## **Supplementary Materials**

## **A.4 Case study data**

The case study involves transporting 30 different orders within the network. Table A.1 presents the origin and destination nodes, demand in terms of TEU hazmat and non-hazmat containers, and the due date for each order. Table A.2 shows the capacity, variable cost, and transfer cost of each mode, adapted from Qu et al. (2014).

**Table A.1.** Case study data on origins, destinations and demands for orders

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Order No. | Origin node | Destination node | Demand of non-hazmat  (TEU container) | Demand of hazmat  (TEU container) | Tk  (hour) |
| 1 | 4 | 3 | 15 | 15 | 70 |
| 2 | 9 | 7 | 84 | 84 | 80 |
| 3 | 2 | 9 | 57 | 57 | 150 |
| 4 | 4 | 11 | 9 | 9 | 150 |
| 5 | 2 | 7 | 13 | 13 | 150 |
| 6 | 11 | 5 | 7 | 7 | 110 |
| 7 | 10 | 3 | 11 | 11 | 70 |
| 8 | 10 | 1 | 25 | 25 | 200 |
| 9 | 11 | 7 | 12 | 12 | 70 |
| 10 | 3 | 6 | 41 | 41 | 230 |
| 11 | 7 | 8 | 69 | 69 | 40 |
| 12 | 1 | 3 | 17 | 17 | 230 |
| 13 | 2 | 11 | 56 | 56 | 110 |
| 14 | 5 | 10 | 6 | 6 | 110 |
| 15 | 5 | 6 | 41 | 41 | 190 |
| 16 | 5 | 8 | 11 | 11 | 160 |
| 17 | 11 | 2 | 87 | 87 | 110 |
| 18 | 8 | 6 | 8 | 8 | 40 |
| 19 | 6 | 5 | 25 | 25 | 190 |
| 20 | 7 | 5 | 29 | 29 | 200 |
| 21 | 3 | 2 | 21 | 21 | 260 |
| 22 | 4 | 2 | 9 | 9 | 260 |
| 23 | 9 | 5 | 16 | 16 | 120 |
| 24 | 4 | 10 | 61 | 61 | 130 |
| 25 | 5 | 10 | 36 | 36 | 110 |
| 26 | 2 | 1 | 20 | 20 | 40 |
| 27 | 6 | 11 | 11 | 11 | 110 |
| 28 | 8 | 9 | 57 | 57 | 40 |
| 29 | 4 | 3 | 13 | 13 | 70 |
| 30 | 8 | 7 | 6 | 6 | 40 |

**Table A.2**. Case study parameters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Transportation mode | Capacity  (TEU container) | Variable cost for non-hazmat containers  (£ per TEU-mile) | Variable cost for hazmat containers  (£ per TEU-mile) | Transfer cost  (£ per TEU) |
| Truck | 2 | 0.504 | 0.605 | 19.474 |
| Rail | 28 | 0.595 | 0.714 | 19.474 |
| Barge | 212 | 0.35 | 0.420 | 19.474 |

## **A.4.1 Socio-environmental factors at different speed levels**

In this subsection, we determine the socio-environmental cost conversion factor for each externality of three modes of transport, using the moderate speed level (i.e., the second speed level appearing in *Vtruck*, *Vtrain* and *Vbarge*), as the baseline. Then, based on the literature, we estimate these factors for the other two speed levels. We derive the related sustainability factors from the studies of Beuthe et al. (2002), Bickel and Friedrich (2005), Hofbauer and Putz (2020), Lindberg (2005), Nash (2003), and Ranaiefar and Amelia (2011). Table A.3 summarizes the results.

**Table A.3.** Socio-environmental cost conversion factors for road, rail, and Inland waterway

|  |  |  |  |
| --- | --- | --- | --- |
|  | Socio-environmental costs (£ct/ TEU.mile) | | |
|  | Road | Rail | Inland waterway |
| GHG emissions | 9.84 | 4.62 | 5.32 |
| Noise pollution | 18.08 | 19.18 | 0 |
| Accidents | 9.84 | 1.4 | 0.7 |
| Traffic congestion | 8.71 | - | - |
| Total (Combined negative externalities) | 46.47 | 25.2 | 6.02 |

***GHG emissions:*** GHG emissions lead to both environmental (e.g., climate change) and social effects (e.g., health-related concerns from air pollution) (Aminzadegan et al., 2022).GHG emissions are quantified in CO2e (United States Environmental Protection Agency, 2023) because carbon dioxide comprises the majority of GHG emissions in logistics operations, making it the standard reference for quantification. Fuel consumption is directly related to CO2e emissions (WLTP, 2018). Generally, emissions from heavy-duty trucks in road transportation increase with higher speeds. A truck traveling at higher speeds requires more energy to overcome air and rolling resistance, resulting in higher fuel consumption and GHG emissions. We consider the recommended speed level (50 mph for road, 37 mph for rail, and 29 mph for waterways) as the baseline level for all three modes of transport (of course this is adjustable for other situations). We also assume underspeeding (e.g., *Vtruck* = 30 mph) reduces fuel consumption and GHG emissions by about 2%, while overspeeding (e.g., *Vtruck* = 60 mph) increases them by about 7%. These estimates were obtained from Demir et al. (2015) and the COPERT method. Emissions at different speed levels are provided in Table A.4.

**Table A.4**. GHG emissions by transportation mode and speed level (kg/TEU-mile)

|  |  |  |  |
| --- | --- | --- | --- |
| Transportation mode | CO2e (kg/TEU-mile) | | |
| Speed level 1 | Speed level 2 | Speed level 3 |
| Truck | 1.37 | 1.40 | 1.50 |
| Rail | 0.49 | 0.50 | 0.54 |
| Barge | 0.35 | 0.36 | 0.39 |

These emissions can be converted into monetary units using the socio-environmental cost conversion factor for emissions () in £/kg. In the UK, this factor is commonly known as the "carbon price". As of 2024, the carbon price is set at £64.9 per tonne of CO2e.

***Noise factor on road:*** The noise factor is modeled using the approach developed by Demir et al. (2015), which indicates that the perception of sound follows a logarithmic scale. Their study reports results for two speed levels of 60 km/h (37 mph) and 80 km/h (50 mph). According to their findings, the noise power in high octave bands increases by approximately 3% when transitioning from 60 km/h to 80 km/h. Therefore, we assume a similar 3% increase in sound power when the speed increases from 50 mph compared to 60 mph.

Further supporting these findings, a report by the Victoria Transport Policy Institute (2022) notes that increasing the speed of an automobile by 10 mph (from 55 to 65 mph) raises the noise level from 72 dB to 75 dB. For trucks, a 10 mph increase results in noise levels from 86 to 88 dB. Consequently, the socio-environmental cost conversion factor for noise pollution at varying speeds in road travel for the three speed levels () is set as follows: [0.1754, 0.1808, 0.1862] (€/container-mile), respectively.

***Road accident:*** Addressing the impact of speed limit on accident costs, a report to the Office of Economic and Strategic Analysis of the U.S. Department of Transportation underlines that after the 1987 federal legislation permitted states to raise the speed limit on rural interstate highways from 55 to 65 mph, the fatality rates on these highways surged by an average of 35% (U.S. Department of Transportation, 2009). In line with this pattern, the social cost conversion factor for road accidents at speed level *v* = [30, 50, 60], is set at [0.06396, 0.0984, 0.13284] (€/container-mile), respectively.

***Congestion:*** The cost of congestion extends beyond fuel expenses and encompasses other factors such as wasted travel time, unreliability of travel times, reduced mobility, and emission- related costs (U.S. Department of Transportation, 2009). To quantify the congestion costs, a specific formula for calculating fuel consumption under congested conditions is provided (U.S. Department of Transportation, 2009):

Average miles per gallon (mpg) = 8.8 + 0.25\* average speed

According to this formula, the average miles per gallon for vehicles traveling at 60 mph (v = 60 mph) is 23.8, at *v* = 50 mph it is 21.3, and at *v* = 30 mph it is 16.3. Therefore, a truck traveling at 30 mph achieves 16.3 mpg of fuel, while at 60 mph, it can cover more mileage. We must note that although this equation suggests that average mpg typically increases with average speed, evidence from the U.S. Department of Transportation indicates a U-shaped relationship between mpg and speed (U.S. Department of Transportation, 2009). Furthermore, the predominant component of congestion costs is travel time costs, accounting for 71% of the total cost, representing the opportunity cost of time wasted on congested roads (U.S. Department of Transportation, 2009). Consequently, the road congestion coefficients for speed level *v* are assumed to be [1.5, 1.10, 1], respectively, implying that a truck traveling at a low speed incurs 1.5 times the congestion cost relative to travelling at higher speed. The socio-environmental cost conversion factor for congestion in road travel at speed level *v* () is set at [0.1307, 0.0958, and 0.0871] (£/container-mile), respectively.

***Negative externalities in rail and waterway travel:*** We posit that negative externalities in rail and waterway travel vary with speed levels, leading to adjustments in the combined socio-environmental cost conversion factors. Specifically, the second speed level, considered moderate/safe/recommended, sees a 10% reduction from the third level and a 10% increase from the first level. Consequently, the combined cost conversion factor for negative externalities in rail travel () is set at [0.2268, 0.252, 0.2772] (£/container-mile) at three speed levels. Similarly, waterways (), the corresponding values are [0.05418, 0.0602, 0.06622]. These adjustments reflect the impact of speed on the cost of socio-environmental externalities in these modes of transport.

## **A.4.2 Probability and consequences of hazmat transportation accidents**

We assume no correlation between accidents, implying independent probability distributions. This approach aligns with previous studies such as those by Verma (2009) and Fontaine et al. (2020). Contrary to previous literature, we posit that both parameters and , representing the probability and consequences of accidents in modal links, are speed-dependent. At the recommended/safe speed, the probability of a vehicle encountering an accident on any given link is 3.82×10−6. Overspeeding increases this probability by 35%. The same ratios/multipliers also apply to accident consequences at those speeds. Furthermore, the probability of accidents in hazmat transportation due to overspeeding is set at 3.5×10−3 for every mph above the safe/recommended speeds across all modes of transport. For underspeeding, the probabilities are 0.002, 0.001, and 0 for trucks, trains, and barges, respectively, for every mph below the safe speeds.

To estimate the risk associated with the transfer process, we refer to Verma (2011), which estimates that the probability of hazmat transportation accidents during the transfer of a hazmat container is 17.13×10−6 at all transfer terminals. The consequences of hazmat transportation accidents are modeled by considering the population exposure (i.e., the number of people potentially affected by hazmat transportation accidents). For this purpose, we have created a buffer zone with a radius of 0.225 miles (360 m) around each modal link and a radius of 1 mile around transfer terminals within the network, using ArcGIS as proposed by Jabbarzadeh et al. (2020). In the case of waterways, we account for a population exposure of 2000 to implicitly include the significant environmental impact that a hazmat transportation accident could have. This way we can comprehensively assess the potential human and environmental consequences of accidents during the hazmat transfer process.

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