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## Article

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## Article

# A Framework for Quantifying Hyperloop's Socio-Economic Impact in Smart Cities Using GDP Modeling

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## Abstract

Hyperloop ultra-high-speed transport presents a transformative opportunity for future mobility systems in smart cities. However, assessing its socio-economic impact remains challenging due to Hyperloop's unique technological, modal, and operational characteristics. As a novel, fifth mode of transportation—distinct from both aviation and rail—Hyperloop requires tailored evaluation tools for policymakers. This study proposes a custom-designed framework to quantify its macroeconomic effects through changes in gross domestic product (GDP) at the city level. Unlike traditional economic models, the proposed approach is specifically adapted to Hyperloop's multimodality, infrastructure, speed profile, and digital-green footprint. A Poisson pseudo-maximum likelihood (PPML) model is developed and applied at two technology readiness levels (TRL-6 and TRL-9). Case studies of Glasgow, Berlin, and Busan are used to simulate impacts based on geo-spatial features and city-specific trade and accessibility indicators. Results indicate substantial GDP increases driven by factors such as expanded 60 min commute catchment zones, improved trade flows, and connectivity node density. For instance, under TRL-9 conditions, GDP uplift reaches over 260% in certain scenarios. The framework offers a scalable, reproducible tool for policymakers and urban planners to evaluate the economic potential of Hyperloop within the context of sustainable smart city development.



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**Keywords:** socio-economic impacts; smart city; logistics; urban development; hyperloop

## 1. Introduction

The concept of the smart city has evolved over the past two decades as a strategic framework for improving the efficiency, sustainability, and livability of urban spaces. In 2024, the world witnessed a continued acceleration in urbanization and digital transformation across multiple regions, driven by infrastructure demands, population growth, and environmental imperatives. Recent studies show that urban demands—including mobility infrastructure, housing, energy consumption, and digital services—have rapidly increased from 2023 to the first quarter of 2025 (UN DESA, 2023). This growth is driven by ongoing urban population expansion, post-pandemic recovery policies, and the acceleration of digital transformation across cities worldwide. These pressures underscore the need for scalable, sustainable, and high-speed transport infrastructure solutions such as Hyperloop.

By 2050, nearly 70% of the global population is expected to live in urban areas, placing immense pressure on existing infrastructure, particularly in the areas of transportation and

logistics (World Bank, 2020). Among the most relevant advances in high-speed ground transportation is Hyperloop technology—a system that proposes near-supersonic travel in vacuum tubes, combining the benefits of rail and air transport. Initially proposed as a futuristic concept in 2012 by Tesla (Tesla.com, 2012), Hyperloop has rapidly evolved into a tangible innovation, reaching Technology Readiness Level 6 (TRL) (Horizon, 2020).

According to (Planing et al., 2025), Hyperloop acceptance reached 51.4% across Europe, indicating expectations in high speed, comfort, and environmental aspects despite risks associated with it (Kang, 2025).

In 2025, European Hyperloop projects are being developed across different regions, for example, Zeleros (Spain) (Zeleros.com, 2025), Nevomo (Poland) (Nevomo.com, 2025), HARDT (the Netherlands) (Hardt.global, 2025), TUM (Germany) (Tumhyperloop.com, 2025), Institute of Hyperloop Technology (Germany) (Iht-emen.de, 2025), Swisspod (Switzerland) (Swisspod.com, 2025), and others. Hyperloop state-of-the-art includes feasibility studies, pilot projects, experimental runs, test tracks (Tumhyperloop.com, 2023), and public–private investments also accelerating its potential deployment in various global regions including the USA (TT Hyperloop) (Hyperlooptt.com, 2025), India (Avishkar (2023), Hyperlink (2023)), and China (CASIC) (Starr, 2024). Hyperloop technology, with its innovative design, ultra-high speeds, and multimodality, has the potential to change existing intercity travel and transform the logistics and freight systems of smart cities (Premasagar, 2022, 2023). Further, its sustainable design supports the goals of the European Green Deal (EC, 2024b) and green (EC, 2023b) and digital transformation (EC, 2023a), which is reflected in recent studies covering Hyperloop’s role in smart city logistics (Hansen, 2020), sustainability modeling (Barbosa, 2020), high-speed transport integration (Noland, 2021), and EU-aligned development strategies (Vesjolijs & Skorobogatova, 2025).

The application of Hyperloop technology to smart city development has become a prominent topic at scientific and industry conferences dedicated to ultra-high-speed transportation. Notably, the Hyperloop Conference 2023, held in Busan, South Korea, brought together a diverse array of stakeholders—including engineers, researchers, industry leaders, and policy experts—from across North America, Asia, and Europe. The conference provided both theoretical insights and empirical data drawn from active pilot implementations and feasibility studies on the integration of Hyperloop mobility within smart city frameworks. The case of Busan’s smart city initiatives, highlighted during the event, showcased the practical viability of Hyperloop implementation in dense urban environments and offered valuable perspectives on logistical optimization, environmental sustainability, and infrastructure planning. Later, Hyperloop projects presented at the European Hyperloop Week events in 2023 and 2024 showcased practical applications across diverse geographies, including Germany, the UK, the Netherlands, Canada, and India. The corresponding studies highlighted use-case innovation (Vesjolijs & Skorobogatova, 2025), cross-border pilot collaborations (Hyperloopconferences.com, 2025), and region-specific infrastructure adaptation (EHW, 2023).

Recent advances in legal frameworks for Hyperloop in the EU demonstrate Hyperloop application potential to smart cities from a regulatory perspective. The European Commission adopted sustainable urban mobility and transport integration principles as main areas for smart cities development in the EU (EC, 2025) and prioritized the design of Hyperloop promotion and development strategy (EC, 2024a). Analysis of scholar literature in the field highlights the lack of research papers dedicated towards legislation and economic development of Hyperloop; currently, more studies are being dedicated to Hyperloop’s system performance (Mitropoulos et al., 2021).

The coherence of smart city principles with Hyperloop technology projects presents a unique opportunity to redefine urban logistics, particularly in the context of mobility as a

service, multimodal integration, and sustainable economic growth. According to [Masrub et al. \(2025\)](#), Hyperloop also contributes to an “eco-friendly future society energy network”, which corresponds with smart city technological innovation goals. Hyperloop has also received wide coverage in media, technical feasibility reports, and public infrastructure white papers—focusing on projected energy efficiency ([Premsagar, 2022](#)), socio-economic potential ([Hansen, 2020](#)), and planning feasibility within urban ecosystems ([Barbosa, 2020](#)). However, its role in driving economic change—particularly through improved urban logistics and accessibility—remains underexplored in academic research.

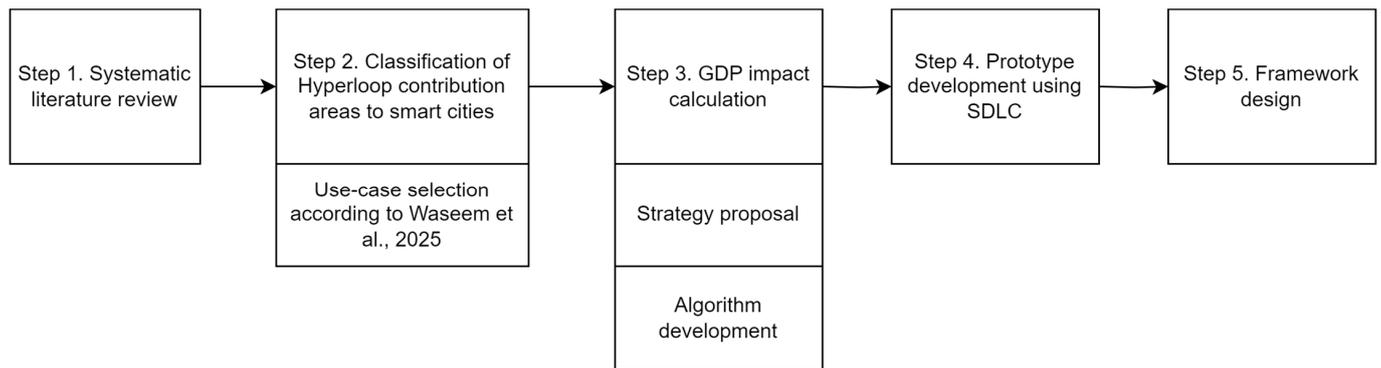
This study is intended to bridge this gap by investigating how Hyperloop technology can contribute to the logistics ecosystem of smart cities. It addresses a critical gap at the intersection of infrastructure innovation and urban economic modeling. Hyperloop has been widely discussed in the engineering and feasibility literature; however, few academic studies offer a reproducible method to quantify its macroeconomic effects, particularly at the city level in the context of smart city urban development. To bridge this gap, the present research introduces a scalable modeling framework that integrates geo-spatial analysis, transport accessibility, and trade elasticity into a GDP-based estimation tool tailored for smart cities. By doing so, the study provides policymakers with a novel, data-driven mechanism to evaluate the socio-economic impact of Hyperloop deployment and inform infrastructure planning within the smart city agenda.

The remainder of this paper is structured as follows. Section 2 outlines the research methodology, including the systematic literature review and the development of the gross domestic product (GDP) impact modeling framework. Section 3 presents the use-case analysis of Hyperloop applications within smart cities, based on technical readiness and transport functionality. Furthermore, it introduces the proposed GDP assessment strategy and explains its integration with geo-spatial and socio-economic data layers. Section 4 describes the case studies of Glasgow, Berlin, and Busan and demonstrates the application of the model. Section 5 discusses the results, comparing GDP impacts across cities and identifying key drivers of economic change. A summary of the findings, limitations, and proposing directions for future research is given in the Conclusions.

## 2. Materials and Methods

To achieve the aim of the study, the authors developed the four-stage methodology presented in Figure 1. While various methods such as cost–benefit analysis, computable general equilibrium (CGE) models, and system dynamics are commonly applied in transport economics, the present study required a scenario-driven, spatially disaggregated, and modular approach aligned with smart city urban development characteristics. Therefore, a four-stage methodology was developed to meet these specific requirements. Step 1 involved a systematic literature review performed by Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, by screening 184 journal articles, white papers, and technical reports published between 2016 and 2025.

The review had two objectives: (i) to catalogue socio-economic mechanisms that the Hyperloop literature claims could affect urban performance, covering passenger benefits, freight logistics, energy demand, land-use change, and emissions, and (ii) to identify the quantitative proxies most frequently used to measure those mechanisms. This scan yielded 44 distinct indicators and confirmed a methodological gap in linking them coherently to gross-domestic-product outcomes. Abstract and full-text screening were conducted manually by the authors using pre-defined inclusion criteria in accordance with PRISMA guidelines. No automated review tools (e.g., Abstrackr, BIBOT, etc.) were used in the selection process.



**Figure 1.** Research methodology overview. Use case selection source: [Waseem et al. \(2025\)](#) (authors' elaboration).

Literature analysis was supported by primary source data from Hyperloop Conference 2023 in Busan, Hyperloop Conference 2024 in Gdansk ([Hyperloopconferences.com, 2025](#)), and European Hyperloop Week 2023 ([EHW, 2023](#)) in Edinburgh, UK ([EHW, 2023](#)). EHW 2023 brought together over 400 students, researchers, and professionals to compete and collaborate on diverse Hyperloop topics from engineering to socio-economic modeling. Primary source data from EHW 2023 provided the necessary information of Hyperloop technology applicability to smart cities in the UK, Germany, and the Netherlands. These insights informed the development of the study's classification framework, use-case matrix, and GDP-impact assessment model.

During Step 2, the indicators were classified into the European Commission's smart city frame: ICT, citizen focus, infrastructure, transport, and mobility. The results of the analyses were consolidated into a short list of passenger and freight use-cases, which confirmed the potential application of Hyperloop to smart cities. With the introduction of GenAI to science, research methods are also advancing, allowing for better determination of blind spots in scientific areas and identification of previously unknown phenomena. Recent studies in liquid AI discussed by scientists and academia representatives at the Future of Information and Communication Conference 2025 ([Saiconference.com, 2025](#)), specifically the method proposed by [Waseem et al. \(2025\)](#), were applied in this study to classify and rank Hyperloop use-cases based on technical readiness and data availability.

Each selected use-case was mapped to a Hyperloop contribution area, creating the bridge between raw engineering attributes and urban policy goals, which helps in understanding how to develop a strategy for GDP calculation and what its components should be. This mapping connects Hyperloop's technical characteristics to urban development goals and enables the formulation of a model to estimate GDP-related impacts of Hyperloop deployment. While GDP as a macroeconomic measure has established methods and components, the proposed framework builds on these foundations to capture city-level changes that may arise.

During Step 3, the classification results were operationalized using the GDP-impact calculation framework developed by the authors in the earlier phase of the study. The two-layer strategy combines a 0.33 km<sup>2</sup> geo-spatial grid with a city-specific Poisson pseudo-maximum likelihood (PPML) module proposed by authors ([Vesjolijs et al., 2025](#)) and a trade-re-balance block; its step-by-step implementation is summarized in a detailed algorithm with specific actions and outputs. Since the solution is focused on cities and not by countries (as in classical international trade gravity models), the model is applied city-by-city, meaning no pooled cross-sectional structure is imposed. Each city's baseline and Hyperloop-enhanced rows are evaluated independently using city-specific regressions, which helps isolate effects and avoids interdependence across spatial units. This also aligns

with our goal of developing a scalable, modular tool applicable to diverse urban settings. Additionally, the PPML specification is particularly suitable for trade flow modeling with heteroskedasticity and zero values, as shown in [Silva and Tenreiro \(2006\)](#).

A working prototype was developed under a conventional software-development life-cycle (SDLC) ([Olorunshola & Ogwueleka, 2022](#)) during Step 4. The requirements were formalized in unified modeling language (UML) use-case diagrams ([Koç et al., 2021](#)); data-ingestion, computation, and visualization layers were coded in Python 3.12 ([Python.org, 2025](#)); unit and integration tests were executed with PyTest and Pandas-based fixtures; and validation was performed on the Glasgow, Berlin, and Busan case studies. The SDLC method, together with step-by-step algorithm for prototype development, allows reproducing the proposed solution and modeling tuning ([Olorunshola & Ogwueleka, 2022](#)).

The authors then summarized the use-case analysis, case study, strategy, algorithm, and prototype into an integrated framework proposed for GDP-impact evaluation of Hyperloop deployment in smart cities (Step 5).

### 3. The Role of Hyperloop Technology for Smart Cities and Urban Development and Examination of Possible Implications for Economic Development

In this section, the authors present the results of a systematic literature review, apply use-case classification using [Waseem et al.'s \(2025\)](#) method, and develop the logic of the empirical assessment of the GDP calculation and evaluation of multifaceted factors.

#### 3.1. Role of Hyperloop Technology for Smart Cities

Use-case analysis provides an overview of the potential that Hyperloop offers to smart cities, contributing to the development of the solution proposed by the authors (Table 1).

#### 3.2. Hyperloop Impact on GDP in the Context of Smart Cities

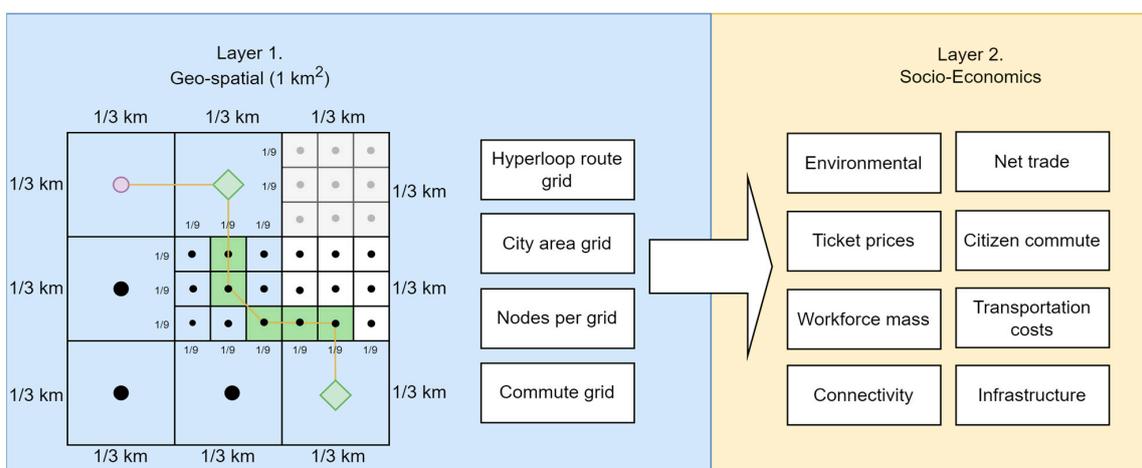
GDP is a well-established macroeconomic indicator used to measure the total value of goods and services produced within a country or region. Traditional GDP measurement encompasses various methods (expenditure, income, and production approaches) and has also faced critiques regarding its adequacy in capturing environmental, social, and distributional dimensions. This study does not aim to alter the theoretical foundations of GDP calculation. Instead, it introduces a modeling framework that estimates the potential change in GDP at the urban level resulting from the deployment of Hyperloop infrastructure. The model is designed to operate within existing GDP frameworks while accounting for spatial accessibility, trade effects, and time-efficiency gains enabled by the new transport mode.

The proposed modeling framework integrates geospatial disaggregation with socio-economic impact assessment to estimate the macro-level returns that a passenger- and freight-Hyperloop corridor could generate for individual smart cities. Analysis of smart cities area maps from Glasgow (UK), Berlin (Germany), Busan (South Korea), Singapore, Oslo (Norway), Amsterdam (the Netherlands), Helsinki (Finland), Zürich (Switzerland), Bridgewater (Canada), Columbus (USA), Brisbane (Australia), Fujisawa (Japan), Shenzhen (China), and other locations revealed that each smart city has unique area, geo-spatial features, and changing boundaries, and they are not homogenous. Another complexity that some cities might have is combined zones. For example, Busan area contains a Free Trade Zone, which, in fact, facilitates geographical advantages or different districts inside one area, which can be considered as separate entities.

**Table 1.** Possible Hyperloop use-cases for smart city integration based on Waseem et al. (2025) methodology. PHS—passenger Hyperloop; FHS—freight Hyperloop (authors' construction).

ID	PHS Use-Case	Source	ID	FHS Use-Case	Source
1	Ultra-high-speed daily commuting between smart city areas	(Swissloop.ch, 2023; S. Chen et al., 2022; Kumar & Singh, 2022)	1	Critical parcel delivery	(Tumhyperloop.com, 2023; Hyperloopptt.com, 2025; Barbosa, 2020; Bhuiya et al., 2022)
2	Airport to city hyper shuttle connector	(Celestin, 2023; Kitika & Suwatcharapinun, 2024)	2	Fresh produce cold chain logistics	(Hansen, 2020; Barbosa, 2020; Noland, 2021)
3	Intercity regional passenger corridors	(Hansen, 2020; Barbosa, 2020; Noland, 2021; Vesjolijs et al., 2025; Silva & Tenreyro, 2006)	3	Pods container shuttle	(Tumhyperloop.com, 2023; S. Chen et al., 2022)
4	Event-based crowd transport	(Celestin, 2023)	4	Airport cargo to downtown consolidation hub	(Tumhyperloop.com, 2023; Hyperloopptt.com, 2025; S. Chen et al., 2022; Kitika & Suwatcharapinun, 2024)
5	Emergency medical evacuation pods	(Premsagar, 2022, 2023; Noland, 2021; Kumar & Singh, 2022)	5	Manufacturing supply line	(EC, 2023b; Kumar & Singh, 2022; Bhuiya et al., 2022; Singh et al., 2021)
6	University connectivity	(Singh et al., 2021; Tudor & Paolone, 2019; J. Li et al., 2021; Aitken et al., 2016)	6	High-value electronics secure transit	(EC, 2023b; Hansen, 2020; Kitika & Suwatcharapinun, 2024)
7	Tourism enhanced access	(Cao et al., 2023; Armağan, 2020)	7	Waste removal	(EC, 2023b; Hansen, 2020; Armağan, 2020)
8	Integrated knowledge hub	(Hansen, 2020; Bhuiya et al., 2022; Kitika & Suwatcharapinun, 2024; Armağan, 2020; Gohar & Nencioni, 2021)	8	Pharmaceutical distribution	(Zhang et al., 2007; Rathore et al., 2015; Edoh, 2017; Schlingensiepen et al., 2016)
9	Rural accessibility	(Tumhyperloop.com, 2023; Hyperloopptt.com, 2025; EC, 2023b; Vesjolijs et al., 2025; Kitika & Suwatcharapinun, 2024; Lingli, 2015; Edoh, 2017)	9	Reverse logistics	(Hyperloopptt.com, 2025; EC, 2023b; Vesjolijs et al., 2025; Silva & Tenreyro, 2006; Singh et al., 2021; Rathore et al., 2015)
10	Inclusion services	(Rathore et al., 2015; Schlingensiepen et al., 2016)	10	Medical organs transportation	(Cao et al., 2023; Rathore et al., 2015; Sheikh et al., 2022; Willems, 2021; Sharma et al., 2024)
11	MaaS ticketing	(Tumhyperloop.com, 2023; Hyperloopptt.com, 2025; EC, 2023b; Hansen, 2020; Silva & Tenreyro, 2006)	11	Disaster relief supply chain support	(EC, 2023b; Hansen, 2020; Python.org, 2025; Kitika & Suwatcharapinun, 2024)
12	Nighttime pod service	(EC, 2023b; Hansen, 2020; Nikitas et al., 2017; McGillicuddy, 2024)	12	Autonomous warehouse-to-warehouse hyper lanes	(Kitika & Suwatcharapinun, 2024; Sane, 2020; Mogaji, 2024)
13	Workforce belt expansion	(Silva & Tenreyro, 2006; Schlingensiepen et al., 2016; Mogaji, 2024)	13	Integration with urban consolidation centers	(Tumhyperloop.com, 2023; Hyperloopptt.com, 2025; Hansen, 2020; Kitika & Suwatcharapinun, 2024; Schlingensiepen et al., 2016)
14	High-frequency business rush-hour shuttles between bottlenecks	(McGillicuddy, 2024; Sane, 2020)	14	High-density energy cell transport	(Gohar & Nencioni, 2021; Mogaji, 2024)
15	Rapid disaster area evacuation	(Gavzy & Scalea, 2022)	15	Post delivery	(Silva & Tenreyro, 2006; Gohar & Nencioni, 2021; Mogaji, 2024)
16	MaaS pods for reduced mobility persons	(Cavar et al., 2011)	16	Urban micro fulfilment node connector	(Hyperlink, 2023; Kitika & Suwatcharapinun, 2024; Yavuz & Öztürk, 2021; Kale, 2019)
17	On-demand autonomous passenger pods	(Avishkar, 2023; A. Chen et al., 2023; Nikitas et al., 2017; Werner et al., 2016)	17	Carbon-neutral freight corridors	(Yavuz & Öztürk, 2021; Kale, 2019; Hyperloop Development Program, 2022; Abraham et al., 2024)
18	Integrated park and ride hyperloop hubs	(Nikitas et al., 2017; Kale, 2019)	18	Private transport relocation	(Rocha et al., 2021; Swiftube, 2024)
19	Education support for rural–urban connections	(Rocha et al., 2021; Legaspi et al., 2020)	19	Urban–rural hubs connectivity	(Avishkar, 2023; Starr, 2024; Hansen, 2020; Noland, 2021; Kitika & Suwatcharapinun, 2024)
20	Carbon-neutral nature parks connections	(Brkljačić et al., 2020; Alawad et al., 2023)	20	Drone relocation	(Nath et al., 2023)
21	Cyber parks	(Brkljačić et al., 2020; Alawad et al., 2023)	-/-	-/-	-/-
22	Aging population support	(Ghosh, 2004)	-/-	-/-	-/-
23	AR/VR MaaS experience	(Anthopoulos, 2017)	-/-	-/-	-/-

Therefore, one of the key requirements for the solution is that GDP calculation should take into account urban area geo-spatial specifics and capture different Hyperloop deployments. For example, a circle-closed-loop Hyperloop can have the same length as a straight-line Hyperloop from point A to point B but at the same time cover a different area. Also, incorporating geo-spatial data has the potential to more accurately represent the transportation network and energy grid if necessary. Further, depending on requirements, users can calculate the application of Hyperloop to a specific district area or zone and to the whole urban area. As a result, the authors proposed a solution that facilitates the above-mentioned requirements. It uses an integrated multi-layer approach, allowing to capture GDP allocation given the geo-spatial specifics of the exact smart city area. A high-level overview is presented in Figure 2.



**Figure 2.** Strategy of GDP impacts assessment that couples a geo-spatial grid with a city-specific PPML socio-economic layer (authors' construction). (Legend for geo-spatial layer on  $1 \text{ km}^2$  sector: squares— $1/3 \text{ km}^2$  grid sectors within a smart city and sectors further subdivision to  $1/9$ ; black circles—current transport connection nodes, purple circle—node representing start of a Hyperloop route; green diamond—new connection nodes; orange lines—graphs representing node connection by identified Hyperloop route; grey sector—out of smart city transportation network).

At the outset, each city is granulated into a grid of  $0.33 \text{ km}^2$  sectors using a pathfinding algorithm proposed by Horzyk and Montebello (2025) for drones' navigation. The method has both empirical and theoretical use-cases. For uncharted areas of smart cities, this can be used to define a grid using the unmanned flying vehicles, and for those areas that already have a detailed grid, it can be applied for mapping. This granular representation allows both the existing urban structure and the planned Hyperloop alignment to be mapped onto a common spatial canvas. Within this layer, the model derives several baseline descriptors: the total number of sectors (city grid size), the share of those cells that lie within a 60 min surface-commute catchment, and the stock of multimodal connection nodes, expressed as density per square kilometer. The Hyperloop right-of-way is then superimposed, and additional passenger-station and freight-terminal nodes are allocated along its footprint, creating a modified network topology without altering the economic core of the city.

Recent studies have also explored advanced traffic modeling techniques using Lagrange-coordinate-based cellular automata frameworks, such as the multi-lane model proposed by X. Li et al. (2021). While the Lagrange-coordinate-based traffic modeling approach proposed by X. Li et al. (2021) offers valuable insights into multi-lane flow dynamics under empirical traffic conditions, the graph-based pathfinding method by Horzyk and Montebello (2025) is more suitable for our study. The Horzyk and Montebello method enables sector-level spatial disaggregation, node-to-node routing, and adaptation to new

or hypothetical transport networks such as the proposed Hyperloop grid, which lacks historical flow data and operates under a fundamentally different infrastructure model.

Building upon this geo-spatial grid, the framework processes physical accessibility changes into high-impact GDP effects. Accessibility is measured by the number of grid sectors that a representative worker can reach within the designated commute time; the Hyperloop scenarios enlarge this opportunity set in proportion to their higher travel speeds. Because commuting occupies only a fraction of the 24 h day, the raw reach expansion is attenuated by a time-budget factor that recognizes practical limits on human mobility. The model further adds a modest line-alignment effect, reflecting property-value uplift and station-area activity that tend to accrue along high-capacity corridors. These steps are carried out independently since every city record is scalable, and it can be applied to the specific districts.

To convert accessibility impacts into GDP levels, the algorithm relies on a Poisson pseudo-maximum-likelihood specification that is calibrated separately for each city using only its own baseline and Hyperloop scenario rows. This city-specific regression links observed gross product to changes in reachable distance, time savings, and the presence of the Hyperloop dummy, thereby yielding internally consistent predictions that remain free from cross-city contamination. The PPML stage acts as a structural bridge between the spatial layer and the economic layer, regularizing random sector-level variations while preserving relative differences generated by the transport intervention.

The PPML model proposed by the authors (Vesjolijs et al., 2025) was chosen to calculate trade within the smart city. A high-level equation of evaluating trade between two economic actors is presented below (Mitropoulos et al., 2021).

$$\ln(\text{Trade}_{ij,t}) = \alpha_0 + \alpha_1 \ln(\text{GPD}_i) + \alpha_2 \ln(\text{GPD}_j) + \alpha_3 \ln(\text{Distance}_{i,j}) + \epsilon_{ij,t} \quad (1)$$

where  $\text{Trade}_{ij,t}$  is the export or import flow from point  $i$  to  $j$  in year  $t$ ;  $\epsilon_{ij,t}$  is the error term.

For the effect evaluation of Hyperloop on trade, the following form is used (Barbosa, 2020):

$$\text{Trade}_{ij,t} = \exp(\beta_0 + \beta_1 \ln(\text{GPD}_{i,t}) + \beta_2 \ln(\text{GPD}_{j,t}) + \beta_3 \ln(\text{Distance}_{i,j}) + \beta_4 \text{HL}_{ij,t} + \beta_3 \ln(\text{TimeReduction}_{ij,t} + 1) + \dots) + \epsilon_{ij,t} \quad (2)$$

where  $\text{Trade}_{ij,t}$  is the export or import flow from country  $i$  to  $j$  in year  $t$ ;  $\beta_4$  and  $\beta_5$  capture effect of potential Hyperloop connectivity on trade flows;  $\exp(\dots)$  means the exponential link for PPML is used;  $\epsilon_{ij,t}$  is the error term, according to (Vesjolijs et al., 2025). The calculation approach adjusted for smart cities answers the following questions:

- How will the workforce mass?
- What is a reduction in transportation time?
- What is the effect on trade?
- What is the effect on transportation costs?
- What is the effect on CO<sub>2</sub> emissions?
- How does GDP change?

The framework is extensible and has therefore been configured to include GDP-impact methodology advanced by TransPod (A. Chen et al., 2023; Delas et al., 2019), whereby the welfare effects of a very-high-speed system are decomposed into (i) consumer surplus from lower ticket prices, (ii) monetized environmental externalities, and (iii) productivity gains attributable to travel-time savings. In practice, the present model embeds a tariff module that first benchmarks Hyperloop fares against prevailing rail/air prices on the same OD pairs and then feeds the differential into a demand-elasticity routine to obtain a static consumer-surplus estimate. A parallel emissions block converts mode-shift tonnage into avoided CO<sub>2</sub> using life-cycle emission factors consistent with EU taxonomy guidelines.

Both monetary streams are finally added to the accessibility-based GDP core, yielding an aggregate that is at the same time compatible with the triple-bottom-line structure proposed by TransPod and also enhances it by additional layers, criteria, and approaches. In addition, the algorithm adopts the 60 min catchment concept proposed by Hardt Hyperloop’s Dutch case study (Sane, 2020). This study assessed a north-to-south corridor linking the Randstad conurbation (Amsterdam–Rotterdam–Utrecht) with Zwolle, Groningen, and the Northern provinces. Hardt’s (Hardt.global, 2025) approach considers that a one-hour door-to-door threshold represents the effective limit of daily labor mobility; any expansion of the reachable area under that time budget translates into a proportional enlargement of the active workforce available to firms. The present model operationalizes this idea by comparing the size of the 60 min isochrones under baseline and Hyperloop speeds, then applying a labor-elastic Cobb–Douglas term to convert the ensuing workforce uplift into additional value added (Mahaboob et al., 2019).

By integrating the Horzyk and Montebello (2025) algorithm, TransPod (A. Chen et al., 2023), and methodologies about Dutch case studies (Hardt.global, 2025; Sane, 2020) and enhanced by the authors’ proposed PPML model (Vesjolijs et al., 2025), the framework captures a richer spectrum of socio-economic impacts on GDP and is specifically tuned to smart city specifications by European Commission (EC, 2025). These impacts are incorporated as independent additive layers on top of the city-specific PPML GDP baseline. The result is a unified yet modular tool capable of reproducing, validating, and extending the headline findings of the Hyperloop economic-impact paradigms within a consistent smart city setting. The step-by-step algorithm for calculation of Hyperloop’s effect on smart cities’ GDP is shown in Table 2.

**Table 2.** Strategy formalization into 17-step-by-step algorithm for calculation of Hyperloop’s effect on smart cities’ GDP (authors’ construction).

Step	Action	Key Output of the Steps
1	Input parameters assessment for smart cities comparison or smart city-specific sectors	Params taken: smc_name, smc_area, smc_population, smc_active_workforce_mass, smc_gdp_current, smc_emissions, public_transport_price, current_commute_speed_kmh, current_commute_time_min, hyperloop_route_length_km, hyperloop_speed_trl6_kmh, hyperloop_speed_trl9_kmh, current_exports, current_imports, current_freight_speed, citizen_commute_time, smc_nodes
2	Select smart city record <i>c</i> from the input table	Raw attributes (area, GDP <sub>0</sub> , exports, imports, HL speeds)
3	Partition the city area into 1/3 km <sup>2</sup> grid sectors	smc_grid ← [area/(1/3)]
4	Define smart city grid	smc_grid' ← smc_grid nodes subdivision [area/1/9]
5	Define smart city 60 min commute coverage	smc_60_min_commute_coverage
6	Lay out the baseline commute zone	reach <sub>0</sub> ← [(speed <sub>0</sub> ·time)/(√(1/3))] sectors
7	Define the Hyperloop route Apply pathfinding for Hyperloop route setup	length <i>L</i> hl_route_grid ← [L/√(1/3)] sectors
	Calculate ticket prices	ticket_price'
8	Calculate node density for Hyperloop grid	hyperloop_route_node_density/area
9	Count connection nodes: Baseline density <i>d</i> <sub>0</sub> (nodes/km <sup>2</sup> ) +/HL sector (passenger) +/HL sector (freight)	nodes_added_total = hl_route_grid'
10	Compute citizen commute reach for TRL-6/TRL-9	reach <sub>6</sub> , reach <sub>9</sub>
11	Apply daily-time attenuation	adj <sub>6</sub> , adj <sub>9</sub> = 1 + (reach <sub>0</sub> - 1)·(commute_min/(24·round_trip))
12	Build pre-PPML GDP	accessibility + line effects
	$G_{6/9} = GDP_0 \times adj_{6/9} + rand(2-6 M) \cdot hl\_route\_grid$	
13	Process exports and imports	exports <sub>6/9</sub> = exports <sub>0</sub> ·(HL speed/freight_speed)
14	Fit PPML	city-specific coefficients; predictions GDP_ppml
15	Add net-trade delta to PPML GDP	GDP_final <sub>6/9</sub> = GDP_ppml <sub>6/9</sub> + (net_trade <sub>6/9</sub> - net_trade <sub>0</sub> )
16	Compute percentage Uplift vs. baseline	diff <sub>6/9</sub> = (GDP_final <sub>6/9</sub> - GDP <sub>0</sub> )/GDP <sub>0</sub>
17	Store all statistics and proceed to the next city <i>c</i> + 1	Resulting metrics are delivered to the end user

Followed by the algorithm provided in Table 2, special software was developed to apply the proposed method using Python programming language ([Python.org](https://python.org), 2025) and was deployed live to end users. The source code is available in the current study's Supplementary Section. The software was developed using the SDLC methodology and tested using the Python unittesting framework ([Python Software Foundation](https://python.org), 2024).

#### 4. Case Study Context and Smart City Selection for GDP Modeling

Smart cities of Glasgow (UK), Berlin (Germany), and Busan (South Korea) were selected to be processed by the proposed method for validating the method's ability to capture changes in GDP for the adoption of Hyperloop. In this section, the authors discuss the smart cities mentioned above and the rationale behind choosing them and also provide insights on input data.

Glasgow has emerged over the past decade as one of the United Kingdom's progressive platforms for data-driven urban transformation ([UK Government](https://www.gov.uk), 2017). The city's "Future City Demonstrator"—funded by Innovate UK in 2013—created an integrated operations center that fuses real-time feeds on transport, energy, public safety, and the environment ([Miao](https://www.glasgow.gov.uk), 2021). Combined with the universities' strength in photonics, fintech, and advanced manufacturing, Glasgow has leveraged its legacy industrial grid to pilot adaptive street lighting, predictive road maintenance, and open-data portals that inform municipal budgeting. The physical fabric remains compact: roughly 175 km<sup>2</sup> is home to ~620,000 inhabitants, yielding a density of 3600 persons km<sup>2</sup>—sufficient to support mass-transit while still leaving latent capacity for a sub-surface Hyperloop ([Glasgow City Region](https://www.glasgow.gov.uk), n.d.).

Berlin, by contrast, is a polycentric metropolis of almost 900 km<sup>2</sup> whose historic rail rings and tram corridors are being upgraded under the "Smart City Berlin" strategy. The Senate's program couples IoT sensor deployment, such as low-power wide-area environmental monitors in the Moabit smart district, with an open urban-digital-twin platform that enables real-time energy-system co-simulation ([Smart City Berlin](https://www.smartcityberlin.com), n.d.). Economically, Berlin has diverged from heavy industry to a knowledge-intensive mix of software start-ups, creative media clusters, and an expanding hydrogen economy; the Brandenburg hinterland supplies both logistics zones and green-field photovoltaic capacity. Its moderate density (~4100 persons km<sup>2</sup>) and existing S-Bahn right-of-way make it a credible European anchor node for Hyperloop freight modules as well as long-distance passenger pods.

Busan—the Republic of Korea's principal port city—illustrates a coastal smart city archetype where maritime logistics dictate both land-use and digital priorities. The "Eco-Delta Smart City" pilot in the Nakdong River estuary is outfitting entire neighborhoods with autonomous water taxi networks, AI-optimized seawater desalination plants, and 5G-edge computing for harbor-crane coordination ([Korea Ministry of Land, Infrastructure and Transport](https://www.korea.net), n.d.). With 3.4 million residents packed into 770 km<sup>2</sup> of mountainous terrain, Busan's effective population density (~4400 persons km<sup>2</sup>) rivals that of the European cases, yet its industrial profile remains dominated by container throughput, shipbuilding, and marine R&D—sectors whose just-in-time supply chains could benefit disproportionately from Hyperloop-enabled high-velocity freight. Another important aspect is the Port of Busan, which is a logistic hub and a gateway to the South Pacific region, and together with the Busan Free Trade Zone ([BJFEZ](https://www.bjfez.com), n.d.), they have the potential for deploying Hyperloop ([Korea.net](https://www.korea.net), 2025).

The authors selected Glasgow, Berlin, and Busan because all three exhibit comparable population densities per square kilometer, even given the completely diverse scale and location. It also helps commute-catchment calculations comparison; sector counts in the 1/3 km<sup>2</sup> grid and Hyperloop station spacing operate on like-for-like geometric scales. This

homogeneity removes density as a confounding factor when benchmarking accessibility gains or PPML-derived GDP elasticities, allowing the analysis to attribute differences in outcomes to economic structure and network topology rather than to simple urban form. Detailed statistics for selected smart cities are shown in Table 3.

**Table 3.** Glasgow, Berlin, and Busan smart cities statistics, based on publicly available data from various internet sources, baseline year 2023 (author’s construction).

Name	Area (km <sup>2</sup> )	Population	Workforce	GDP (bln, USD)	Emissions	Export (USD)	Import (USD)
Glasgow	175	635,000	325,000	2.59	400,000	4,790,000	46,000,000
Berlin	891.8	3,748,148	2,014,000	5.35	500,000	1,390,000,000	1,760,000,000
Busan	768	3,400,000	1,670,000	91	1,800,000	52,000,000,000	48,100,000,000

At the same time, the cities are heterogeneous in economic composition, geographic setting, and cultural governance: a post-industrial Atlantic hub, a continental creative capital, and an export-oriented Pacific port. Given diversity provides a step towards the framework’s scalability, if a single algorithm can accommodate Glasgow’s compact grid, Berlin’s radial-ring morphology, and Busan’s mountainous littoral while still generating credible GDP uplifts, policymakers can be more confident in transferring the methodology to yet other smart city contexts. Also, cultural and geographical diversity contributes for common regional strategies development by decision makers and will help guide future developers of Hyperloop.

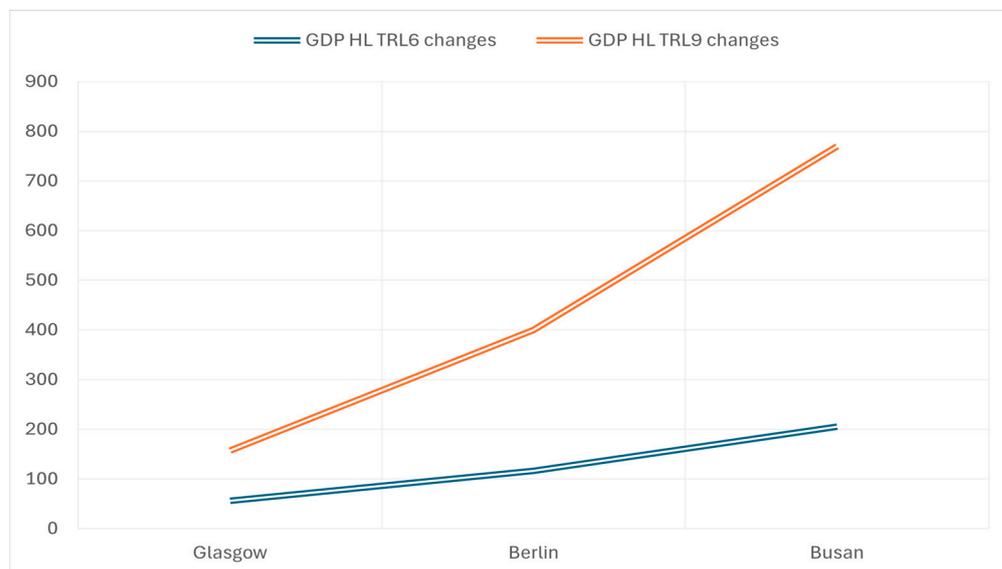
## 5. Results and Discussion

The following section presents the quantitative outputs generated by the two-layer Hyperloop × Smart City model for the reference cases of Glasgow, Berlin, and Busan. Table 4 summarizes the baseline macroeconomic indicators and the scenario-specific deltas associated with TRL-6 and TRL-9 Hyperloop deployments. For each city, we report (i) present-day GDP; (ii) projected GDP under TRL-6 and TRL-9, together with the corresponding percentage changes; (iii) variations in net-trade position resulting from the freight-speed differential; and (iv) a suite of geo-spatial statistics—total number of 0.33 km<sup>2</sup> grid sectors, commute-reach sectors under each speed regime, the number of grid cells intersected by the Hyperloop corridor, and the incremental connection nodes attributable to passenger and freight portals. The proposed solution results are shown in Table 4.

**Table 4.** Results of Hyperloop implementation impacts on smart cities of Glasgow, Berlin, and Busan (authors’ construction).

Stat/Smart City	Glasgow	Berlin	Busan
GDP current (USD, thsd)	2,590,000	5,350,000	91,000,000
GDP HL TRL-6 (USD, thsd)	4,045,528	11,544,812,876	277,863,082
GDP HL TRL-9 (USD, thsd)	6,649,112,008	26,735,351	791,719,679
Current Net Trade (USD, thsd)	−41,210	−370,000	3,900,000
Net Trade TRL-6 (USD, thsd)	−22,050	4,263,333	177,233,333
Net Trade TRL-9 (USD, thsd)	19,090	17,128,555	658,522,222
Smart City Grid (sectors)	525	2675	2304
Smart City Reach Current (sectors)	67	83	112
Smart City Reach Current HL TR-L6	779	675	675
Smart City Reach Current HL TRL-9	2118	2118	2118
HL Route Grid (sectors)	17	155	207
Smart City Nodes with HL (mean/sector)	27.14	35.26	42.4
Smart City Nodes Change with HL (total)	25	232	310

The comparison of final GDP calculations for Glasgow, Berlin, and Busan is shown in Figure 3. Detailed results are available in the Supplementary Materials Section (/data/smart\_city\_metrics\_output\_ppml.csv).



**Figure 3.** Comparison of anticipated GDP changes for Glasgow, Berlin, and Busan after implementing Hyperloop in TRL-6 and TRL-9 (authors' construction).

The simulated results reveal a markedly asymmetric distribution of Hyperloop benefits across the three case cities. Glasgow, although starting from the smallest baseline economy ( $\approx$ USD 2.6 billion), realizes the largest percentage uplift when Hyperloop operates at TRL-9, with gross product projected to rise by roughly 157%. That out-sized elasticity stems from the city's compact geometry: only 67 grid sectors ( $0.33 \text{ km}^2$  each) lie inside the present 60 min commute band, yet the Hyperloop catchment expands to more than 2100 sectors. Because the PPML model converts this 30-fold reach shock into output with diminishing but still super-linear returns, Glasgow's relative gain outstrips Berlin's and Busan's. Conversely, the absolute GDP increment remains modest in global terms, underlining that large percentage swings in smaller urban economies translate into lower absolute value added.

Berlin occupies the middle ground. Its baseline reach is broader (83 sectors), and the Hyperloop corridor is much longer (155 sectors intercepted), but the accessibility multiplier is tempered by a polycentric labor market that already enjoys extensive S-Bahn coverage. Consequently, GDP is forecasted to climb by  $\sim 116\%$  under TRL-6 and  $\sim 400\%$  under TRL-9—substantial in absolute terms yet proportionally smaller than Glasgow's surge. The model also registers the largest positive swing in net trade ( $\approx$ USD 17 million at TRL-9), reflecting Berlin-Brandenburg's export-heavy, advanced-manufacturing cluster and the assumed freight-speed elasticity.

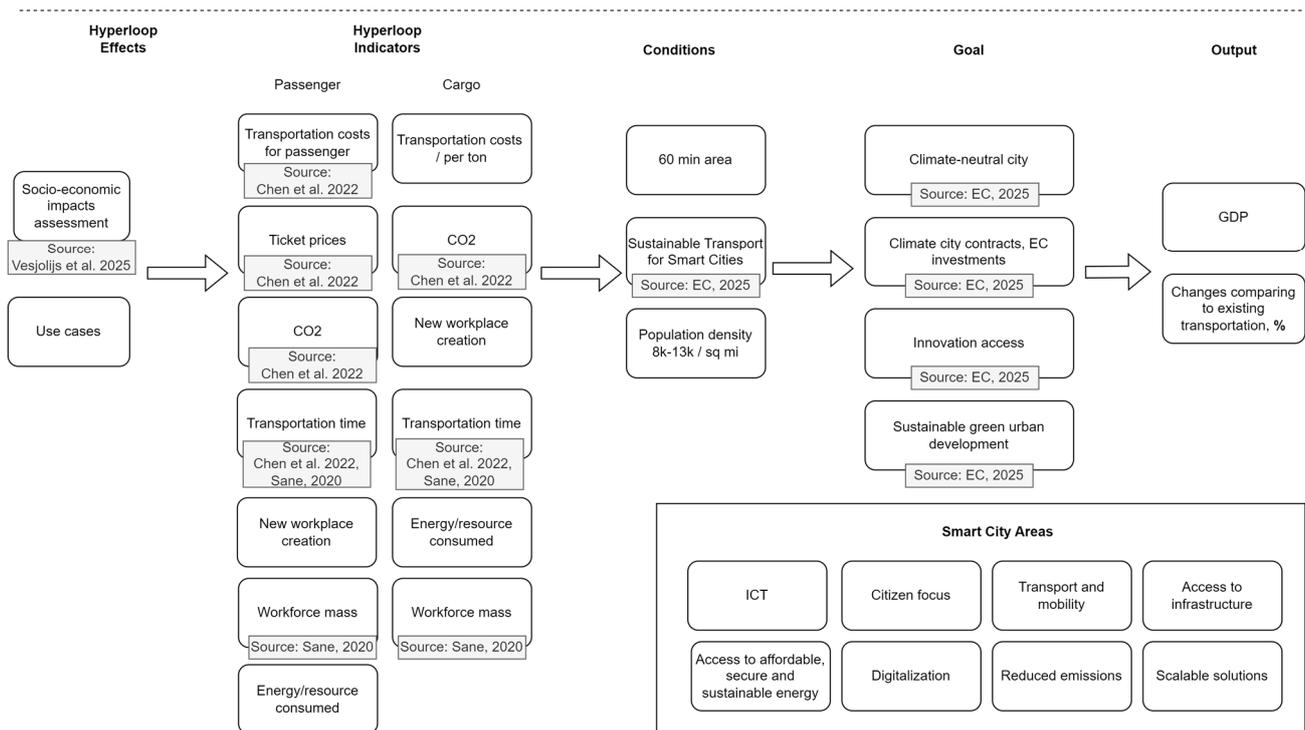
Busan illustrates how a port-centric metropolis can dominate in absolute magnitudes. Starting from a baseline GDP of  $\sim$ USD 91 billion and a heavyweight trade surplus, the city still manages a 205 % (TRL-6) to 770 % (TRL-9) expansion thanks to hyper-efficient long-distance freight channels. Yet, its accessibility gain is the most modest—the reach grid rises from 112 to 675 sectors—highlighting that for large, already dense conurbations, freight-induced net-trade effects and corridor-station value capture outweigh commuter catchment gains. Busan also records the largest step-change in node infrastructure ( $\approx 310$  new portals), potentially reinforcing its role as North-East Asia's intermodal gateway.

The obtained results can be compared with those from the HARDT Hyperloop study for the Province of North Holland, which reported an increase from approximately USD 0.6 billion to USD 1.3 billion associated with the implementation of a regional Hyperloop corridor (Dabrowska et al., 2021); however, that study did not calculate direct impact on GDP and was applied to the Hyperloop corridor rather than a city area. According to an industry report conducted by Geuze et al. (2020), the increase in GDP is 183% on the 60 min commute in the above-mentioned North Holland corridor. Subsequently, these values can be compared to TRL-6 results (205%) from the current study. Notably, analysis of the North Holland corridor was also conducted for Hyperloop in TRL-6. While this figure aligns with the scale of GDP change observed by the author's model, the approach used in the present study incorporates a different range of criteria, including geo-spatial sector coverage for smart city area, multimodal node density, emissions savings, and workforce and trade flows. As such, the results reflect a more multi-dimensional and spatially adaptive framework capable of application across diverse urban contexts beyond a single regional corridor, serving as an alternative modeling approach for future transportation planning in urban development.

The combined results suggest that Hyperloop's economic leverage is conditioned by three interacting factors: (i) the ratio of new to existing commute reach, which favors smaller or less well-connected urban cores; (ii) the scale and orientation of the traded-goods sector, where export-heavy economies gain disproportionately from high-velocity freight; and (iii) line length and station density, which drive local corridor value capture and node multiplication. These divergent pathways underscore the importance of tailoring Hyperloop business cases to each city's spatial morphology and industrial profile rather than assuming a uniform benefit coefficient.

Figure 4 presents the original framework developed by the authors to assess the economic impact of Hyperloop deployment in smart cities. The framework is grounded in the methodological steps outlined in the Materials and Methods Section and synthesizes elements derived from geo-spatial accessibility modeling, trade rebalancing logic, and PPML-based GDP estimation. Its structure reflects the dual passenger–freight role of Hyperloop technology and the operational pathways through which it affects smart city performance: accessibility, cost, emissions, and trade. Each layer of the framework is supported by variables introduced in the use-case analysis (Section 3) and implemented step-by-step through the algorithm presented in Table 2. The framework aims to provide a modular, transparent structure that links Hyperloop technology specifications with measurable economic outcomes for smart city urban development.

The framework is structured as a left-to-right chain beginning with Hyperloop effects—the direct physical or service characteristics that differentiate the system from incumbent rail, road, and air transport. These effects are subdivided according to two demand classes, passenger and cargo, and draw from the empirical work of authors (Vesjolijs & Skorobogatova, 2025; Vesjolijs et al., 2025) as well as operator-specific research conducted by Transpod (A. Chen et al., 2023) and Hardt (Hardt.global, 2025; Sane, 2020). For the passenger version of Hyperloop, the relevant indicators include point-to-point transportation costs, ticket prices, CO<sub>2</sub> emissions per trip, travel-time savings, and station-area job creation; for freight, they comprise cost per ton-kilometer, life-cycle CO<sub>2</sub>, transit-time reductions, and the productivity of newly accessible logistics clusters. The dual column underscores that Hyperloop's economic reach extends well beyond commuter mobility, also addressing the high-value, time-critical cargo segment. The main components of the framework are the solution (Figure 2, Table 2) proposed by the current study and PPML model developed by the authors (Vesjolijs et al., 2025).



**Figure 4.** A framework for GDP calculation of Hyperloop technology impact on smart cities. Sources: S. Chen et al. (2022), Sane (2020), EC (2025), Vesjolijs et al. (2025). (authors' construction).

Conditions for the given framework are derived from the European Commission's "Sustainable Transport for Smart Cities" initiative (EC, 2025). First, the 60 min isochronal catchment is retained as the operative spatial boundary for day-to-day labor and knowledge exchange, which was initially proposed by Sane (2020). Second, a population-density criterion of 8000–13,000 inhabitants per square mile ( $\approx 3100\text{--}5000\text{ km}^2$ ) is introduced to differentiate metropolitan areas capable of supporting high-frequency Hyperloop operations without inducing excessive urban sprawl. Cities meeting these thresholds are applicable for the proposed solution; for other existing use-cases, the solution might change.

The framework aligns Hyperloop deployment with three strategic smart city goals articulated by the European Commission's 2022 policy package: climate-neutral urban systems, inclusive innovation access, and sustainable green urban development. Hyperloop contributes to climate neutrality through reduced per-passenger-kilometer emissions and the potential to catalyze climate-city contracts that unlock EU investment tranches (EC, 2021). Innovation access is fostered by shrinking effective distances between specialized labor pools and research campuses, while sustainable development is supported by shifting inter-urban freight from diesel trucking to electrified tube conveyance. These macro-objectives are mapped onto four functional smart city areas—ICT, citizen focus, transport and mobility, and physical infrastructure—creating a modular interface through which further urban-systems models (e.g., energy or housing) can be coupled.

Framework output is a quantified GDP calculation containing multiple streams that are consolidated into a single gross-domestic-product metric and expressed as a percentage change relative to the legacy transport baseline. Framework aggregation supports transparency and contributes to data-driven decision-making.

To summarize, the developed solution (a suggested framework) operationalizes a modular path that links Hyperloop engineering attributes to strategic EU smart city goals and, ultimately, to macroeconomic performance, thereby offering policymakers a reproducible template for scenario appraisal across diverse urban contexts.

## 6. Conclusions

An end-to-end method has been proposed to estimate how Hyperloop deployment may alter the macroeconomic dynamics of data-driven smart cities. The study's main objective was achieved by introducing a framework designed to support GDP-impact calculation for Hyperloop implementation in the context of smart city development.

The conducted research confirmed the benefits offered by the Hyperloop technology by applying it to a smart city context and mapping a catalogue of passenger and freight use-cases using the liquid AI method, demonstrating multidisciplinary and multifaceted aspects of ultra-high-speed technology deployment.

A structured GDP-impact assessment strategy that couples a geo-spatial grid with a city-specific PPML socio-economic layer (Figure 2) was developed, bridging the gap between empirical geo-spatial pathfinding algorithms and socio-economic aspects of Hyperloop. The strategy was formalized into a reproducible 17-step algorithm (Table 2), beginning with sector-level reach calculations and concluding with the adjustment of gross product based on net trade effects. The algorithm is scalable and can be developed as a digital application, which is confirmed by the applied software development lifecycle method. The algorithm was executed for three contrasting yet density-comparable smart cities—Glasgow, Berlin, and Busan—demonstrating internal consistency and revealing distinct benefit pathways: commuter-reach expansion for Glasgow, corridor-led value capture and export uplift for Berlin, and freight-dominated gains for Busan.

The numerical results confirm that Hyperloop can deliver significant GDP increases (more than 30%) under current HL TRL-6 and TRL-9 performance assumptions. The GDP effect increase is achieved by simultaneously densifying multimodal connection nodes, expanding the commute zone, and decreasing effective travel times inside the EU's 60 min smart city benchmark. The final solution presents a framework (Figure 4) that positions Hyperloop within the European Commission's climate-neutral and innovation-access agendas, and it is ready for direct use by planners and investors for smart cities applications. The study provides the first scalable, policy-aligned toolkit for quantifying Hyperloop's economic leverage across diverse urban contexts and therefore fulfils the research aim.

**Limitations.** Calculations were conducted for a 1-year period. While the current study relies on 2023 static input data for illustrative purposes, the framework was designed to be data-agnostic and can be applied using higher-frequency, real-time, or longitudinal datasets as they become available. Results of the calculations heavily depend on Hyperloop specification in the corresponding TRL. In case of Hyperloop technical specification changes, the result might change dramatically, even to negative values. Research did not evaluate system dynamics of Hyperloop projects overtime.

**Future study.** The next step is to apply the solution to the most relevant data from 2025 when they are published by the corresponding smart cities. Future research will focus on integrating dynamic urban data streams to refine the model's temporal sensitivity and better support predictive planning tools for smart cities. Further, the authors aim to propose a development strategy to the European Commission for Hyperloop implementation and an appropriate framework for the existing Hyperloop industry projects. Further, it is recommended to conduct a case study for more nuanced implementation with specific components, for example, with or without vacuum or Maglev, and to consider quantifying social factors and use-cases' impact on smart cities development.

**Supplementary Materials:** The following supporting information can be downloaded at [https://github.com/pirrencode/hpl\\_smart\\_cities](https://github.com/pirrencode/hpl_smart_cities), accessed on 14 June 2025. smart\_city\_gdp\_model.py: Python Program for GDP calculation of Hyperloop on smart cities; /data/smc\_input.csv: Input data

for case studies; /data/smart\_city\_metrics\_output\_ppml.csv: Results of GDP calculation for case study scenarios.

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