP4 model encourages the integration of data from distributed travel providers as well as the orchestration of services like expert journey planning. The Interoperability Framework will make things easier by allowing applications based on multiple standards or code lists to communicate meaningfully without requiring costly application adjustments. Expected impact: increased demand for rail transport.

TD4.3 - Booking & Ticketing will manage multiple but concurrent interactions with several booking, payment, and ticketing engines, including the all-important roll-back activities. The traveller will have easy access to the whole and integral components of his or her journey,

[39] EURail. 2022. Innovation Programme 3. [Available at: https://shift2rail.org/research-development/ip3/]
[40] https://shift2rail.org/research-development/ip4/

including easy generation of the entitlement tokens required for all ticket validation controls encountered en-route, thanks to the concept of a unique passenger identify and wallet. It will drastically simplify the traveller's life by eliminating the uncertainties associated with several booking, payment, and ticketing processes that take place "behind the scenes". Expected impact: improved customer experience (information).

TD4.4 - Trip-tracker will provide travellers with in-trip assistance when navigating transportation nodes, as well as personalized information (based on predefined preferences) and up-to-date status reports on subsequent legs of the journey; it will also assist them in the event of a disruption by suggesting updated booking options as well as updated travel rights. Expected impact: improved customer experience (information).

TD4.5 Travel Companion keeps and communicates traveller's personal preferences in a wallet, the traveller will have complete control over their journey. It will provide access to all travel services, including purchasing and booking, as well as the ability to store travel rights. Retailers and operators will be able to identify and authorize the Travel Companion to access their systems at the same time. Expected impact: improved customer experience (information).

TD 4.6 - Business Analytics Platform will be in charge of managing those data. Novel 'big data' technologies, such as 'intentional' semantic information (denoting objects by properties rather than values), will enhance the ability to analyse distributed and heterogeneous linked data, opening up a slew of new opportunities for all ecosystem actors to gain unprecedented insights and new intelligence for the benefit of operators and travellers.

Despite the fact that IP4 is organized around six Technology Demonstrators (TDs) with distinct and non-overlapping goals, all contributions will go to a single **IP4-integrated Technical Demonstrator (TD4.7),** which will act as the orchestrator of other TDs' developments and ensure the systems approach to integrating the various TDs' outcomes.

Dependencies in IP4. TD4.1, TD4.2 and TD4.5 need to be finalised before the benefits for the other TDs can arise. Trip Planning TD4.2 is essential and the minimum functionality in IP4. To plan a journey the Interoperability Framework TD4.1 and the Travel Companion TD4.5 are needed. So, these three need to be clustered. The other three which are Booking & Ticketing TD4.3, Trip Tracking TD4.4 and Business Analytics TD4.6 are optional an can be added occasionally.

TD4.1 will be something between 20% and 90% depending on how many TSP are connected to the interoperability framework. Implementation can be done together, but benefits will only arise once all is (at least largely) implemented.

IP 5: rail freight performance

IP5 is focused on modernising and digitalising freight rolling stock. It is structured around 5 TDs[41]:

TD 5.1 - Fleet Digitalisation and Automation intends to improve important sectors of rail freight transportation by creating key technologies that will enable a digital and automated rail freight system. Condition-based Maintenance (CBM), Automatic Coupling, Freight Automatic Train Operation (ATO), and Connected Driver Advisory Systems are all covered in TD 5.1. (C-DAS). Additional systemic topics, such as autonomous train preparation, are

[41] https://shift2rail.org/research-development/ip5/

covered as subordinate topics in these innovation fields[42]. Expected impact: increased capacity and lower OPEX.

TD 5.2 - Digital Transport Management is a term used to describe the management of digital transportation. The goal of this TD is to develop freight solutions that are highly reliable and flexible, and that enable the optimization of overall transport time, in particular by increasing rail freight operations' average speed and reducing handling and set up times at marshalling yards and terminals using new automation technology, but also by ensuring that rail freight can better operate in conjunction with passenger traffic in order to maximize efficiency[42]. Expected impact: increased capacity and lower OPEX.

The main goal of the **TD 5.3 - Smart Freight Wagon Concepts** project is to develop technical demonstrations of the next generation of freight bogies and freight wagons in order to demonstrate their competitiveness and demonstrate that a rail freight option is capable of meeting the freight market demands of the year 2020+, allowing for a modal split change[42]. Expected impact: increased quality & attractiveness of service.

TD 5.4 - New Freight Propulsion Concepts is a collection of new freight propulsion ideas. The goal of this TD is to improve the overall performance of today's locomotives by introducing and integrating new technologies and functionalities. Future locomotives will offer great flexibility for operation on non-electrified and electrified lines, as well as hybridization of locomotives with electric traction for shunting, low-speed operations, and other applications. Increase operational efficiency by automating various activities such as train start-up, train preparation, start of mission, stabling and parking, and generally shunting; Feature remote control for distributed power, allowing the train length to be increased up to 1500m and thus improving the cost efficiency of rail transport[42]. Expected impact: improved service (higher speeds), lower operational costs and lower dependence to price volatility of energy carriers.

TD 5.5 - Business analytics and implementation strategies guarantee that IP5 develops technologies in line with industry needs and with well-thought-out plans for market release. Migration strategies for large-scale implementation of new technological solutions, establishing market niches, and developing specifications and Key Performance Indicators for freight to offer this[42]. Expected impact: more targeted investments and lower risk investments.

TD dependencies & technology readiness level in IP5. There is no particular interdependencies recognised in this IP. However, the technology readiness level will be a notable factor in the deployment of this IP. This is especially relevant for TD5.3 which is a rather futuristic concept and will require a certain period of technology development before it becomes viable. As noted by the IP expert, this period will be about 10 years, making the start date of TD5.3 in 2042. All other TDs are able to start today.

The deployment period (if needed):

The 10 years period is due to the fact that most of the traffic management systems are national/company-based and the lead times to integrate on European level is therefore long.

Step by step some processes could be aligned e.g via RFCs and other projects. It means faster implementation in this case (3-5 years) and involves interested and participating countries (only).

[42] EURail. 2022. Innovation Programme 5. [Available at: https://shift2rail.org/research-development/ip5/]

Annex 7: Selection of graphs and diagrams displayed individually

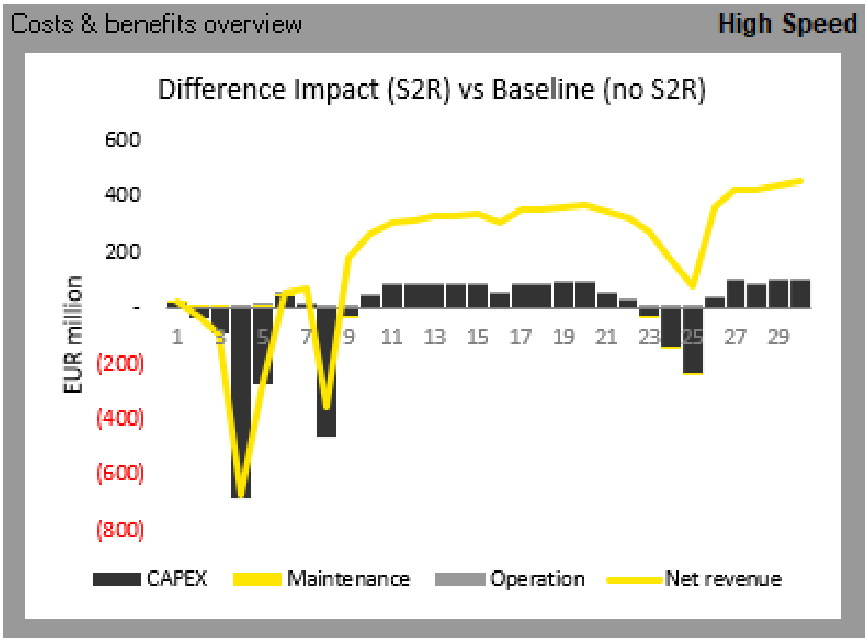


Figure 20: SPD1 – Impact of S2R on cash flow as compared to the baseline (future without S2R) scenario

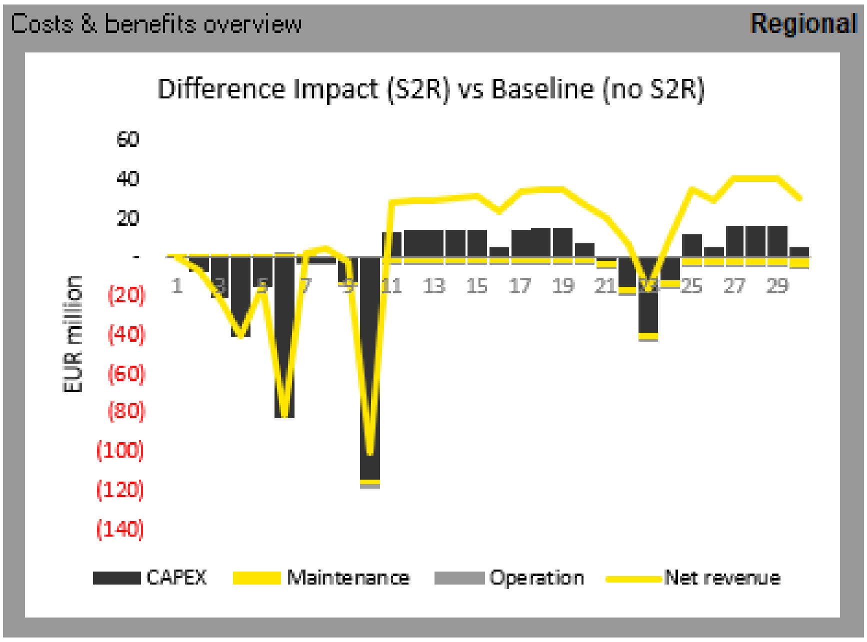


Figure 21: SPD2 - Impact of S2R on cash flow as compared to the baseline (future without S2R) scenario

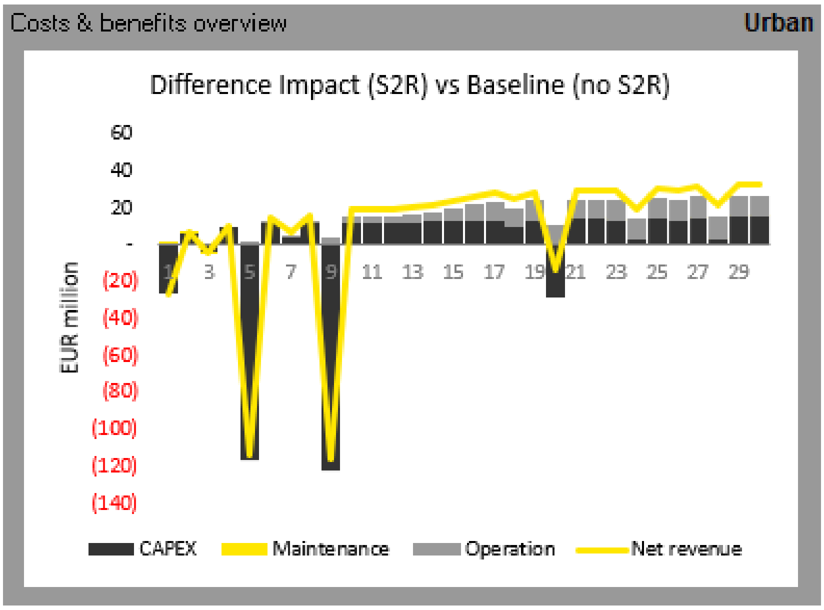


Figure 22: SPD3 - Impact of S2R on cash flow as compared to the baseline (future without S2R) scenario

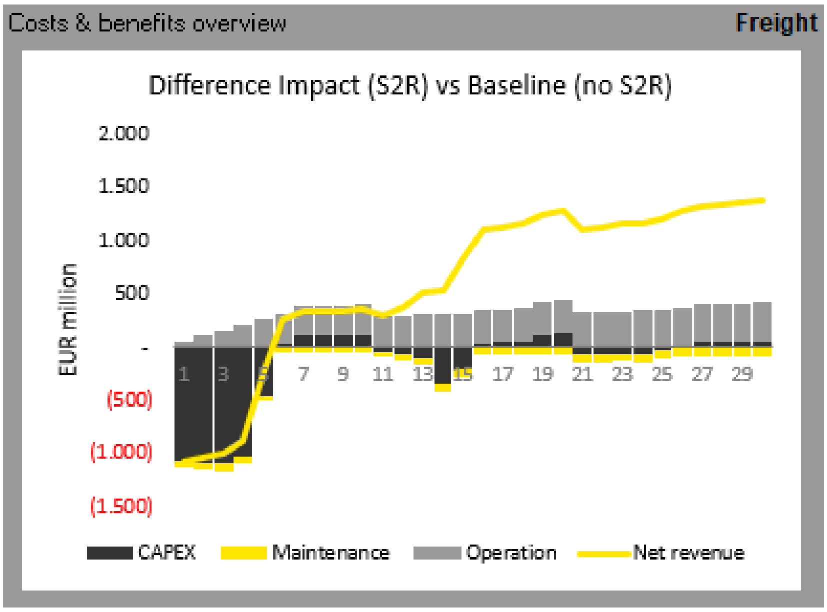


Figure 23: SPD4 - Impact of S2R on cash flow as compared to the baseline (future without S2R) scenario

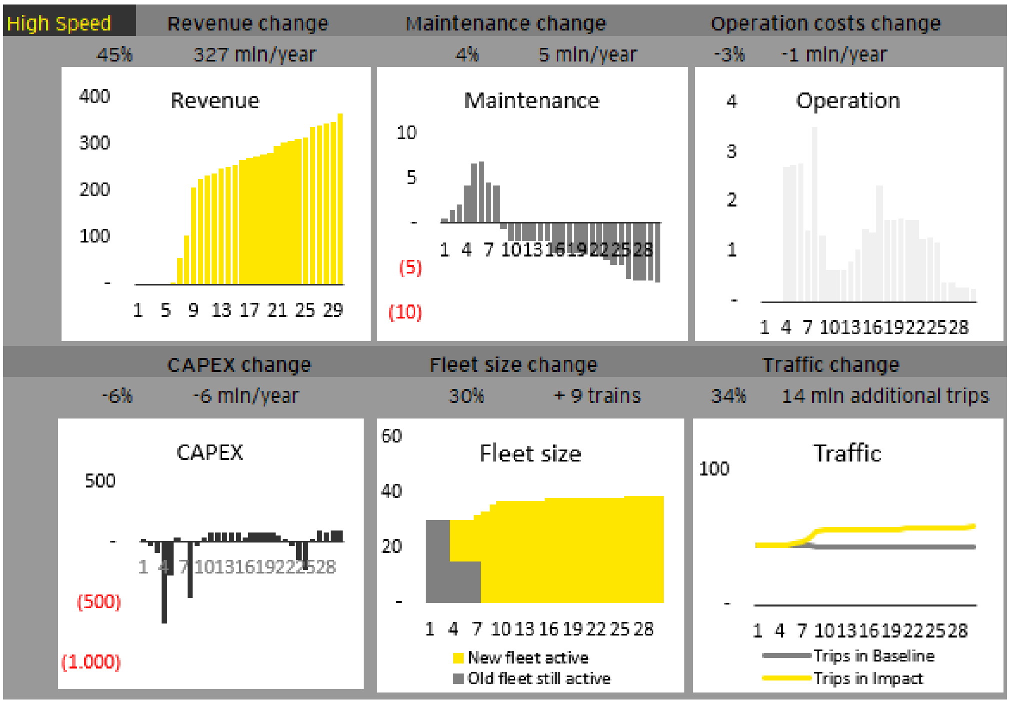


Figure 24: SPD1 - Differences between the impact and baseline scenarios

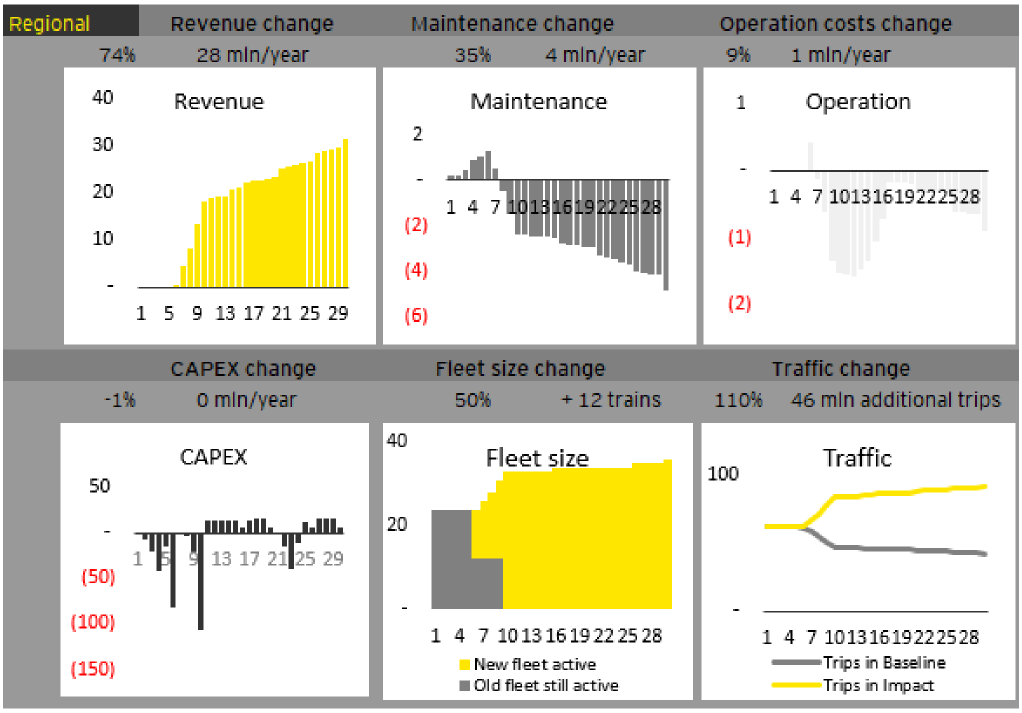


Figure 25: SPD2 - Differences between the impact and baseline scenarios

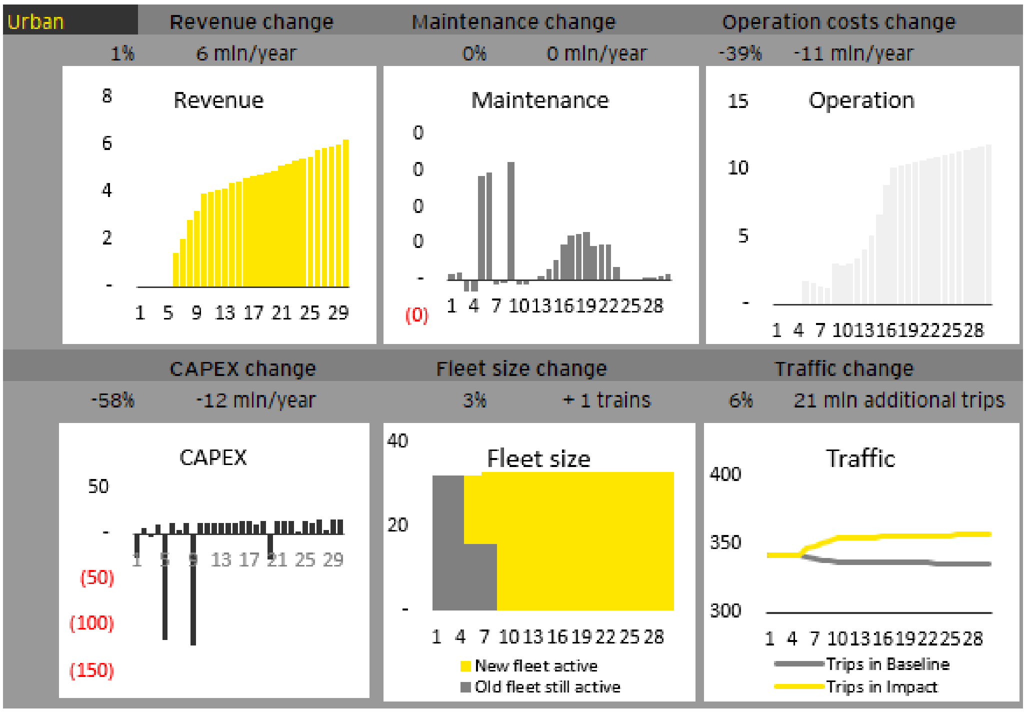


Figure 26: SPD3 - Differences between the impact and baseline scenarios

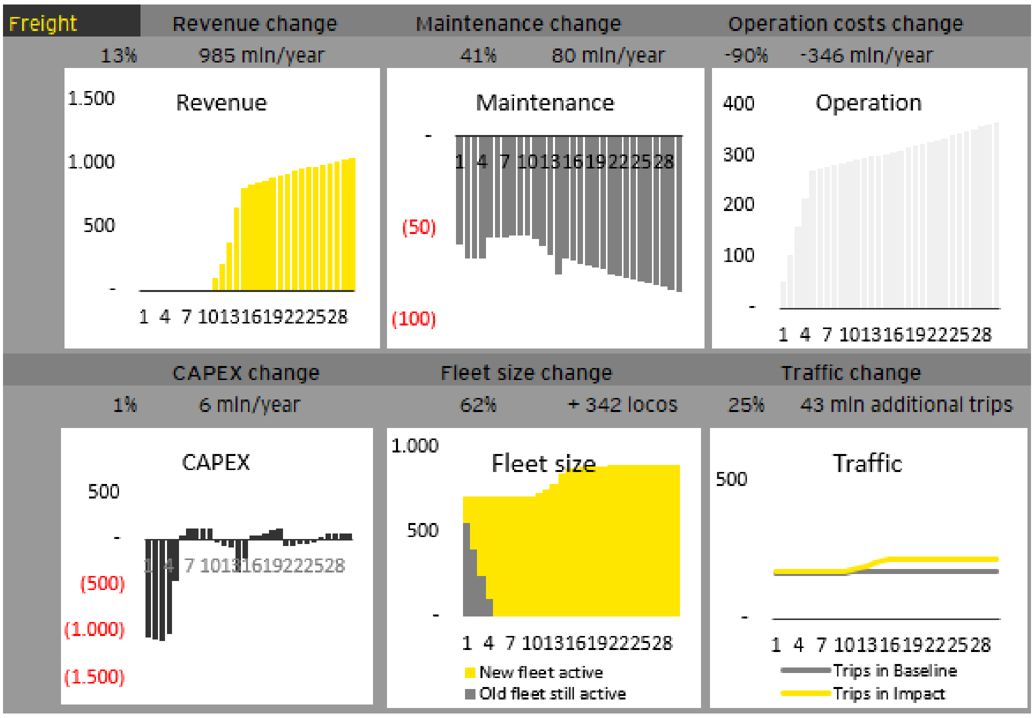


Figure 27: SPD4 - Differences between the impact and baseline scenarios

Annex 8: References

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