EXPLORATORY RESEARCH

Multimodal Performance Framework

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Copyright Statement

TRANSIT

TRAVEL INFORMATION MANAGEMENT FOR SEAMLESS INTERMODAL TRANSPORT

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Abstract

This deliverable presents a multimodal assessment performance framework. It initially reviews the existing air transport and ground transport performance assessment frameworks and their indicators. It discusses the gaps to properly address multimodality and proposes transformations to fill this gap. Finally, it develops a multimodal performance framework, analyses the trade-offs between the proposed key performance areas and indicators, and discusses how the proposed performance indicators can be measured and modelled

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1 Introduction

1.1 Scope and objectives

The goal of TRANSIT is to develop a set of multimodal key performance indicators (KPIs), mobility data analysis methods and transport simulation tools allowing the evaluation of the impact of innovative intermodal transport solutions on the quality, efficiency and resilience of the door-to-door passenger journey.

The specific objectives of the project are the following:

1. Propose innovative intermodal transport solutions based on information sharing and coordinated decision-making between air transport and other transport modes.
2. Develop multimodal KPIs to evaluate the quality and efficiency of the door-to-door passenger journey.
3. Investigate new methods and algorithms for mobility data collection, fusion and analysis allowing a detailed reconstruction of the different stages of long-distance multimodal trips and the measurement of the new multimodal KPIs.
4. Develop a modelling and simulation framework for the analysis of long-distance travel behaviour that allows a comprehensive assessment of intermodal solutions in terms of the proposed multimodal KPIs.
5. Assess the expected impact of the proposed intermodal concepts and derive guidelines and recommendations for their practical development and implementation.

This document aims to:

- review existing performance assessment frameworks both for ATM and ground transport;
- analyse existing indicators and identify the main gaps to analyse multimodal trips;
- propose a new framework that fills these gaps and enables the analysis of intermodal solutions.

To write this document, an extensive literature review has been carried out. The methodology followed to do so, has been the following:

- Read the key papers identified in the Transit proposal;
- Read the key ATM Performance Frameworks;
- Read the most relevant papers cited by the key papers identified in the Transit proposal;
- Read the papers that cite the key papers identified in the Transit proposal; and
- Repeat the latter two steps with the new papers iteratively until no more relevant papers are found.

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1.3 List of acronyms

Table 1.1. List of acronyms

Acronym	Definition
ANS	Air Navigation Services
ARES	Airspace Reservation/Restriction
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CDR	Conditional Route

Acronym	Definition
CFIT	Control Flight Into Terrain
CJTD	Customer Journey Time Delay
D2D	Door to Door
D2K	Door to Kerb
DIS	Deviation Index based on Stops
DUC	Determined Unit Cost
EC	European Commission
EI	Earliness Index
FUA	Flexible Use of Airspace
ICAO	International Civil Aviation Organisation
IR	Interconnectivity Ratio
IVTT	In-Vehicle Travel Time
JTBI	Journey Time Buffer Index
K2G	Kerb to Gate
KPA	Key Performance Areas
KPI	Key Performance Indicators
NUTS1	First-level Classification of Territorial Units for Statistics
OTP	On-Time Performance
OVTT	Off-Vehicle Travel Time
PIR	Punctuality Index based on Routes
PM	Particulate Matter
RAT	Risk Analysis Tool
RBT	Reference Business Trajectory
RI	Running Index
SES	Single European Sky
SESAR	Single European Sky ATM Research
SSDI	Second Order Stochastic Dominance Index
TMA	Terminal Manoeuvring Area
TTR	Travel Time Ratio
TTW	Travel Time Window
VOC	Volatile Organic Compound
WDI	Weighted Delay Index
WI	Width Index

2 Indicators and Performance Frameworks

2.1 Introduction

Indicators are essential tools for the control and monitoring of processes. They could be defined as "**specific variables suitable for quantification (measurement)**" (Litman, 2007). The use of indicators is highly recommended because of the advantages they bring (Briguglio, 2003; Mitchell et al., 1995):

- Support decision-making.
- Focus the discussion with stakeholders.
- Promote the idea of integrated action.
- Monitor and evaluate developments.
- Allow the synthesis of masses of data.
- Show the current position in relation to desirable states.
- Demonstrate progress towards goals and objectives.

The set of indicators designed to monitor and evaluate the effects of a policy is known as **Impact Assessment Framework**. The indicators of such framework should be equipped with pre-defined thresholds (targets) that represent the achievement of a goal (Litman, 2007). These frameworks allow policy makers to evaluate the outcomes of their decisions.

2.2 Indicator characteristics

There is abundant documentation discussing the most important characteristics that a good Impact Assessment Framework should have (Litman, 2012; Zito & Salvo, 2011; Haghshenas & Vaziri, 2011; CIVITAS GUARD, 2010; Castillo & Pitfield, 2009; DISTILLATE project, 2005). These could be summarised as:

- The framework should be **comprehensive**: indicators should take into account various impacts, such as economic, social and environmental impacts.
- The indicators should be:
    - **Measurable**: indicators should be capable of being measured.
    - **Target relevant**: indicators should be closely related to the target they measure.
    - **Familiar / easy to understand**: indicators should be understandable to all stakeholders.
    - **Independent**: indicators should be independent of each other.
- The **data** used to calculate the indicators should have the following properties:
    - Available, reliable and regularly updated data.
    - Cost-effective data collection.
    - Standardisation aiming to facilitate comparison.

From the previous list, data quality is probably one of the most important and decisive characteristics. Without appropriate data, indicator values are not reliable and it is not possible to evaluate the degree of achievement of the objectives previously established. The TRANSIT project pays special attention to the extraction of useful information from new data sources, such as mobile phone data and data from open trip planners, as well as from more traditional data sources, such as travel surveys. The appropriate use of these data sources could lead to an improvement in the measurement of certain indicators.

2.3 The need for a multimodal performance framework

Even though multimodality is at the spotlight of European transport policy, at the moment there is not an integrated framework of measures and indicators for assessing the performance of multimodal transport systems. **The performance assessment of a multimodal system cannot be made by simply adding the performance of the different legs**. While monetary cost and travel time, for instance, are usually additive indicators, other indicators (e.g., time variability) cannot be obtained by adding the same indicators for each leg. **Time variations of each leg of the trip may be correlated**, e.g. the variation of the in-vehicle time for one leg can be absorbed by the waiting time at the transfer, hence reducing the time variability corresponding to the concatenation of the two modes. Another example are **safety indicators, which exhibit the "weakest link" phenomenon: the safety factor of the trip is determined by the factor of the worst link regardless of factors of the other modes** (Kanafani et al., 2010). Most of the indicators used to measure the performance of multimodal systems oversee these relations (Dixit et al., 2019). Kanafani et at. (2010) propose a methodology for defining measures of performance for travel time and related quantities (e.g., time variability), monetary cost, safety, reliability and flexibility for a multimodal corridor, from both the supply (transport system) and the demand (user centric) side. Influence factors affecting the reliability of travel time, such as delays and the punctuality of scheduled transport services, are discussed in Wanjek et al. (2017). Dixit et al. (2019) propose a methodology to measure travel time reliability, extending the concept of reliability buffer time proposed by Chan (2007), which measures the difference in travel time between the 95th percentile and the average travel time, by including different frequency-based transport modes. This methodology is demonstrated in a real case for multimodal trips on public transport in Amsterdam using information from smart card data.

This document aims to define a comprehensive multimodal performance indicators framework. In addition to the desirable characteristics of an indicator presented in the Section 2.2, the process to create this framework has been guided by the following principles:

- **Exploit the existing indicators and performance assessment frameworks**. TRANSIT not only analyses the air leg of the trip but also the chain of stages for a ground transport trip. Valuable performance assessment frameworks have been developed in both fields, so it is advisable to integrate the knowledge previously generated. To do so, existing ATM and ground transport performance frameworks have been reviewed in depth.
- **Apply the rationale and classifications commonly used among ATM community**, by organisations like ICAO (ICAO, 2014) and SESAR (SESAR JU, 2019) and projects like Dataset 2050 (Dataset 2050, 2017).

Table 2.1. Structure of ATM Performance Frameworks

ICAO EUR PF	SESAR PF	DATASET 2050 PF
Key Performance Areas (KPAs)	KPAs	KPAs
Focus Areas (FAs)	FAs	Mobility Focus Areas (MFAs)
Key Performance Indicators (KPIs)	KPIs and PIs	KPIs

The abovementioned structure has been used to review not only the ATM performance framework, but also the ground transport and the multimodal performance framework. This is due to the fact that the ground transport performance frameworks found in the literature lack a common structure, that the multimodal transport performance framework is built from scratch in this document, and (most importantly) that the ATM structure is sensible for both frameworks.

As it can be observed in Table 2.1, the SESAR 2020 Performance Framework has both KPIs and PIs, distinguishing between those indicators that have associated a Validation Target (KPIs) and those that do not (PIs). The same distinction will be used in the TRANSIT multimodal performance framework.

3 Review of ATM indicators

Table 3.1 and Table 3.2 below consolidate a list of KPAs, Focus Areas, KPIs and PIs used in four different ATM frameworks:

- ICAO EUR is the first framework, which contains six KPAs: safety, capacity, efficiency, environment, cost effectiveness and participation by the ATM community.
- SESAR defines another Performance Framework with 10 KPAs, which contains safety, security, environment, capacity, predictability and punctuality, cost-efficiency, flexibility, civil-military cooperation and coordination, human performance and access and equity.
- The third considered framework is the one proposed by Dataset 2050 project, which has 10 KPAs: access and equity, cost-effectiveness, efficiency, flexibility, interoperability, predictability, safety, security, sustainability (environment) and capacity.
- Finally, the SES Performance Scheme establishes a performance framework divided into four KPAs: safety, environment (efficiency), capacity and cost-efficiency.

Many of the presented KPI and PI can be adapted to an multimodal context.

Table 3.1. ATM indicators - KPIs

KPA	KPI	Source	Could it be used in an Multimodality context?
SAFETY	Total number of fatal accidents and incidents with ATM Contribution per year.	SESAR	Yes, can be adapted to become an multimodal indicator[1]
	Number of deaths per million passengers' journeys	Dataset 2050	Yes, it's an additive value
CAPACITY	Average en route ATFM (air traffic flow management) delay generated by airspace volume	ICAO	Yes, it's an additive value
	Average ATFM delay per flight in the main airports	ICAO	Yes, it's an additive value
	TMA throughput, in challenging airspace, per unit time.	SESAR	Yes, can be adapted to become an multimodal indicator

[1] In section 3 and section 4, the ATM and Transport indicators from the literature will be listed. In section 5, the transformation to include multimodality in the indicator will be specified.

KPA	KPI	Source	Could it be used in an Multimodality context?
	En route throughput, in challenging airspace, per unit time.	SESAR	Yes, can be adapted to become an multimodal indicator
	Peak Runway Throughput (Mixed mode).	SESAR	Yes, can be adapted to become an multimodal indicator
	En route ATFM delay per flight attributable to ANS (measured in minutes of delays vs the estimated time of arrival)	SES	Yes, it's an additive value
	Arrival ATFM delay per flight attributable to terminal and airport ANS and caused by landing restrictions at the destination airport	SES	Yes, it's an additive value
	Additional time in the taxi-out phase	SES	Yes, it's an additive value
	Additional time in terminal airspace	SES	Yes, it's an additive value
EFFICIENCY	Average horizontal en route flight efficiency (length of the en route part of the actual trajectory/last flight planned route vs great circle)	ICAO	No
	Average time efficiency	Dataset 2050	Yes, it's an additive value
	Average horizontal en route flight efficiency of the last filled flight plan trajectory	SES	No
	Average horizontal en route flight efficiency of the actual trajectory	SES	No
	Additional time in the taxi-out phase	SES	Yes, it's an additive value
	Additional time in terminal airspace	SES	Yes, it's an additive value
ENVIRONMENT	Actual average fuel burn per flight	SESAR	Yes, can be adapted to become an multimodal indicator

KPA	KPI	Source	Could it be used in an Multimodality context?
COST EFFECTIVENESS	Flights per ATCO-Hour on duty (air traffic controller)	SESAR	Yes, can be adapted to become an multimodal indicator
	Technology Cost per flight.	SESAR	Aggregated value, difficult to use on an multimodal context
PREDICTABILITY AND PUNCTUALITY	Variance of Difference in actual & Flight Plan or RBT durations.	SESAR	Yes, can be adapted to become an multimodal indicator
	% Flights departing within +/- 3 minutes of scheduled departure time due to ATM and weather-related delay causes.	SESAR	Yes, can be adapted to become an multimodal indicator
	Variability on intra-European flights - standard deviation in arrival time of scheduled flights at their destination airport around the mean arrival time of that flight.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Variability on airport public transport - standard deviation in arrival time of public transport surface access modes at the airport around the mean arrival time of their journey.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Punctuality of intra-European flights - % of scheduled flights that arrive within 10 minutes of their scheduled arrival time (irrespective of their departure time).	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Punctuality of airport public - % of scheduled public transport journeys that arrive at the airport within 5 minutes of their scheduled arrival time.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Reliability of airport public transport - % of scheduled public transport journeys cancelled or delayed by more than 30 minutes.	Dataset 2050	Yes, can be adapted to become an multimodal indicator

KPA	KPI	Source	Could it be used in an Multimodality context?
	Likelihood of missing a flight - probability that delays in the D2K and K2G segments of the journey will result in the passenger´s not being able to board their plane.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Likelihood of arriving more than 15 minutes late at destination - probability that individual delays in each leg of a journey will result in a final delay greater than 15 minutes, including total cancellation.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
	Minimum buffer time required - average minimum buffer time required at the door of origin to ensure a 95% chance of arriving at destination within 15 minutes of the planned arrival time.	Dataset 2050	Yes, can be adapted to become an multimodal indicator
ACCESSIBILITY AND EQUITY[2]	4-hour reach	Dataset 2050	Yes
	Low-income access	Dataset 2050	Yes
	Medium-income access	Dataset 2050	Yes
	High-income access	Dataset 2050	Yes
	Income access disparity	Dataset 2050	Yes
	Careless access	Dataset 2050	Yes
	Disabled access	Dataset 2050	Yes

[2] In ICAO and SESAR frameworks, Access and Equity refers to a fair treatment of airspace users, while in the Dataset 2050 the concept is more related to accessibility and social inclusion. Given the passenger-centric focus of the TRANSIT project, here we have adopted the second interpretation and renamed this KPA as 'Accessibility and Equity).

KPA	KPI	Source	Could it be used in an Multimodality context?
	Affordability	Dataset 2050	Yes
	Unaffordability	Dataset 2050	Yes

Table 3.2. ATM indicators - PIs

KPA	PI	Source	Could it be used in an Multimodality context?
SAFETY	Effectiveness of Safety Management (Safety Maturity Questionnaire)	ICAO	No
	Level of State/Safety culture (Safety Culture Questionnaire)	ICAO	No
	Adoption of an harmonised occurrences severity classification methodology	ICAO	No
	Mid-air collision – En route	SESARI	Yes, it's an additive value
	Mid-air collision – TMA (Terminal Manoeuvring Area)	SESAR	Yes, it's an additive value
	Runway collision accident	SESARI	Yes, it's an additive value
	Runway excursion accident	SESAR	Yes, it's an additive value
	Taxiway collision accident	SESAR	Yes, it's an additive value
	CFIT (Control Flight Into Terrain) accident	SESAR	Yes, it's an additive value
	Wake related accident	SESAR	Yes, it's an additive value
	Effectiveness of safety management	SES	No
	Application of the severity classification based on the RAT (Risk Analysis Tool)	SES	Yes
	Level of presence and absence of just culture	SES	No
	Application of automated safety data recording for separation minima infringement monitoring	SES	No
	Application of automated safety data recording for runway incursion monitoring	SES	No
	Level of occurrence reporting	SES	No

KPA	PI	Source	Could it be used in an Multimodality context?
	Number of separation minima infringements, runway incursions, airspace infringements and ATM specific occurrences	SES	No
CAPACITY	ARES Capacity	SESAR	No
	Peak Departure throughput per hour (Segregated mode)	SESAR	Yes, can be adapted to become an multimodal indicator
	Peak Arrival throughput per hour (segregated mode)	SESAR	Yes, can be adapted to become an multimodal indicator
	Unaccommodated traffic reduction	SESAR	Yes, can be adapted to become an multimodal indicator
	Loss of Airport Capacity Avoided.	SESAR	Yes, can be adapted to become an multimodal indicator
	Airport time to recover from non-nominal to nominal condition	SESAR	Yes, can be adapted to become an multimodal indicator
	Loss of Airspace Capacity Avoided	SESAR	Yes, can be adapted to become an multimodal indicator
	Airspace time to recover from non-nominal to nominal condition	SESAR	Yes, can be adapted to become an multimodal indicator
	Minutes of delays	SESAR	Yes, can be adapted to become an multimodal indicator
	Number of cancellations	SESAR	Yes, can be adapted to become an multimodal indicator
	Delay elasticity with respect to throughput - average number of additional minutes of travelling time triggered by an additional passenger in the system	Dataset 2050	Aggregated value, difficult to use on an multimodal context

KPA	PI	Source	Could it be used in an Multimodality context?
	ATFM slot adherence	SES	No
	ATC pre-departure delay	SES Performance Scheme	Yes, it's an additive value
EFFICIENCY	Fastest possible mode or combination of modes is selected (D2K)	Dataset 2050	Yes, it's an additive value
	Shortest possible time, (a) with, (b) without, bags, allowing for arrival at gate within minimum (boarding process) time specified by the carrier (K2G)	Dataset 2050	Yes, it's an additive value
	Shortest terminal, taxi-out, available routing in taxi-in configurations (G2G)	Dataset 2050	Yes, it's an additive value
	Shortest possible time, (a) with, (b) without, baggage reclaim (G2K)	Dataset 2050	Yes, it's an additive value
	Pax time efficiency - best possible journey time/actual time travel	Dataset 2050	Yes, it's an additive value
	Effective use of CDRs (Conditional Routes)	SES	No
	Effectiveness of booking procedures for flexible use of airspace (FUA)	SES	No
	Rate of planning of conditional routes (CDRs)	SES	Yes
ENVIRONMENT	CO_2 emissions related to inefficiencies in route extension	ICAO	Yes
	CO_2 emissions	SESAR	Yes
	Reduction in average flight duration	SESAR	Aggregated value, difficult to use on an multimodal context
	CO_2 per passenger km	Dataset 2050	Yes, it's an additive value
	NO_x per passenger km	Dataset 2050	Yes, it's an additive value
	Global warming potential per km of air journey	Dataset 2050	Yes, it's an additive value

KPA	PI	Source	Could it be used in an Multimodality context?
	Global potential of intra-European air travel	Dataset 2050	Aggregated value, difficult to use on an multimodal context
	Total global warming potential of intra-European travel	Dataset 2050	Aggregated value, difficult to use in an multimodal context
	Relative noise scale	SESAR	No
	Size and location of noise contours	SESAR	Yes
	Number of people exposed to noise levels exceeding a given threshold	SESAR	Yes
COST EFFECTIVENESS	IFR (instrument flight rules) Flights (en route) per ATCO hour duty	ICAO	No
	IFR flight hours per ATCO hour on duty	ICAO	No
	IFR movements per ATCO hour on duty	ICAO	No
	Direct ANS (air navigation service) Gate-to-gate cost per flight.	SESAR	Yes, it's an additive value
	Direct operating costs for an airspace user.	SESAR	Yes, it's an additive value
	Indirect operating costs for an airspace user	SESAR	Yes, it's an additive value
	Overhead costs for an airspace user	SESAR	Yes, it's an additive value
	Passenger distance per euro spent	Dataset 2050	Yes, it's an additive value
	Passenger distance per euro airline cost	Dataset 2050	Yes, it's an additive value
	DUC (Determined Unit Cost) for en route ANS (called DUR in RP1)	SES	Yes, it's an additive value
	DUC for terminal ANS	SES	Yes, it's an additive value
	Terminal ANS costs	SES	Yes, it's an additive value
	Terminal ANS unit rates	SES	Yes, it's an additive value

KPA	PI	Source	Could it be used in an Multimodality context?
	EUROCONTROL costs	SES	Yes, it's an additive value
PARTICIPATION BY ATM COMMUNITY	Level of participation to meetings	ICAO	No
	Level of responses to planning activities	ICAO	No
	Level of provision of performance results	ICAO	No
SECURITY	Number of cyber-security events	Dataset 2050	Yes, it's an additive value
CIVIL-MILITARY COOPERATION AND COORDINATION	Available/Required training Duration within ARES	SESAR	No
	Allocated/ Optimum ARES dimension	SESAR	No
	Transit Time to/from airbase to ARES	SESAR	No
	Fuel and Distance saved (for GAT operations)	SESAR	No
	GAT planning efficiency of Available ARES	SESAR	No
HUMAN PERFORMANCE	Suitability of technical system in supporting the tasks of human actors	SESAR	Yes
	Adequacy of team structure and team communication in supporting the human actors	SESAR	Yes
	Feasibility with regard to HP-related transition factors	SESAR	Yes
FLEXIBILITY	Distance diversity of destinations. It measures the possibility of reaching a large number of destinations from a given origin putting an emphasis in the distance range, i.e., the fact that reaching very different destinations is more important for this KPI than reaching similar destinations. It is believed that having a wide range of destinations will likely imply a larger number of trips.	Dataset 2050	Yes
	Cultural diversity of destinations. Number of NUTS1 regions reachable from an airport. It is believed that having a wide range of destinations will likely imply a larger number of trips.	Dataset 2050	Yes

KPA	PI	Source	Could it be used in an Multimodality context?
	Cultural diversity of performance. Percentage of population whose "Cultural diversity of destinations" indicator exceeds 1372, which comes from multiplying 2/3 to the number of NUTS1 in the EU (98) and multiplying ¾ to the number of countries in the EU (28)[3]. Therefore, it measures the accessibility to other countries and regions. It is believed that having a wide range of destinations will likely imply a larger number of trips.	Dataset 2050	Yes
	Mean time to fix (Average time necessary for a replacement service to be available to replace a cancelled one)	Dataset 2050	Yes
INTEROPERABILITY	Journey transition time - Total time spent in transitions during a JT	Dataset 2050	Yes, it's an additive value
	Number of phases - Number of phases required to complete a journey	Dataset 2050	Yes, it's an additive value
	Transition-journey ratio - average of (time spent during transitions / total travel time for the journey)	Dataset 2050	Yes, it's an additive value
	Average time per transition - average of time spent per transition	Dataset 2050	Yes, it's an additive value

[3] At the time when Dataset 2050 was written, the EU had 28 members.

4 Review of transport indicators

There is a large set of indicators that can be used to measure different aspects of ground transport modes. The capacity of a road, a train, or a bus, the frequency of a public transport service, the pollution per km or vehicle, and the number of accidents or casualties per km are just some examples. Another important aspect when evaluating a trip is travel time. When evaluating a **multimodal trip**, travel time is composed of access time, waiting time (if a public transport mode is used), in-vehicle time, transfer time (if a transfer is made) and egress time.

Several studies have defined a performance framework for ground transport. Most of them define an economic KPA, a social KPA and an environmental KPA, with several KPIs inside each KPA. In addition to that, some studies define KPIs on capacity, time reliability and predictability, etc. Unlike the ICAO case for ATM, there is no common framework from which all the KPAs and KPIs come from. This is why the ATM frameworks have been used as a reference and the different KPI have been categorised accordingly. The abovementioned transport KPAs (economic and social) can be easily and reasonably split into cost effectiveness, safety, security, and access and equity.

The table below gathers a list of relevant ground transport indicators found in the literature, and indicates whether they can be adapted to an multimodal context:

Table 4.1. Ground transport indicators - KPIs

KPA	KPI	Source	Could it be used in an Multimodality context?
SAFETY	Death and injuries from traffic	Marletto & Mameli (2011)	Yes, it's an additive value[4]
	Per capita traffic casualty (injury and death) rates	Litman (2012)	Yes, it's an additive value
ENVIRONMENT	CO2 from transport	Marletto & Mameli (2011)	Yes
	Waste from transport	Marletto & Mameli (2011)	Yes

[4] In section 3 and section 4, the ATM and Transport indicators from the literature will be listed. In section 5, the transformation to include multimodality in the indicator will be specified.

KPA	KPI	Source	Could it be used in an Multimodality context?
PREDICTABILITY AND PUNCTUALITY	**Reliability Buffer Time** (RBT) RBT = T95 - Taverage T95 is travel time percentile 95% and Taverage is the average travel time	Dixit et al. (2019)	Yes, can be adapted to become an multimodal indicator
	Reliability Buffer Time Metric (RBT) = T95 - Tmedian T95 is travel time percentile 95% and Tmedian is the median travel time	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Buffer Index (BI) = T95 / Taverage T95 is travel time percentile 95% and Taverage is the average travel time	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Punctuality Index based on Routes (PIR) is the probability that a bus will have an operating time within some interval of the scheduled operating time	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Buffer Time - Tb = T90%(95%) – Taverage T95 is travel time percentile 95% and Taverage is the average travel time	Sharov et al. (2016)	Yes, can be adapted to become an multimodal indicator
	Buffer Index - Ib = Tb/Taverage*100 Taverage is the average travel time	Sharov et al. (2016)	Yes, can be adapted to become an multimodal indicator
	On-time performance (OTP) - ratio on time trips vs all trips	Guittens and Shalaby (2015)	Yes
	Headway regularity (HR) -measures the fraction of observed headway that fall within an acceptable interval	Guittens and Shalaby (2015)	No
	Wait assessment (WA) - measures the fraction of observed waiting time that fall within an acceptable interval	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Excess Wait Time (EWT) is the difference between Actual Wait Time (AWT) and scheduled Wait Time (SWT)	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator

KPA	KPI	Source	Could it be used in an Multimodality context?
	Potential Wait Time (Wpotential) is the difference between W0.95 and the mean wait time.	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	The **passenger waiting index (PWI)** is the ratio of mean passenger waiting time to the frequency of the transport service.	Kumar et al. (2013)	No

Table 4.2. Ground transport Indicators - PIs

KPA	PI	Source	Could it be used in an Multimodality context?
SAFETY	Safety risk "weakest link"	Kafani and Wang (2010)	Yes, it's an additive value
CAPACITY	Length/density of railways by railway category	Vulevic (2016)	Yes, it's an additive value
	Number of ports	Vulevic (2016)	Yes, it's an additive value
	Number of airports	Vulevic (2016)	Yes, it's an additive value
	Capacity of road	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Capacity of railway track	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Capacity of ferry link	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator

KPA	PI	Source	Could it be used in an Multimodality context?
	Capacity of road nodes (intersections, tollbooth)	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Capacity of airport by category	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Capacity of port by category	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Capacity of intermodal terminals	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Number of departing/arriving trains by category and destination	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Number of departing/arriving flights by category and destination	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Number of departing/arriving ferries by category and destination	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Number of passenger cars	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
	Number of public transport vehicles by type	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator

KPA	PI	Source	Could it be used in an Multimodality context?
	Number of goods vehicles by type	Vulevic (2016)	Yes, can be adapted to become an multimodal indicator
ENVIRONMENT	CO2 from transport	Marletto & Mameli (2011)	Yes
	Waste from transport	Marletto & Mameli (2011)	Yes
	Per trip emissions of greenhouse gases (CO2, CFCs, CH4, etc.)	Litman (2012)	Yes, it's an additive value
	Air quality standards and management plans	Litman (2012)	Yes
	Per trip emissions (PM, VOCs, NOx, CO, etc.)	Litman (2012)	Yes, it's an additive value
	Management of used oil, leaks and stormwater	Litman (2012)	Yes
	Per capita impervious surface area	Litman (2012)	Yes, it's an additive value
	Per capita and devoted to transport facilities	Litman (2012)	Yes, it's an additive value
	Support for smart growth development	Litman (2012)	Yes
	Policies to protect high value farmlands and habitat	Litman (2012)	Yes
	Per capita transport energy consumption	Litman (2012)	Yes, it's an additive value
	Per capita use of imported fuels	Litman (2012)	Yes, it's an additive value
	Transport emissions of greenhouse gases, acidifying gases, organic compounds; Consumption of mineral oil products	Lautuso and Toivanen (2000)	Yes, it's an additive value
	Land coverage, consumption of construction materials	Lautuso and Toivanen (2000)	Yes, it's an additive value

KPA	PI	Source	Could it be used in an Multimodality context?
	Exposure to particulate matter (PM), nitrogen dioxide (NO2), carbon monoxide (CO); Exposure to noise; Traffic deaths; Traffic injuries	Lautuso and Toivanen (2000)	Yes, it's an additive value
	Justice of exposure to PM, NO2, CO; Justice of exposure to noise, Segregation	Lautuso and Toivanen (2000)	Yes, it's an additive value
	Fuel consumption	Kafani and Wang (2010)	Yes, it's an additive value
	Pollutants : NOx, SO2, VOC, etc.	Kafani and Wang (2010)	Yes, it's an additive value
	Traffic noise levels	Litman (2012)	Yes, it's an additive value
	% of people exposed to harmful noise	Marletto & Mameli (2011)	Yes, it's an additive value
COST EFFECTIVENESS	Household expenditures for public transport	Maretto & Mameli (2011)	Yes, it's an additive value
	Household expenditures for private transport	Maretto & Mameli (2011)	Yes, it's an additive value
	Service delivery unit costs compared with peers	Litman (2012)	No
	Generalised cost to motorway entrances by road	Vulevic (2016)	Yes, it's an additive value
	Generalised cost to railway stations by road	Vulevic (2016)	Yes, it's an additive value
	Generalised cost to airports by road	Vulevic (2016)	Yes, it's an additive value
	Generalised cost to airports by rail	Vulevic (2016)	Yes, it's an additive value
	Generalised cost to ports and logistic centres by road	Vulevic (2016)	Yes, it's an additive value

KPA	PI	Source	Could it be used in an Multimodality context?
	Generalised cost to ports and logistic centres by rail	Vulevic (2016)	Yes, it's an additive value
	Gasoline, car insurance, mileage cost, maintenance, etc.	Kafani and Wang (2010)	Yes, it's an additive value
	Discounts	Kafani and Wang (2010)	Yes, it's an additive value
	Congestion	Marletto & Mameli (2011)	Yes
PREDICTABILITY AND PUNCTUALITY	**lambda.var** = (T90-T10)/(T50) Measures the travel time variability comparing the travel time difference between percentile 90% (T90) and 10% (T10) to the percentile 50% (T50) and 10% (T10).	Rakha et al. (2010)	Yes, can be adapted to become an multimodal indicator
	Travel Time Window (TTW) range of TT that encompassed 68% of observations	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Variability Index (VI) - peak to off-peak TT variation = (upper95%-lowe95%)peak/(upper95%-lowe95%)off-peak	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Reliability Factor (RF) captures the proportion of TT within a defined interval of the mean TT	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Punctuality Index based on Routes (PIR) is the probability that a bus will have an operating time within some interval of the scheduled operating time	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Travel Time Ratio (TTR): The travel time ratio, defined as the travel time by public transport divided by travel by car between the same origin and destination.	Kumar et al. (2013)	Yes

KPA	PI	Source	Could it be used in an Multimodality context?
	Level of Service: The ratio **OVTT/IVTT** (off-vehicle travel time / in-vehicle travel time) is frequently used not only as the level-of-service indicator for public transport trips but also to assess demand elasticity.	Kumar et al. (2013)	Yes
	Running index (RI) is defined as the ratio of total service time to the total travel time. As RI increases, efficiency of the system decreases.	Kumar et al. (2013)	Yes
	Travel Time Index - Travel time peak / Travel time off-peak	Sharov et al. (2016)	Yes
	Weighted delay index (WDI) is the average delay giving a certain weight to each passenger	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Earliness index (EI) is the ration between the number of buses that depart before their scheduled time and the total number of buses	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Coefficient of variation of headway - stand dev / mean	Guittens and Shalaby (2015)	No
	Deviation Index based on Stops (DIS) is the probability that the headway between successive buses at a given stop will differ from the dispatched headway by some predefined amount	Guittens and Shalaby (2015)	No
	Width Index (WI) captures the width of the distribution of headway deviations, measured from the 5th and 95th percentiles	Guittens and Shalaby (2015)	No
	Second Order Stochastic Dominance Index (SSDI) to measure headway deviations at stops.	Guittens and Shalaby (2015)	No

KPA	PI	Source	Could it be used in an Multimodality context?
	Customer Journey Time Delay (CJTD) metric measures the difference between a traveller's expected and actual trip times from the time they begin waiting at the stop until they arrive at the destination.	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Journey Time Buffer Index (JTBI) - proposed here accounts for the bus travel time variability that passengers experience through an "arrival penalty". A "wait penalty" is added to capture the variability in departure times at the origin stop.	Guittens and Shalaby (2015)	Yes, can be adapted to become an multimodal indicator
	Interconnectivity Ratio (IR): The interconnectivity ratio can be defined as the ratio of the combination of access and the egress time to the total trip time.	Kumar et al. (2013)	Yes
SECURITY	Risk of insecurity "weakest link"	Kafani and Wang (2010)	Yes, it's an additive value
	Traveller assault (crime) rates	Litman (2012)	Yes, it's an additive value
ACCESSIBILITY & EQUITY	Public and private service accessible via telephone and computer	Marletto & Mameli (2011)	Yes
	Walkability and "cyclability"	Marletto & Mameli (2011)	Yes
	Quantity and quality of public transport	Marletto & Mameli (2011)	Yes
	Vehicles and vehicles*km per km2	Marletto & Mameli (2011)	Yes
	Walkability and "cyclability"	Litman (2012)	Yes
	Quality of road and street environments	Litman (2012)	Yes

KPA	PI	Source	Could it be used in an Multimodality context?
	Access to education and employment opportunities	Litman (2012)	Yes
	Support to local industries	Litman (2012)	No
	Availability and quality of affordable modes (walking, cycling, ride sharing and public transport)	Litman (2012)	Yes
	Portion of low-income households that spend more than 20% of budgets on transport	Litman (2012)	Yes
	Service quality	Litman (2012)	Yes
	Portion of travel by walking and cycling	Litman (2012)	Yes
	Land use mix	Litman (2012)	Yes
	Preservation of cultural resources and traditions	Litman (2012)	No
	Responsiveness to traditional communities	Litman (2012)	No
	Level of service of public transport and slow modes; Vitality of city centre; Accessibility to the centre; Accessibility to services	Lautuso and Toivanen (2000)	Yes
FLEXIBILITY	Transport system diversity	Litman (2012)	Yes
	Portion of destinations accessible by people with disabilities and low incomes	Litman (2012)	Yes
	Feasible duration of taking the mode "weakest link"	Kafani and Wang (2010)	Yes

5 From unimodal frameworks to a multimodal framework

5.1 Gaps in current impact assessment frameworks

Most of the indicators found in the literature are unimodal. In other cases, some indicators have multimodal[5] traits, but their definition should be extended to fully address multimodal trips; this is the case, for example, of the reliability buffer time proposed by Dixit et al. (2019), which does not accommodate scheduled services. Finally, some of the reviewed indicators are fully multimodal and therefore no adaptation is needed to be included in the multimodal performance framework. This is the case, for example, of the "weakest link" safety indicator proposed by Kanafani et al. (2010). According to the relationship between the performance of the different legs of the trip and the performance of the door-to-door trip, multimodal indicators can be classified into three different categories:

- Additive.
- Weakest link.
- Door to door (D2D).

When analysing an multimodal trip, many of the indicators have an **additive** nature, i.e., by adding the different legs of the trip chain, the overall trip indicator can be derived. This is the case, for example, of travel time, as well as of the great majority of environmental indicators. The sum of the travel time or pollution of the different legs of the trip accounts for the whole trip travel time or pollution. Accident ratio has also an additive nature. The overall accident ratio is the sum of all the accident ratios. Therefore, to adapt the additive indicators, a simple summation is enough to address multimodality.

Weakest link indicators measure a categorical or binary variable. For example, whether a certain noise level is exceeded or not is a binary variable. This would respond to a "weakest link" indicator, i.e., the worse link of the trip chain defines whether an alternative exceeds the threshold or not. Similarly, the capacity a trip chain is determined by the lowest value of the chain. Some subjective indicators are also integrated into this type of indicators: for example, the perception of safety or security of a leg of the chain can determine the perception of the overall trip chain. Thus, the least safe or most insecure link may determine how a user perceives the safety and security of the full trip chain.

Other indicators require considering the whole trip chain to be calculated. For example, the travel time variability or the likelihood of actually finishing a trip cannot be calculated as the sum of its parts. This

[5] Multimodality is the movement of passengers from door-to-door using a combination of different transport modes. In this document, intermodality has been used as the coordinated use of more than one transport model in one trip. Different definitions of multimodality and intermodality have been found in the literature. However, the used definitions are the ones reflected in the proposal and the grant agreement.

also applies when the measured indicators of the different legs are correlated. These indicators have been named as **D2D indicators**.

5.2 Specification of TRANSIT's multimodal performance assessment framework

Taking into account the review of existing indicators and the classification of multimodal indicators described above, a multimodal performance assessment framework has been developed. The framework includes a set of indicators, which are considered to be relevant to this project, addressing each KPA. The terminology used for describing a multimodal trip includes the following concepts:

- A trip is a displacement between the location of two activities.
- Trips are composed by several legs, between different modal change points.
- A trip has one of more alternatives to be performed, each of them composed of a chain of one or more legs.

Safety

The Safety multimodal KPA has three safety indicators (see table 5.1). The first one is the sum of the accident ratios of each leg, which results in the accident ratio of the alternative (*additive*). The second one is the perceived safety of an alternative. This one is dependent on the worst accident ratio of the alternative as users may perceive the worst ratio of the alternative as the overall accident ratio (*weakest link*). The last one measures the "social distance" of an alternative, measuring the space passengers have along the trip chain composing an alternative. The leg with the lowest "social distance" will determine the value of the alternative (*weakest link*). This indicator could be considered a comfort indicator, but during the COVID-19 crisis is considered a safety indicator. Additionally, it is expected that in the near future, once the COVID-19 crisis is overcome, passengers will still have health concerns.

Table 5.1. Safety indicators

Indicator	Description	Type	KPI/PI	Source
Accident ratio	Probability of having an accident, which is cumulative for each leg of the trip.	Additive	KPI	Litman (2012)
Perceived safety	Highest probability of having an accident among the legs.	Weakest Link	PI	Kafani and Wang (2010)
Social distancing index	Measures the minimum distance between passengers of an alternative. It aims to illustrate whether the social distance is kept or not.	Weakest Link	KPI	Own elaboration

Capacity

The Capacity multimodal KPA measures the capacity available in a given origin-destination pair and points out the *weakest links* in two capacity indicators (see table 5.2). The first one considers all the possible alternatives to make a trip between an Origin-Destination (OD) pair and sums the capacities. Subsequently, it identifies the potential bottlenecks in the OD pair, i.e., where the capacity is at its lowest (*weakest link).* The second one analyses the trip chain of an alternative and identifies the leg with the lowest capacity, i.e., the potential bottleneck of this alternative *(weakest link).* The capacities are measured from live data whenever no disruptions occur.

Table 5.2. Capacity indicators

Indicator	Description	Type	KPI/PI	Source
Overall OD capacity	Maximum number of passengers for an OD considering all the alternatives.	Weakest Link	PI	Own elaboration
Alternative capacity	Maximum number of passengers on an alternative.	Weakest Link	PI	Own elaboration

Resilience

The Resilience multimodal KPA measures the system reactivity to a disruption and it is of special interest for multimodal trips, given the interaction between the different legs of the trip chain of an alternative. Three resilience indicators are proposed. The first one compares the capacity when a disruption occurs (non-nominal) with the nominal capacity (*weakest link)*. The next two indicators analyse the time to react to this disruption (*weakest link*) and the time to restore the nominal capacity (*D2D*). The latter is a D2D KPI because the disruption can propagate through the system. Having spare system capacity makes the whole system more resilience altogether, as the reduction of capacity due to a disruption can be absorbed (partially) by this spare capacity.

Table 5.3. Resilience indicators

Indicator	Description	Type	KPI/PI	Source
Capacity reduction	Ratio between nominal capacity and non-nominal capacity (i.e., the capacities without disruptions and when disruptions occur, respectively).	Weakest Link	PI	Own elaboration
Time required to start to recover	The time interval between the beginning of the system disturbance and the first response activity.	Weakest Link	PI	Camila Maestrelli Leobons et al (2018)
Time required to restore normal operation	The time interval between the beginning of the event and the system recovery, i.e., the moment when the system recovers the nominal capacity.	D2D	KPI	Camila Maestrelli Leobons et al (2018)

Efficiency

The Efficiency KPA measures travel time and its different components:

- Access and egress time, which is the time to reach the "first intermodal change" of the chain, for example the walking time to reach the first bus stop or underground station, and the time from the "last modal change" to the destination, for example the walking time from the underground station to the office (destination). This definition could be extended to the access to the main leg of the trip chain, for example time to access the airport, and to egress from the main leg of the trip chain, for example time to egress from the airport.
- In-vehicle time, i.e., time inside or on a vehicle, be it bus, underground, private vehicle, etc.
- Transfer time, which is the time to transfer between the different multimodal options, for example the time to reach the public transport from the terminal. This time can include the purchase of a ticket.
- Waiting time, which is the time waiting for a service, normally a public transport service on a station or stop.

The different average times are compared against the overall average travel time (all of them are *additive*). In addition, the fastest average route for the different legs and trip purposes is analysed and also the comparison between public and private travel times (both of them are *additive*). It must be pointed out that this KPA analyses averaged travel times, while their distributions are analysed in a separate KPA (predictability and punctuality).

Table 5.4. Efficiency indicators

Indicator	Description	Type	KPI/PI	Source
Fastest average travel time	Time to complete the trip with the fastest option, taking into account the different alternatives, passenger legs and needs (luggage, no luggage, etc.).	Additive	PI	Dataset 2050
Total Travel Time	Time to complete the whole door to door trip.	Additive	KPI	Own elaboration
Ratio TTprivate / TTtp	Ratio between the time to complete the trip by (private) car and public transport.	Additive	PI	Kumar et al. (2013)
Ratio In-vehicle Time / Total Travel Time	Ration between the sum of in-vehicle times and the total travel time.	Additive	PI	Kumar et al. (2013)
Ratio Waiting Time / Total Travel Time	Ratio between the sum of waiting times and the total travel time.	Additive	PI	Kumar et al. (2013)

Indicator	Description	Type	KPI/PI	Source
Ratio Transfer Time / Total Travel Time	Ratio between the sum of transfer times and the total travel time.	Additive	PI	Own elaboration
Ratio Access time / Total Travel Time	Ratio between the access and egress and the total travel time.	Additive	PI	Own elaboration
Pax time efficiency - best possible journey time/actual time travel	Ratio between the best possible journey time and the average travel time by users.	Additive	PI	Dataset 2050

Environment

The Environment KPA includes different indicators related to emissions, noise, and use of resources (e.g., land use). Used land is an intermediate indicator which is subsequently transformed into emissions (CO2, NOx and PMx).

Table 5.5. Environmental indicators

Indicator	Description	Type	KPI/PI	Source
CO2 per passenger-km	Grams of CO2 per passenger and per km.	Additive	KPI	Marletto & Mameli (2011)
NOx per passenger km	Grams of NOx per passenger and per km.	Additive	KPI	Marletto & Mameli (2011)
PMx per passenger km	Grams of PMx per passenger and per km.	Additive	KPI	Marletto & Mameli (2011)
Used land	Used land to provide an alternative.	Additive	KPI	Own elaboration
% of people exposed to harmful noise	% of people exposed to harmful noise.	Additive	KPI	SESAR; Marletto & Mameli (2011)

Cost effectiveness

The Cost Effectiveness KPA measures the cost of the different alternatives (see table 5.6). The proposed KPIs are direct costs, indirect costs and bundle costs (all of them are *additive*).

Table 5.6. Cost effectiveness indicators

Indicator	Description	Type	KPI/PI	Source
Direct cost	Costs that are borne by users directly: taxes, travel tickets, tolling fees, etc.	Additive	KPI	Kafani and Wang (2010)
Indirect costs	Costs that are borne by users indirectly: gasoline, car insurance, mileage cost, maintenance, etc.	Additive	KPI	Kafani and Wang (2010)
Bundle costs	Some costs are bundled between agencies resulting in discounts. For example, a traveller may get a free shuttle bus ticket when he/she books from a certain airline.)	Additive	PI	Kafani and Wang (2010)

Punctuality and predictability

While the Efficiency KPA focuses on average travel times and their components, the Punctuality and Predictability KPA focuses on the travel time distribution and it takes into account correlations between the different legs of the alternative. Travel time variance and temporal variability measure the travel time variability. Lambda skew measures the travel time skewness, which is the asymmetry of the distribution. Buffer time aims to illustrate the delay or scheduled delay required so that 95% of the trips are on time. Similarly, potential wait time sheds light on the wait time distribution and it measures the difference between the percentile 95 and the average waiting time. On-time performance measures the ratio between on-time trips and all trips. To determine whether a trip is on-time or not, an "acceptable delay" is defined. This one depends on the utility of the activity at the destination. For example, a 30 minutes delay to watch a movie is most likely not acceptable, but is probably acceptable if we are making a 10,000 miles trip to go on holidays. The percentage of cancelled trips is also included as a KPI, in order to measure when a service with no alternatives is cancelled. Finally, the maximum GEH_t is a statistic derived from the traffic engineering GEH statistic, which measures traffic volumes. GEH_t measures both the absolute and relative variability of the travel time at the same time. Only the right-hand side of the distribution is considered, given that the travel time distributions tend to be heavy-tailed. Illustrating which leg is the one that affects the most to the overall trip variability (*weakest link*). All the KPIs but the last one (GEH) are D2D KPIs. This is due to potential correlations between the different legs travel times. For example, having a longer than expected rail trip can reduce the expected waiting time at an airport, which would imply a correlation between the different stages of the trip.

Table 5.7. Predictability and Punctuality indicators

Indicator	Description	Type	KPI/PI	Source
Travel time variability	Measures the overall travel time variance, analysing the dispersion of the travel time.	D2D	PI	Own elaboration
lambda skew	Measures the travel time skewness comparing the travel time difference between percentile 90% (T90) and 50% (T50) to the difference between percentile 50% (T50) and 10% (T10). lambda skew = (T90-T50)/(T50-T10)	D2D	PI	Rakha et al. (2010)
Buffer Time	Measures the difference of the travel time percentile 95% (T95) and the average travel time (Taverage). In expands Litman's buffer time definition by including scheduled services and by checking both the buffer time on the arrival and the departure. Buffer time = T95 - Taverage	D2D	KPI	Own elaboration
Temporal Variability Index (TVI)	Measures the travel time variability between the highest demand hour and the lowest demand hour. TVI = $\frac{(T_{95}-T_5)_{peak}}{(T_{95}-T_5)_{off-peak}}$ *Being T95 the percentile 95% of an alternative and T5 the percentile 5% of an alternative at peak or off-peak. The index will (normally) take low values for PT options since its service is more reliable/frequent at peak hours and will (tend to) take higher values for private transport options.*	D2D	PI	Guittens and Shalaby (2015)
On-time performance (OTP) - ratio on time trips vs all trips	Measures the ratio between the on-time trips and all the trips. Whether a trip is on-time or not depends on an acceptable delay which is a share of the activity utility.	D2D	KPI	Own elaboration

Indicator	Description	Type	KPI/PI	Source
% of cancelled trips - when there is no other plausible option	Measures the % of trips that can't be completed given a service cancelation. *It is a modellable KPI, but it is not measurable with the current sources of data.*	2D2	KPI	Own elaboration
Potential Wait Time	Time difference between waiting time percentile 95% (W95) and the average waiting time (Waverage).	2D2 (potential correlations between waiting times)	KPI	Guittens and Shalaby (2015)
Maximum GEH_t (T90 and Taverage)	GEH_t combines both an absolute and relative analysis of time at the same time. $GEH = \sqrt{\frac{2(T_{90} - T_{average})^2}{T_{90} + T_{average}}}$ *Being T_{90} the link's travel time percentile 90% and Taverage the link's travel time average*	Weakest Link	PI	Own elaboration

Security

There proposed Security KPIs measure the travellers assault risk of an option. Like the safety KPIs, one is the sum of the assault ratios (*additive*) and the other one is the highest ratio of the option (*weakest link*) which defines the perceived assault risk. In addition, there is a cyber security indicator that measures the probability of receiving a cyber-attack (*weakest link*).

Table 5.8. Security indicators

Indicator	Description	Type	KPI/PI	Source
Traveller assault (crime) rates	Probability of being assaulted, which is cumulative for each leg of the trip.	Additive	PI	Litman (2012)
Perceived traveller assault risk (crime)	Highest probability of being assaulted among the legs.	Weakest Link	PI	Litman (2012)
Cyber security	Probability of receiving a cyber-attack.	Weakest Link	PI	Own elaboration

Accessibility and Equity

Within the Accessibility and Equity KPA, three KPIs have been identified. 4-hour reach measures the percentage of trips that can be completed within 4-hours. Whether an alternative is either accessible for disabled people (*weakest link*) or affordable (*additive*) is also measured. Additionally, to address Equity aspects, the segmentation the indicators in the different KPAs according to different population groups can be of particular interest.

Table 5.9. Accessibility and equity indicators

Indicator	Description	Type	KPI/PI	Source
4-hour reach	% of trips that can be completed within 4-hours in Europe.	D2D	PI	Dataset 2050
Disabled access	Access of disabled people to an alternative.	Weakest Link	PI	Dataset 2050
Affordability	Affordable access to an alternative, measured as a % of passengers' income.	Additive	PI	Dataset 2050

Flexibility

Only one Flexibility indicator has been identified, which measures the number of alternatives to make a trip (*additive*) (see table 5.10).

Table 5.10. Flexibility indicators

Indicator	Description	Type	KPI/PI	Source
Number of options to make a trip	Number of available options to make a trip.	Additive	PI	Dataset 2050

Interoperability

The Interoperability KPA measures the number of interchanges along the trip chain composing an alternative (see table 5.11). Three interoperability indicators have been identified. They measure the number of modes, number of legs used to make a trip (*both additive*), and the number of tickets required to complete the trip (*D2D*).

Table 5.11. Interoperability indicators

Indicator	Description	Type	KPI/PI	Source
Number of legs	Number of legs required to complete a journey for an alternative.	Additive	PI	Dataset 2050
Number of modes	Number of modes used to complete a journey for an alternative.	Additive	PI	Own elaboration
Number of required tickets	Number of tickets used to complete a journey for an alternative.	D2D	PI	Own elaboration

6 Qualitative assessment of indicators' room for improvement and trade-offs

6.1 Introduction

The application of TRANSIT's multimodal performance assessment framework requires taking into account two aspects: (i) the interdependences between KPAs, both in general and in the context of multimodality; and (ii) the requirements for measuring and simulating the evolution of each indicator. The goal of this section is to describe the trade-offs between KPAs and its KPIs, identify the data sources for measuring the indicators, and evaluate to what extend these indicators can be modelled. With regard to the interdependences between KPAs, the work is mainly based on a thorough literature review of research papers and policy reports. We first provide the big picture of the interdependencies between KPAs and then we analyse in more detail each specific trade off, focusing on the aspects that are relevant to assess multimodality. The evaluation of the indicators is based on their definition and the knowledge on the state-of-the-art methodologies for data analysis and modelling in the transport sector.

6.2 Overview of interdependencies between KPAs

Some of the KPAs of the defined performance scheme are interdependent, meaning that there may be **cause-effect relationships** or merely **correlations** between different KPIs. The interdependencies may be (i) positive (win-win). This is the case for example if a more efficient flight trajectory provides environmental benefits and in addition also an improvement in cost-efficiency; or (ii) negative (win-lose). This is the case, for instance, if an ATM provider improves capacity at the cost of lower cost-efficiency. When there are negative interdependencies, there is normally a trade-off between KPAs.

INTUIT (2016) distinguishes two main research approaches in the study of ATM KPA interdependencies: studies taking a macro-focus and studies taking a micro-focus. Macroscopic studies typically consider performance trade-offs at a broad geographical scale and take into account multiple interdependencies between performance areas. These studies usually rely on simplifying assumptions on certain relationships to be able to include multiple interdependencies. On the other hand, microscopic studies typically focus on a single, or maximum two, performance interdependencies, by means of a case-study in a single (or a small number of) airspace sectors. This more targeted research focus allows a more detailed representation of structural performance drivers in the analysis.

Figure 6.1 shows a selection of the most relevant papers from the literature review and places the interrelationships on a canvas with the **four binding performance areas of the SES performance framework**. We observe that most of the research focuses on the performance areas of capacity and cost-efficiency, and their interrelationship. Interdependencies with environment are less common in the research literature, although there are some studies which focus on the relationship between capacity and flight-efficiency. Safety performance and its interdependencies have so far received less attention by researchers.

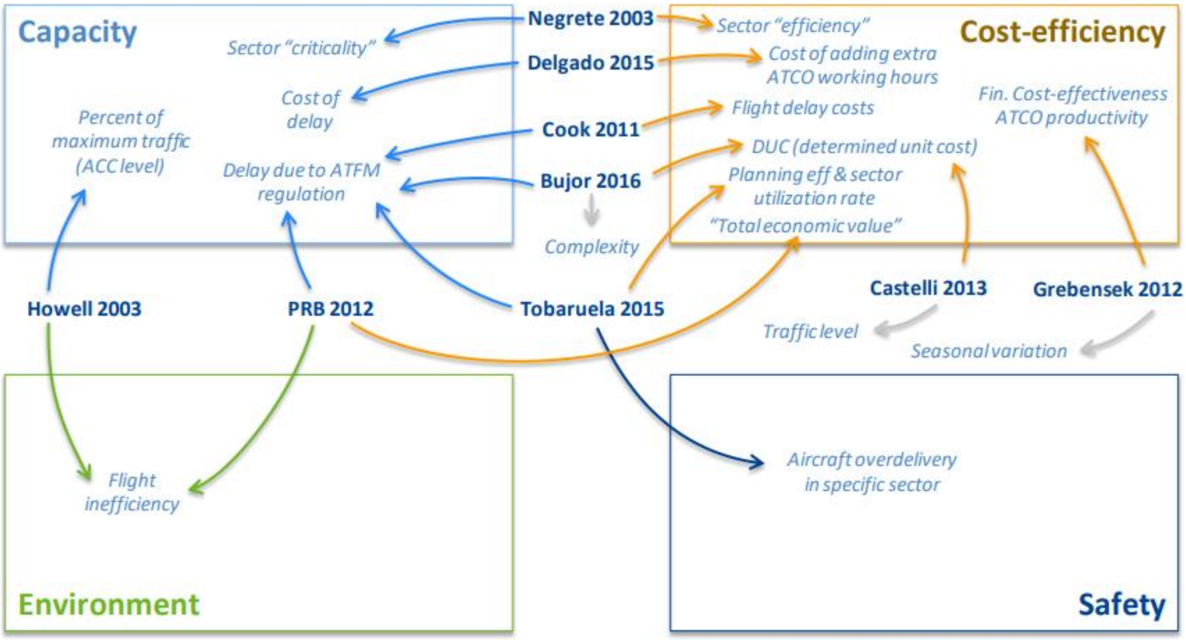

Figure 6.1. Interdependencies among KPAs as identified in literature review (INTUIT, 2016)

SESAR details a series of interdependencies in its ATM performance framework. All the areas may have an impact in any **cost-effectiveness** aspect. Even when limiting the scope to direct ANS costs, any solution that may imply the deployment of a solution will affect cost-effectiveness, either positively or negatively, in the short or in the long term. The interdependencies identified are the following:

- **Safety** is a transversal and overarching area, which is furthermore the highest priority. Any improvements in the other areas should be seen in the context of always keeping or improving the safety levels. Safety is closely linked to cost as, like other improvements, Safety comes with a financial cost (investment and operation). Safety can also be improved by limiting controller workload – which links very directly to Capacity. In essence then, Safety requirements play a large part in defining Capacity.
- **Capacity** also influences results in all the others, especially in those related to quality of service. Obviously, it also relates to cost-effectiveness and safety, since capacity has a cost and the increase in traffic has to be handled safely. Capacity is also influenced by Human Performance.
- **Civil-military** coordination and cooperation is shown as a background of the global picture framework, since it will also influence all the performance areas with more or less impact due to the presence of national security requirements which drive military airspace user requirements. For some of the chosen areas or indicators this aspect is perceived as more influencing than for others, e.g. as is the case for fuel efficiency.
- **Resilience** (Focus Area within Capacity KPA) is the ability to deliver performance goals during abnormal operating conditions (by reducing impact and decreasing time to recover) and Security is the ability to reduce impact of malicious events. Both affect capacity.

The remaining KPAs are shown as influencing and being influenced by the "surrounding" ones, but there are also interdependencies between them, e.g. Punctuality vs. Flexibility. In this case Airspace Users want to be able to adapt the times and trajectories of their flights to unexpected events, like cargo and passengers boarded earlier than planned or a storm en-route, and thus Flexibility is an advantage as it allows the agreed trajectory to be modified. However, the shifts in time or trajectory may bring conflicts downstream to the airspace and the allocation of routes which had been planned originally, which may cause a reduction in Punctuality (departure delayed due to ATFM regulation) and/or Predictability (extended arrival holding due to bunching).

New relations due to multimodality

Adding multimodality to the equation strengthens some KPA relations and brings new ones to surface (Figure 6.2). All the KPAs relate to Cost-Efficiency as any investment trying to enhance a KPA will tend to result in better performance of the KPA in question. Some KPAs, such as Resilience and Interoperability, can be enhanced with a Safety compromise, which is most likely unwanted. Predictability or Punctuality is closely related to Resilience and Capacity and can depend on the number of alternatives to make the trip. Similarly, Efficiency (e.g., the average journey time) is closely related to Capacity as well as the number of alternatives to make a trip.

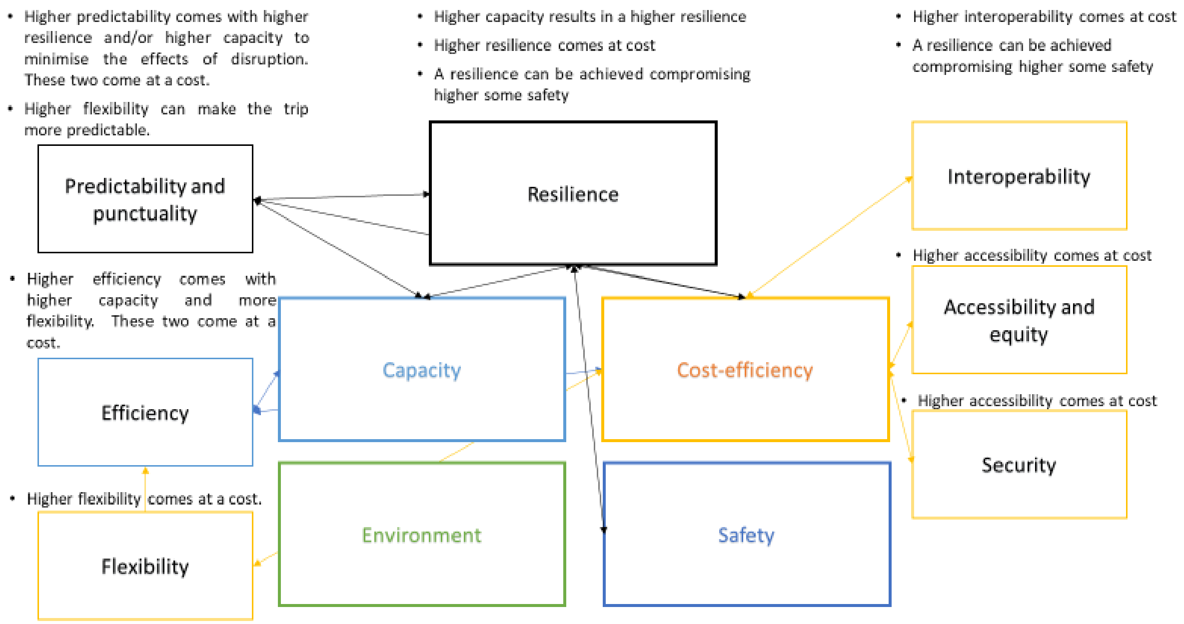

Figure 6.2. Extension of the interdependencies between KPAs in a multimodal context

Resilience

In the ATM literature review (see section 3), the Resilience KPA is a focus area within the Capacity KPA. In a multimodal context, this KPA gains more relevance, hence the suggestion to have a KPA of its own and to illustrate the relations and trade-offs with other KPAs.

Resilience has the following trade-offs with other KPAs:

- All things being equal, a higher resilience could be obtained to the detriment of **safety**. For example, if trains were to run closer together when a disruption event happened, the capacity would increase and the network would "recover" faster. However, applying this measure would diminish the safety of the network.
- **Capacity** or more importantly the spare capacity of the network determines the resilience of the network. If the capacity is enhanced, the network will be more resilient.
- **Predictability and punctuality** are closely related to resilience as the journey time dispersion depends strongly on disruptions.
- **Cost effectiveness** is highly intertwined with the other KPAs. Having more spare capacity or better technologies in place to have a more resilient network comes with an associated cost.

6.3 Assessment of multimodal KPIs

The previous subsection focuses on the relation and existing trade-offs between the different KPAs. This subsection details the data sources needed to measure and monitor the evolution of a given KPI, if it can indeed be measured, and states whether a KPI is "modellable" with the state-of-the art modelling techniques. The indicator is considered as modellable if it can be used either as an input to define the simulation scenarios (e.g., capacity indicators related to transport supply) or as an output of state-of-the-art transport models (e.g. travel times).

Safety

- **accident ratio** is both measurable with transport safety data and modellable.
- **perceived safety** is measurable with transport safety data, but can only be modelled in a coarse manner.

Capacity

- **Overall OD capacity** is both measurable with transport supply data and modellable.
- **Alternative capacity** is both measurable with transport supply data and modellable.

Resilience

- **Capacity reduction** is both measurable with transport supply data and modellable.
- **Time required to start to recover** is both measurable with transport supply data and modellable. Modelling also requires the modelling of demand, as it will have an impact on the time to recover.
- **Time required to restore normal operation or near it** both measurable using transport supply and demand data and modellable.

Efficiency

- **Fastest average travel time** is both measurable using transport supply and demand data and modellable.
- **Total Travel Time** is both measurable using transport supply and demand data and modellable.
- **Ratio TTprivate / TTtp** is both measurable using transport supply and demand data and modellable.
- **Ratio In-vehicle Time / Total Travel Time** is both measurable using transport supply and demand data and modellable.
- **Ratio Waiting Time / Total Travel Time** is both measurable using transport supply and demand data and modellable.
- **Ratio Transfer Time / Total Travel Time** is both measurable using transport supply and demand data and modellable.
- **Ratio Access time / Total Travel Time** is both measurable using transport supply and demand data and modellable.
- **Pax time efficiency - best possible journey time/actual time travel** is both measurable using transport supply and demand data and modellable.

Environmental

- **CO2 per passenger km** is both measurable using transport supply and demand data and modellable.
- **NOx per passenger km** is both measurable using transport supply and demand data and modellable.
- **PMx per passenger km** is both measurable using transport supply and demand data and modellable.
- **Used land** is both measurable in transport supply data and modellable.
- **% of people exposed to harmful noise** is both measurable, using noise propagation and population distribution data, and modellable.

Cost-efficiency

- **Direct costs** are both measurable using transport supply and demand data and modellable.
- **Indirect costs** are both measurable using transport supply and demand data and modellable.
- **Bundle costs** are both measurable using transport supply and demand data and modellable.

Predictability and punctuality

- **Travel time variance** is both measurable using journey time data and modellable.
- **Lambda skew** is both measurable using journey time data and modellable.

- **Buffer Time** is both measurable using journey time data and modellable.
- **Temporal Variability Index (TVI)** is both measurable using journey time data and modellable.
- **On-time performance (OTP) - ratio on time trips vs all trips** is both measurable using transport supply, demand and journey time data and modellable.
- **% of cancelled trips - when there is no other plausible option** is both measurable using supply and demand data and modellable.
- **Potential Wait Time** is both measurable using journey time data and modellable.
- **Maximum GEH (T90 and Taverage)** is both measurable using journey time data and modellable.

Security

- **Social distancing index** is both measurable using transport supply and demand and modellable.
- **Traveller assault (crime) rates** is both measurable using transport supply and demand data together with other socioeconomic data, and modellable, although only at a very crude level.
- **Perceived traveller assault risk (crime)** is both measurable using transport supply and demand data together with other socioeconomic data, and modellable, although only at a very crude level.

Accessibility and equity

- **4-hour reach** is both measurable using transport supply and demand data and modellable.
- **Disable access** is both measurable with transport supply data and modellable.
- **Affordability** is both measurable using socioeconomic, transport supply and demand data and modellable.

Flexibility

- **Number of options to make a trip** is both measurable with transport supply data and modellable.

Interoperability

- **Number of legs** is both measurable with transport supply data and modellable.
- **Number of modes** is both measurable with transport supply data and modellable.
- **Number of required** tickets is both measurable with transport supply data and modellable.