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VALUATION OF A ROAD MAINTENANCE PROGRAMME

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SUMMARY

This note sets out a comprehensive methodology for evaluating the socio-economic and fiscal impacts of road maintenance in Georgia. Moving beyond a purely technical cost perspective, it frames maintenance as a strategic investment that drives regional development, productivity, and fiscal sustainability.

The proposed framework links four core components: transport modelling, accessibility analysis, productivity estimation, and fiscal impact simulation. Improved road quality reduces travel times, widens access to jobs and services, and strengthens urban agglomeration effects – delivering measurable gains in GDP and tax revenues.

The methodology follows eight sequential steps: assessing current road conditions, forecasting traffic, modelling infrastructure deterioration, quantifying accessibility improvements, estimating productivity impacts, and projecting additional tax revenues using a Socio-Economic and Fiscal Assessment Model. Dynamic programming techniques can then be applied to optimize the timing and spatial allocation of maintenance activities.

Designed as a modular, scalable tool, the framework can be implemented with existing data in the short term and progressively refined through dedicated surveys, model calibration, and Georgian-specific parameters. It supports evidence-based infrastructure planning, provides a transparent basis for prioritizing investments, and underpins the case for dedicated funding mechanisms.

By demonstrating the economic and fiscal returns of well-planned maintenance, this approach repositions road upkeep from a budgetary burden to a catalyst for sustainable territorial and economic growth.

Key Words: Georgia, road maintenance, wider economic benefits, fiscal, accessibility.

JEL: R42, H54, R11, R41, H71, 018

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INTRODUCTION

This note presents a methodology for assessing the socio-economic and fiscal impacts associated with improved road maintenance across Georgian regions.

Georgia's road network plays a crucial role in connecting remote mountainous regions with urban centers and international corridors. Around 95% of passenger and freight movements rely on road transport (Benmaamar et al.2015). However, nearly 40% of the secondary and local network is in poor condition, particularly in rural and highland areas (Asian Development Bank, 2022). This creates significant disparities in accessibility and limits integration into regional markets.

The primary objective is to provide policymakers with a rigorous framework for quantifying the expected benefits of various maintenance scenarios, particularly in terms of travel conditions, accessibility, productivity, gross domestic product (GDP), and tax revenues. The latter two aspects are largely overlooked in both academic literature and practical evaluations, yet we consider them essential for justifying public expenditure on road maintenance.

The approach draws on tools from transport modelling, accessibility analysis, urban economics, and microsimulation of tax systems. It rests on the central assumption that better road infrastructure quality reduces travel times, enhances access to jobs and services, and generates productivity gains – especially in urban areas where agglomeration effects are significant (Combes, et al., 2012). These productivity gains translate into increased economic activity, both formal and informal, with measurable fiscal returns.

Accessibility is measured using origin-destination (OD) matrices disaggregated by vehicle type, based on survey data or assumptions regarding trip purposes and values of time (VOT). User welfare gains are assessed using the logsum formulation, a well-established method in the transport economics literature and widely accepted in discrete choice modelling. Sectoral variations in GDP are then estimated using elasticities derived from the literature, with scope for subsequent adjustment based on Georgian-specific data.

Fiscal impacts are assessed using a Socio-Economic and Fiscal Assessment Model, which estimates the additional tax revenues generated by the increase in GDP,

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distinguishing between household and business contributions.[1] These revenues could, where appropriate, feed into a dedicated road maintenance fund. For a discussion of road funds, see e.g. Gwilliam and Shalizi, (1999).

The methodology is designed to be implemented progressively. An initial phase relies on available data and parameters drawn from the literature. Subsequent phases may incorporate dedicated surveys, model calibration, and the spatial and temporal optimisation of maintenance programme using dynamic programming techniques.

This analytical framework is therefore intended to provide Georgian authorities with a robust, transparent, and scientifically grounded decision-support tool, enabling the prioritization of road infrastructure investments based on their economic returns and social relevance. Our aim in this document is to explain the fundamental concepts, which can only be operationalized at a later stage, notably by deploying a dynamic traffic model simulating flows of motorized vehicles.[2]

OBJECTIVE AND METHODOLOGY

The objective is to define a scientifically sound process to estimate the additional tax revenues required to finance the maintenance of the road network. The logical sequence of the process is as follows:

Assessment of the road network condition and traffic flows.

1. **Traffic forecasting** for heavy goods vehicles (two types), buses, and light vehicles (three types).
2. **Simulation of the road network's quality evolution** over time, based on traffic levels and maintenance intensity.

[1] See for example of the GLOPRAM model (Amar and Piron, 2020).

[2] I wish to express my gratitude to Luc Leruth for his valuable comments and suggestions. I am also indebted to Émile Quinet (Paris School of Economics), Robin Lindsey (University of British Columbia, Canada), Vincent Piron (Piron Consulting, France), Nathalie Picard (University of Strasbourg, France), Stef Proost (KU Leuven, Belgium), and Moez Kilani (Université du Littoral, France) and Gilles Duranton (Wharton) for their constructive contributions regarding cost–benefit analysis and maintenance policies.

3. **Computation of IRI (International Roughness Index)** and other road quality indicators affecting travel speeds.
4. **Modelling of travel time dynamics,** depending on both network conditions and travel demand.
5. **Estimation of changes in accessibility** to jobs and commercial areas.
6. **Evaluation of GDP growth effects**, based on improved accessibility.
7. **Estimation of potential additional tax revenues**, disaggregated by user group.

Step 1 is standard and can be conducted by a conventional consulting firm (such as EGIS). For step 2, the forecasting process needs to be enhanced by switching to software that enables a dynamic modelling of speed. Recommended tools include EMME4, HUBSIM, MATSIM, or METROPOLIS (Vosough, de Palma, Lindsey, 2022: see Section 10).

Steps 3 and 4 can be handled using the L^2R and HDM-4 software packages, once appropriately calibrated. Steps 5 and 6 can be modelled using EMME4, HUBSIM, MATSIM, or METROPOLIS. A new, dedicated methodology will be developed for step 6, with step 7 derived from the outputs of step 5, supplemented by external datasets. Alternatively, step 7 can be directly inferred from step 5 using simplified assumptions regarding the value of time.

Finally, step 8 involves a detailed fiscal analysis, using a tax modelling framework (using a Socio-Economic and Fiscal Assessment Model. This will provide a comprehensive fiscal balance and identify politically acceptable levels of tax contributions by user category. The resulting revenues could be allocated to a dedicated maintenance fund, in line with the Road Maintenance Fund. Technical details are relegated in the appendix.

The purpose of this note is to provide a detailed description of steps 6 and 7.

ACCECCIBILITY

An analytical model of road maintenance was developed by de Palma, Kilani, and Lindsey (2007). See also Newberry (1988) and Harvey (2012).

In Georgia, accessibility gaps are especially pronounced between Tbilisi and

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secondary cities such as Kutaisi, Batumi, and Telavi. The East–West Highway corridor has seen significant improvements through international financing, yet many rural communities remain underserved. Travel times can double during winter months in mountainous regions, underscoring the importance of systematic maintenance for equitable access.

The value of time α_K^P depends on the trip purpose p, the vehicle type m, and, for business- related trips, it may or may not depend on the activity sector k.

An origin-destination (O-D) matrix is available for each of the five modes m: private car (v), taxi (c), minibus (b), medium freight trucks (r), and articulated lorries (s). Drivers of freight vehicles (r and s) have only one mode available, whereas other workers can choose between the three other modes (v, c, and b).

These matrices should be disaggregated by trip purpose. If survey data do not allow for more precise segmentation, we will rely on ad hoc assumptions to allocate trips by purpose and vehicle type. The O-D matrices will be entirely business-related for freight vehicles (r and s). The household travel survey may be used to estimate the purpose distribution for the other three modes (v, c and b).

Let V_{ijkmpt} denote the deterministic component of utility for an individual travelling from origin i to destination j for purpose p. For home-to-work trips, i is the place of residence and j is the workplace of a firm in sector k located in j at time t, using mode m, with a travel time $tt_{ijm}(t)$.

This individual, with a **value of time** (VOT): α_K^m and an **intrinsic preference** δ_K^{mp} for mode

$$V_{ijkmt} = \delta_K^{mp} - \alpha_K^{mp} tt_{ijm}(t)$$

Utility, V, is expressed in **monetary units.**

The **modal shares** for O_i, D_j pair in sector k at time t are given by (see McFadden, 2001) :

$$\mathbb{P}_{ijkt}^{mp} = \frac{\exp\left(\delta_K^{mp} - \alpha_K^{mp} tt_{ijm}(t)\right)}{\sum_{m'=v,c,b} \exp\left(\delta_K^{m'p} - \alpha_K^{m'p} tt_{ijm'}(t)\right)}$$

The parameters $\delta_K^{mp}$and α_K^{mp}**can be calibrated** to best reproduce the **observed modal shares** by activity sector and O-D pair (origin–destination). This requires the availability of **modal shares for each O-D pair**. These modal shares can be

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calculated from the **traffic O-D matrices** available for each mode.

Information on **modal shares** and **trip purposes** may also be estimated from the **household travel survey**, even if such estimates only distinguish between sectors in a later phase.

The **surplus** of an individual undertaking a trip from i to j for purpose p, using their **optimal mode**, is given by the **logsum formula**, expressed in **monetary units** (see Ben-Akiva and Lerman, 1985 and Anderson, de Palma and Thisse, 1992):

$$LS_{ijkt} = ln\left[\sum_{m=v,c,b} \exp\left(\delta_K^m - \alpha_k tt_{ijm}(t)\right)\right]$$

This formula measures the benefit to users while accounting for their preferences. It corresponds to the user surplus in economic terms (i.e. the area under the demand curve), expressed in euros.

For example, it allows us to quantify the loss of welfare resulting from pricing a given mode of transport at a certain level (e.g., by reducing the constant term δ\delta$\delta$ for a mode by two euros when a toll of two euros is introduced for that mode). In such a case, users may either continue to use the same mode and "lose" two euros, or switch to another mode (initially less attractive) and experience a reduction in utility (longer travel time, higher cost, or lower intrinsic preference for the new route). This welfare loss is also captured by the logsum formula, which reflects user preferences across the different road transport modes v, c, and b.

The logsum is computed only across the three modes v (private car), c (taxi), and b (minibus), excluding freight vehicles, which are limited to a single available mode.

For **freight vehicles**, which only have **a single available mode** mmm, the surplus simplifies to a deterministic expression. Since the **variation in surplus does not depend on**

$$\delta_K^m - \alpha_K^m tt_{ijm}(t)$$

there is no need to estimate this parameter for **freight vehicles** (whether articulated or not).

By summing over all origins iii, we obtain – from the point of view of a **firm located in j** and operating in sector k – the **accessibility to the entire workforce**. This

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corresponds to the **surplus associated with a job located in j** in sector k:

$$\mathcal{A}_{jkt} = \mu ln\left[\sum_i \exp\left(\frac{LS_{ijkt}}{\mu}\right)\right] = \mu ln\left\{\sum_i\left[\sum_{m=v,c,b}\exp\left(\delta_K^m - \alpha_k tt_{ijm}(t)\right)\right]^{(1/\mu)}\right\},$$

where μ is a **scale parameter** capturing the **unobserved heterogeneity** of workers in sector k – that is, their specific preferences (not individually observable, but collectively estimable). This **accessibility measure** $\mathcal{A}_{jkt}$ depends on the full set of travel times and corresponds to the well-known **logsum** term in the literature.

We discuss the role of the **heterogeneity parameter** in more detail below.

Symmetrically, by summing over all destinations j, we obtain the **accessibility of workers to the labor market** (or to shops), which corresponds to the **surplus of a worker/consumer** residing in iii and working or consuming in sector k (with $k = 0$ for consumption):

$$\tilde{\mathcal{A}}_{jkt} = \tilde{\mu} ln\left[\sum_j \exp\left(\frac{LS_{ijkt}}{\tilde{\mu}}\right)\right] = \tilde{\mu} ln\left\{\sum_j\left[\sum_{m=v,c,b}\exp\left(\delta_K^m - \alpha_k tt_{ijm}(t)\right)\right]^{(1/\tilde{\mu})}\right\},$$

where $\tilde{\mu}$ is a parameter capturing the **unobserved heterogeneity of jobs in sector** k (**or of retail opportunities when** $k = 0$).

If the value of the parameter $\tilde{\mu}$ is zero (or close to zero), users choose the job or retail destination with the **highest deterministic utility** (i.e., the term inside the logsum). Conversely, if $\tilde{\mu}$ is very large, all destinations become **equally probable**.

A number of other unobservable factors also influence individual choices – such as the perceived quality of the environment at the destination, which varies across individuals, or idiosyncratic preferences for specific jobs or retail locations. The modeler, not being omniscient, represents these factors using a probability distribution (typically a normal distribution, or in this case a Gumbel distribution, which is similar to the normal) with zero mean and a standard deviation proportional to μ. This parameter captures the degree of preference heterogeneity, which plays a crucial role in modelling individuals' taste for variety.

Depending on the data available, it will be necessary to determine which sectors are to be included in the analysis: primary, secondary, tertiary, and informal sectors. The methodology remains the same across all sectors, although the parameter values will differ a priori.

To calculate the **benefit resulting from proper road network maintenance** compared to a strictly minimal maintenance scenario, **two sets of travel time matrices** will systematically be created, and the selected **transport model will be run twice**.

In **Phase 1**, it is assumed that **origins and destinations remain unchanged**. Accessibility will therefore need to be calculated **for both scenarios**, allowing us to obtain the **difference in accessibility** between the two maintenance regimes at time t: $\Delta\mathcal{A}_{jkt} = \mathcal{A}^1_{jkt} - \mathcal{A}^0_{jkt}$.

IMPACT ON PRODUCTION AND ON GDP

GDP is the total monetary or market value of all finished goods and services produced within the country's borders in a year.

Georgia's economy is heavily service-oriented (61% of GDP in 2023), with tourism, logistics, and trade playing central roles (GeoStat, 2024). Poor road quality raises transport costs for agricultural exports (notably wine, nuts, and mineral water) and reduces competitiveness in regional trade. Conversely, road improvements have been shown to increase agricultural market participation and rural household incomes (World Bank, 2022).

Productivity measures how efficiently these goods and services are produced. For the purpose of this note, we assume that **GDP is proportional to the sum of the productivities of workers**, whether formally or informally employed. This assumption can be refined depending on the **available data**. **Productivity is proxied by wages** (with or without employer contributions, before or after tax, depending on how the informal sector is treated).

When comparing two scenarios, the change in GDP, ΔPIB_{kt}, **resulting from a change in accessibility** in sector k at time t, is determined by the **variation in accessibility**, as detailed below.

According to the literature on **agglomeration effects** (see, for example, Combes et al. 2012), **improved accessibility increases worker productivity**. Several mechanisms are at play: better matching between workers and employers, reduced transport costs for goods (both inputs and outputs), and greater interaction between workers, fostering innovation, among others.

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The **elasticity** υ_k of **productivity with respect to accessibility** varies depending on the sector (k). Estimating **sector-specific elasticities** requires detailed data, which are unlikely to be available or usable in the initial phase.

Some studies also suggest that this elasticity **depends on the skill level** of the individual worker. However, we will assume – at least in the short term – that this effect is **captured by the distribution of qualifications within each sector**.

Time is indexed by t, individuals by i, residential location by j, and **sector of activity** by k. Let $X_{i,t}$ denote the **individual characteristics** of person i at time t.

The **productivity** ω_{ikt} of individual i, residing in j and working in sector k at time t is given by the **standard formula**:

$$\ln\left(\omega_{ikt}\right) = \beta X_{i,t} + \gamma_k + \delta_t + \upsilon_k \mathcal{A}_{jkt}$$

where β, γ_k, δ_t, and υ_k are **parameters to be estimated**, if the data allow for it. Otherwise, we will rely on **values from the literature**, particularly from the work initiated by **Combes and Puga, 2010.** The **elasticity** υ_k plays a **crucial role** in this study, as explained below.

We show below that, as a **first-order approximation**, if the **variation in accessibility within sector** k is not too heterogeneous, then the **change in GDP in sector** k depends **only on the change in accessibility in sector** k and on the **elasticity parameter** υ_k.

When comparing **scenario 1** to a **reference scenario 0**, the **change in productivity** resulting from an **increase in accessibility** i: $\Delta\mathcal{A}_{jkt} = \mathcal{A}^1_{jkt} - \mathcal{A}^0_{jkt}$ is given by:

$$\ln\left(\frac{\omega^1_{ikt}}{\omega^0_{ikt}}\right) = \ln\left(\omega^1_{ikt}\right) - \ln\left(\omega^0_{ikt}\right) = \upsilon_k\left(\mathcal{A}^1_{jkt} - \mathcal{A}^0_{jkt}\right) \equiv \upsilon_k \Delta\mathcal{A}_{jkt}$$

All productivities in sector k must therefore be **multiplied by**: $\exp[\upsilon_k \Delta\mathcal{A}_{jkt}]$.

It follows that if the **improvement in accessibility is spatially homogeneous** (i.e. ($\Delta\mathcal{A}_{jkt}$) does not depend on j – which does not restrict the spatial variability of the **level** of accessibility), then the **GDP of sector** k must also be **multiplied by the same factor**: $\exp[\upsilon_k \Delta\mathcal{A}_{kt}]$.

If, however, the improvement in accessibility is **spatially heterogeneous**, then the expression $\exp[\upsilon_k \Delta\mathcal{A}_{kt}]$ is only an **approximation of the change in GDP** in sector k. The **exact calculation** can be carried out by **disaggregating by sector** k and **zone**

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j, assuming homogeneous productivity within each (j, k) pair. If **worker characteristics** $X_{i,t}$ are heterogeneous within zone j and sector k, then the disaggregation should be **at the individual level.**

In the longer term, one could also consider that **some workers change sector** as a result of changes in accessibility. The above formula could then be **trivially extended**, subject to the **availability of data** to quantify these new sources of variation.

We will assume that the v_k parameters are **constant**. Consequently, **only changes in travel time** will affect the values of $v_k \Delta \mathcal{A}_{jkt}$.

In the longer term, it will be necessary to determine whether **data sources** (such as census data, wage statistics, and firm-level data) are available to **estimate these elasticities**. Over the **initial project duration (five months)**, it will not be possible to estimate them directly. Therefore, values will need to be **drawn from the literature**, particularly from the work of **Combes et al, 2011** . Where **sector-level data** (aggregated) are available, the **sector-specific elasticity values** may be used for Georgia. For example, the World Bank derives employment multipliers from sectoral GDP multipliers combined with differentiated employment–GDP elasticities for agriculture, industry, and services, thereby producing sectoral elasticities for a country's main economic sectors.

At a later stage, it may be useful to **estimate GDP variations by type of transport activity**: the **Port**, **shippers**, **freight operators (HGVs)**, **light vehicles**, **taxis**, **minibuses**, and **buses**.

A number of **additional elements** should also be taken into account when assessing the **impacts of road maintenance**: accidents, vehicle maintenance costs, fuel consumption, noise, and emissions (both local and global pollutants). These factors are part of a **cost– benefit analysis**, but are **not covered in the present study**. They can be addressed using **HDM-4** and integrated directly into a Socio-Economic and Fiscal Assessment Model.

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BUDGETARY IMPACT

The calculated **GDP increase** represents the **growth in formal economic activity** carried out by businesses and households (purchases) in the **Georgian regions** following the implementation of **effective road maintenance**. These businesses and individuals pay **taxes, including income taxes and VAT**, and the additional employees will also pay these **taxes**.

The Socio-Economic and Fiscal Assessment Model will provide an estimate of the **additional taxes and specific levies** potentially paid by each category of stakeholders resulting from the increase in **GDP by type of activity.** This is based on a **socio-economic analysis**, and existing **fiscal and social rules**.

Public authorities may choose to allocate part of these surpluses to a **dedicated maintenance fund** (see Gwilliam and Shalizi, 1999).

OPTIMAL MAINTENANCE

The proposed formulation will make it possible to assess the consequences of various road maintenance scenarios, each characterized by different schedules and geographical allocations of maintenance activities, as defined and provided by the relevant authorities or planning bodies. These scenarios may vary in terms of the timing, frequency, and intensity of interventions, as well as the prioritization of specific road segments or regions. By simulating their impacts on travel conditions, accessibility, productivity, and fiscal returns, the framework offers a robust basis for comparing and ranking alternative strategies.

In the longer term, once the model has been fully calibrated and validated using context- specific data – particularly regarding travel behavior, infrastructure conditions, and economic responses – it could serve as a decision-support tool not only for evaluating predefined scenarios, but also for determining the **optimal maintenance strategy**. This would involve identifying the allocation of resources over time and across space that maximizes net social and economic benefits, taking into account constraints such as public budgets, maintenance costs, and infrastructure degradation rates.

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To achieve this, **dynamic programming techniques** could be applied to model the sequential nature of maintenance decisions and the intertemporal trade-offs involved. This optimization approach would allow planners to anticipate how current investments affect future road conditions, user benefits, and fiscal revenues, thereby supporting the design of a more efficient and sustainable maintenance policy. Such an approach would be particularly valuable in a context of limited resources and growing infrastructure needs, ensuring that maintenance interventions are timed and located to generate the highest possible return on investment over the medium to long term.

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CONCLUSIONS

The economic assessment of a road maintenance programme extends far beyond calculating technical costs. It demands a comprehensive view of territorial dynamics, production systems, and the long-term viability of public policies. This note has outlined an integrated framework that connects transport modelling, accessibility metrics, productivity analysis, and fiscal impact assessment – providing a clear pathway to quantify how infrastructure quality shapes local and regional economic growth.

The mechanisms at play – agglomeration effects, improved labour–employer matching, time savings, and efficiency gains – are well established in theory. Yet practical challenges remain. Chief among them are the availability and quality of data: robust estimates require detailed spatial information on jobs, wages, travel flows, and modal behaviour. Equally important is the ability to calibrate and regularly update key parameters, including values of time, productivity elasticities, and modal preferences.

For these reasons, the proposed methodology is intentionally evolutionary. It can be applied initially with literature-based parameters and available datasets, while progressively improving through targeted surveys, empirical feedback, and iterative calibration. Over time, this adaptive approach can align transport, land-use, and fiscal policies more closely with observed economic realities.

Beyond its technical value, this work addresses a strategic policy question: how to sustainably finance road maintenance. For Georgia, improving road maintenance is not only a technical necessity but also a strategic enabler of regional integration, tourism development, and rural inclusion. By quantifying economic and fiscal returns, the proposed framework can help bridge the gap between infrastructure policy and Georgia's broader goals of inclusive and sustainable growth, as articulated in Georgia 2030 Strategy (Government of Georgia, 2021).

By quantifying its positive economic and fiscal spillovers, it opens the way for value capture mechanisms – whether through increased tax revenues or dedicated maintenance funds. In doing so, it reframes road maintenance from a recurrent expense to a high-return investment and a key lever for sustainable territorial and economic development.

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APPENDICES

DATA AND IMPLEMENTATION FRAMEWORK

Data Needed

Only the data essential for carrying out the first phase are listed here. They are detailed according to their intended use in the project.

All data must be provided in CSV format, along with the corresponding documentation.

Computation of Accessibility

The **calculation of accessibility** requires access to the following:

For each maintenance scenario at each date:

An **OD matrix of travel times**, by vehicle type

An **OD matrix of traffic volumes**, by vehicle type

The **location of workers, population and/or households**, at a sufficiently disaggregated geographical level (e.g. dividing the Tbilisi region into 5 to 50 or 100 zones).

The **location of businesses/jobs and retail outlets**

Values of time (VOT) by trip purpose, and for professional purposes, by **sector of activity**, and where relevant, by **vehicle type** (it is assumed that VOT does not vary over time or between scenarios).

If VOT data are not available, they may be estimated using the **transport survey**. In the worst case, **VOT values from the literature** may be used. However, **transport survey data are essential** for estimating the parameters δ_K^m and α_k.

The **transport survey** should provide, for each trip using mode v, c, or b, the **trip purpose**, **origin**, **destination**, and the **time of travel**. This allows for the computation of **travel times** for each of the three modes.

The parameters δ_K^m and α_k can then be estimated using a **Multinomial Logit**

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model. The **coefficient vector** can only be estimated **up to a multiplicative constant**, and the **mode constants** only **up to an additive constant**.

The **multiplicative factor** can be recovered by referencing a **benchmark VOT value** (proportional to α_k). For the **additive constant**, for each sector k, one may apply a **normalisation** such as setting $\delta_K^m = 0$ for $m = b$, for example.

Calculation of Productivity Variations

It is necessary to have access to **data describing the distribution of employment by sector of activity**, ideally **with spatial detail**, along with information on the **distribution of wages**, both **by sector** and **by location**. Part of this information is likely to be available from **census data**, while another part would typically come from **firm-level data**, **surveys**, or **tax records** (par HDM-4).

TRAFFIC SIMULATOR: METROPOLIS

This section provides an overview of METROPOLIS, a traffic simulator that can be used to forecast the flow of vehicles on the different road according to their type, road quality (function of the level of maintenance) and the time of the day.

METROPOLIS simulator models movements of individual transport users and public transit in urban or peri-urban areas. This multi-agent explicitly captures individual user choices, with each traveler represented as an **agent.** It employs a dynamic approach, **explicitly accounting for congestion effects continuously throughout the day,** as a continuous variable represents time. By tracking **vehicle trajectories at an individual level,** METROPOLIS facilitates detailed analyses of travel-related well-being, both for individual travelers and aggregated user groups. In this study, we specifically focus on **weekday morning commuting patterns**.

The METROPOLIS dynamic network equilibrium simulator models individual travelers' choices of mode, departure time, and route within a road network, all determined endogenously. Building on Vickrey’s (1969) framework, road travelers are assumed to have individual-specific preferred arrival time windows at their destination and face schedule delay costs for arriving either earlier or later. The generalized systematic cost of public transport is assumed to be exogenous and independent of time of day. The generalized systematic cost of an auto trip is additively separable in travel time costs, schedule delay costs, and flat taxes, and it is given by a piece-linear function. The demand model employs a two-stage nested logit model (Anderson et al., 1992), with mode choice represented in the outer nest (see Figure 1, and the associated discussion, below). At the bottom stage, users select the dynamic shortest paths (once the mode choice and departure time choice have been made).

The departure time choice is modeled within the inner nest, by a standard continuous logit specification. In the simulations presented in this note, the allowable departure time window spans 6:00 AM to 12:00 AM, as depicted. Route choice follows a heuristic derived from a generalization of Wardrop's minimum-cost principle, which closely aligns with the minimum generalized cost (de Palma et al., 2005).

On the supply side, congestion is essentially described as a series of journeys where speed depends on the level of occupancy. Additionally, traffic slows down at specific points in the network, known as bottlenecks. The time required to clear a bottleneck depends on the ratio between the number of vehicles in the bottleneck and its capacity. The spill-back option may be activated.

A day-to-day adjustment process, incorporating exponential learning by drivers, governs changes in mode choice, departure time, and route choice, steering the system toward a stationary state. Further details on the learning process can be found in de Palma et al. (1997). Simulation experiments across various networks demonstrate that different initial conditions lead after converging to the same stationary regime.

The core of the METROPOLIS simulator is developed in Rust, while the input and output (I/O) modules are written in Python. Users have the flexibility to modify these external I/O modules as needed.

The workflow of METROPOLIS can be described through the diagram in Figure 1. In the first phase, input data is read, cleaned, and transformed into Parquet files, which are compatible with the METROPOLIS simulator. The simulator then processes this data through multiple iterations to generate output data. The stopping rule can either be exogenous (a predetermined number of iterations) or endogenous (based on some convergence criterion). Finally, the output data is transformed and sent to an output module that analyzes it.

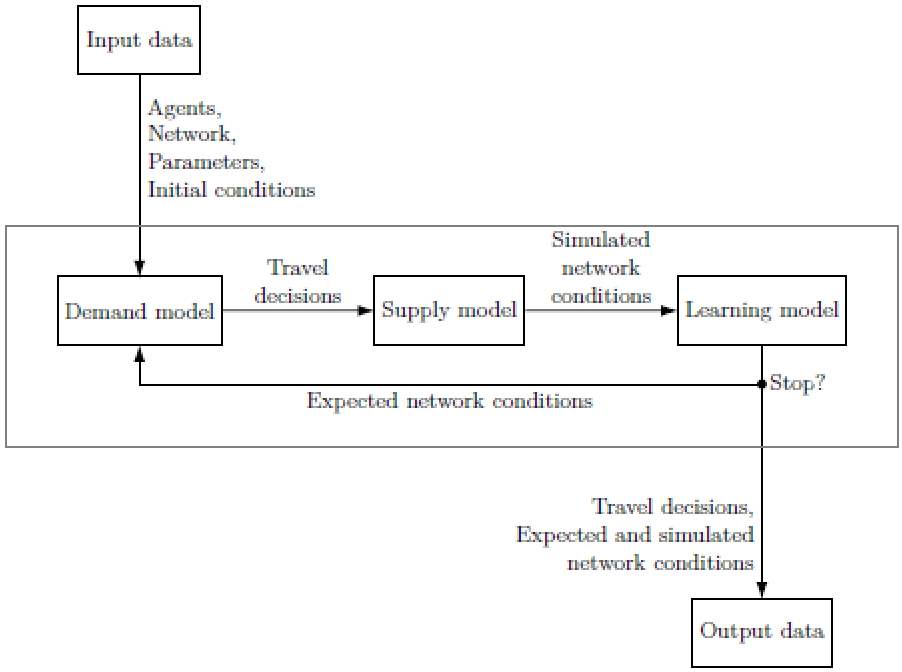

Figure 1: Workflow of the simulation process in METROPOLIS for the current project (Javaudin, 2024)

The whole process involves the following three main steps (see de Palma and Javaudin, 2024):

Python scripts process raw data to create the simulator's input data

The simulator reads input data and writes output data in Parquet or CSV format

Python scripts are processing the simulator's output data to create output tables, graphs, and maps

PAVEMENT DAMAGE AND MAINTENANCE MODELLING: INTEGRATION WITH ROAD MAINTENANCE FRAMEWORK

Purpose and Link to Main Framework

This appendix develops the physical road-wear component that underpins several modules of the Georgia road maintenance methodology (Sections 4, 5, and 6 of the note). By explicitly modelling pavement deterioration and marginal damage costs, it strengthens the economic–fiscal linkages described in the Socio-Economic and Fiscal Assessment Model, enabling more accurate forecasts of accessibility, productivity, and tax revenues under alternative maintenance strategies.

Pavement Types

The deterioration module distinguishes between:

Rigid pavements – Portland cement concrete; crack under repeated stress, lower deformation rates, longer maintenance cycles for structural integrity but higher repair costs when failures occur.

Flexible pavements – Asphaltic concrete; more compressible, more sensitive to heavy axle loads and temperature variation, typically requiring shorter maintenance intervals.

These distinctions are relevant for:

Step 3 (simulation of network quality evolution)

Step 8 (fiscal evaluation, as maintenance costs differ by pavement type).

Deterioration Functions and Dynamics

Empirical evidence (e.g., RoadBotics, 2019) and engineering practice suggest pavement quality follows a **logistic deterioration curve**:

Initial slow decline after construction or major rehabilitation.

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Accelerated deterioration phase, where quality drops quickly without intervention.

Flattening phase at low quality levels, when further deterioration is slower.

Key implications for the optimization framework (Section 6):

Logistic deterioration can yield **multiple optima**: short maintenance intervals (to avoid the steep decay) or long/no intervention (if usage is low and discount rates are high).

Usage decline on deteriorated roads may itself slow the deterioration rate, creating non-linear feedbacks between demand and quality.

Marginal Damage Costs by Road Class

The *FHWA Cost Allocation Study* (1982) provides benchmark U.S. estimates:

Rural interstates: **$0.09/vehicle-mile**

Urban arterials: **$0.66/vehicle-mile**

Urban local streets: **$0.80/vehicle-mile**

These will be adapted to Georgian conditions using:

Local unit maintenance costs (L^2R, HDM-4)

PPP-adjusted price levels

Traffic composition outputs from METROPOLIS (Step 2 and Step 5)

In the fiscal model (Section 5), higher marginal damage cost segments will show stronger returns from preventive maintenance.

Integration with the Modelling Workflow

The enhanced deterioration module operates in parallel with the main eight-step process:

1. **Traffic simulation** (METROPOLIS) → daily and cumulative axle loads by road link and vehicle class.
2. **Deterioration function** → updated International Roughness Index (IRI) values for each link.

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3. **IRI to speed/capacity** mapping → revised OD travel time matrices (affecting accessibility in Section 3).
4. Accessibility changes → productivity changes (Section 4) → GDP impacts.
5. GDP impacts → additional tax revenue estimates (Section 5).

This creates a **dynamic feedback loop** between physical infrastructure quality and the socio- economic outputs of the main framework.

Data Requirements for Implementation

Pavement type classification for all modelled links.

Time series of IRI values from road condition surveys.

Seasonal weather data (temperature, precipitation, freeze–thaw cycles).

Unit maintenance/reconstruction costs by pavement type and road class.

Historical and forecast traffic by vehicle class (from Step 2).

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