Investigating the robustness of route-based sensor location policies under variable network demand

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1 Introduction

Traffic management applications rely on timely, precise and as complete as possible traffic flow information, in order to appropriately react to the road network's situation. Considering the sensing infrastructure required to collect said information, several approaches have been developed in order to determine both quantity and location of sensors required to reach a sufficient level of information, both in terms of quality and quantity [1].

Among others, the link flow inference problem leverages the algebraic relationships between different flows in a network, considering both node-link relations (conservation of flows at nodes) and link-route relations (conservation of vehicles at routes) [2]–[4]. These works are largely static in nature: optimal sensor locations are determined based on the network topology itself, without explicit consideration of changes in the network's behaviour due to the dynamic nature of transportation demand. Few works in literature have focussed on developing sensor location approaches that explicitly consider this variability, by means of stochastic optimisation [5]–[8], at an unavoidable loss in computational efficiency.

In this work we evaluate, through comparative analysis, how link flow inference-based sensor location approaches, albeit static in nature, behave when dealing with different demand levels. Specifically, our objective is assessing the amount and variability of estimation error induced by disregarding the stochasticity of demand when determining the optimal set of sensor locations.

By comparing two different static sensor location problem methodologies we showcase both how relevant the chosen static algorithm is, and quantify the effective information loss due to demand variability.

2 Methodology

Variations in the volume of traffic demand induce considerable changes in the user's preferred route set: when overall demand is very low, users will choose the topologically shortest path to their destination, disregarding any other, longer alternative. As demand rises, the formation of congestion pushes users towards other alternatives, in order to maintain their own perceived cost as low as possible [9]. In link flow inference problems, route information is assumed fixed and static, and the resulting sensor locations are largely related to which routes are included in the chosen set [10].

In this work we compare the impact of two different route set enumeration policies, namely the simpler K-Shortest Path [11] and our recently developed hypergraph-based approach [12], and evaluate how the sensor locations determined through this static selection of routes compares to those dynamically arising from deterministic assignment. Full observability solutions are obtained for both route enumeration approaches using Castillo's Pivoting technique [13]. The overall comparative approach is summarised in Figure 1.

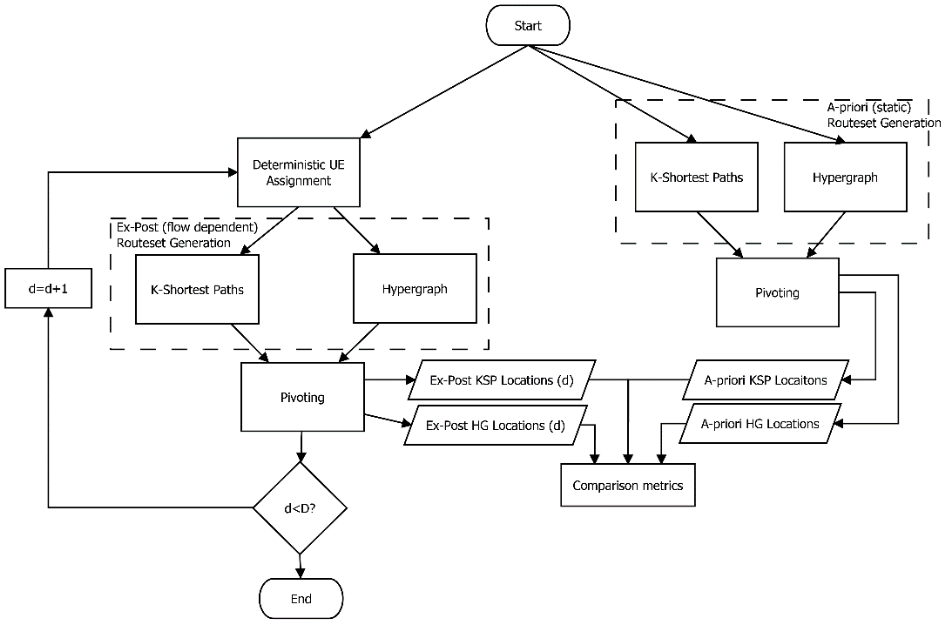

Figure 1: Flowchart of this work's comparative approach

Both a-priori sensor location sets $\Omega_{KSP}, \Omega_{HG}$ are determined based solely on topological network costs, whereas the ex-post counterparts $\Omega_{KSP}(d), \Omega_{HG}(d)$ are determined considering the link travel costs arising from Dial's B deterministic traffic assignment procedure [cit dial]. Repeated assignment is carried out considering a base Origin-Destination demand matrix $X_b \in \Re^{n \times n}$, which is gradually multiplied by an amplitude modifier $\alpha = [\alpha_1, ..., \alpha_D]$. This implies that, rather than considering variations in the spatial distribution of demand, we are focussing, in these preliminary results, in demand amplitude variations, and how these affect the overall user's route choice.

Demand-dependent cross-comparison is carried out considering three indicators:

- The total amount of sensors necessary to fully observe the given network;
- The percental overlap between the sensors resulting from the a-priori approaches and those of the ex-poste approach
- The partial observability level resulting by locating only sensors according to the a-priori approaches, as measured by the NSP metric (eq. 1)

$$NSP(\Omega_*(\alpha)) = \frac{\| \Omega^T{}_*(\alpha) B_*' \|_F}{\| \Omega^T{}_*(\alpha) \|_F} \tag{1}$$

where $\Omega_*(\alpha)$ is the full observability matrix pertaining to the ex-post solution, while B_*' is the partial observability solution obtained by considering the set of sensors in the intersection $\Omega_*(\alpha) \cap \Omega_*$, that is, those sensors pertaining both to the a-priori and the ex-post solution.

3 Experimental results

We apply our cross-comparison on a simplified version of the road network pertaining to the Dutch city of Rotterdam, including its Ring Road and the main surrounding motorway accesses, as shown in Figure 2.

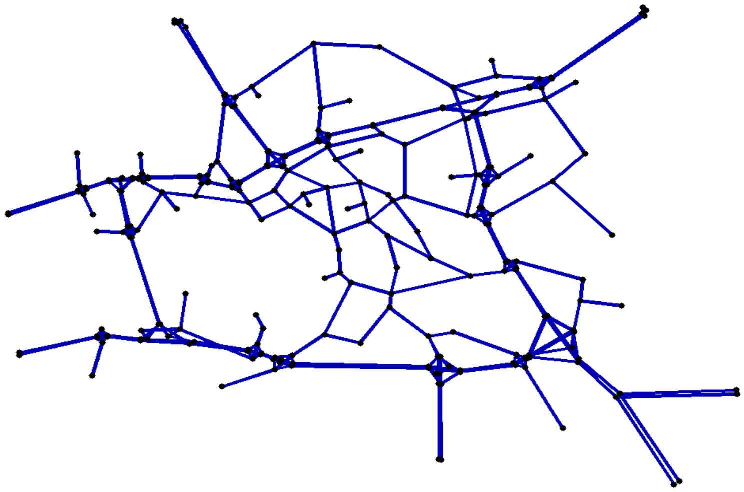

Figure 2: The Rotterdam road network.

Demand representing morning peak conditions is used as the base scenario, we consider multiplicative factors $\alpha = [0.1, \ldots, 3]$ with steps of 0.1. The three comparative metrics discussed above are showcased in Figure 3.

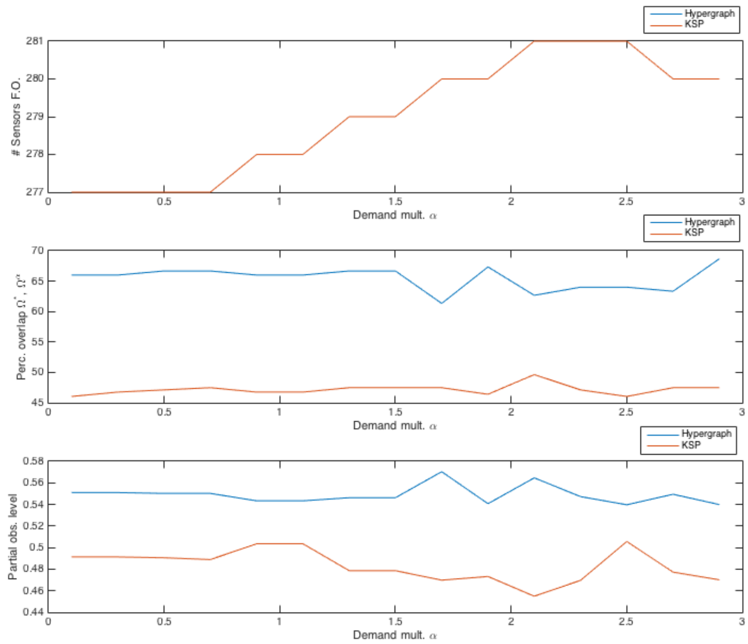

Figure 3: Test results for the three chosen comparison metrics

Interestingly, while the total amount of sensors required to fully observe the network increase with demand (which is rather expectable, as higher demand levels directly imply a more widespread usage of the network), this quantity is independent of the chosen route set generation approach. Conversely, considerable differences arise both in terms of percental overlap between a-priori and ex-post sensor locations, and resulting partial observability level. Indeed, the hypergraph generated approach, due to its inherent higher level of prior information, is an overall better candidate than the standard K-Shortest Path approach, even for varying levels of demand. From this preliminary analysis we can anyhow conclude that, using the better approach, information loss due to route choice mismatch reaches an average level of 40%, attesting to the fact that while static solutions can be lossy, a considerable amount of information on link flows can still be extracted successfully.

Further comparison results, considering variations not only in the amplitude of demand, but also on its geographical distribution, will be presented at the symposium.

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