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The impact of distance on mode choice in freight transport

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Abstract

Purpose: The purpose of this paper is to examine the impact of distance on choosing between intermodal rail-road and unimodal road transport and to examine the hypothesis that distance is an important factor influencing the mode choice in freight transport.

Methods: In order to make comparisons between the two options, the ideas and elements of the analytical transport system modelling found in the literature are used. The calculation of break-even distances is based on a Monte Carlo simulation that takes randomly generated shipper and consignee locations in two separated market areas, independently of a certain transport corridor, into account.

Results: The results confirm the importance of distance for the mode choice and show there is not only one but in fact many break-even distances between the two options. They vary considerably depending on different travel plans, and the transport infrastructure conditions.

Conclusions: Despite assumptions inevitable in such general analysis, the results show that intermodal transport can provide a competitive alternative to unimodal road transport, even over relatively very short distances if the drayage costs are not too high. We believe the paper can help improve understanding of competitiveness in the freight transport sector and may also be useful for policy- and other decision-makers to better evaluate the opportunities and competitiveness of intermodal rail-road transport.

Keywords: Distance, Break-even distance, Modal choice, Intermodal transport, Monte Carlo simulation

1 Introduction

The ever-increasing use of road freight transport brings a variety of negative, external effects such as congestion, pollution, and accidents [1]. Becoming aware of the growing freight transport volumes and ever more congested roads, the European Commission [2] suggested a shift from road transport to other, more sustainable transport modes in order to reduce the transport sector's environmental impact. As the European Commission [2] noted, 30% of road freight transported over 300 km could be shifted to other modes like rail or waterborne transport by 2030, and more than 50% by 2050, facilitated by efficient and green freight corridors [3]. Some researches, such as Rutten [4], state that all road transport over distances exceeding 100 km is basically suitable for shifting over to intermodal transport on the condition that, with respect to the goods considered, the

intermodal, also known as multimodal, transport's quality and service is comparable to or better than that provided by road haulage. This means the additional costs and time incurred by drayage as well as transshipments must be offset during the rail haul by the lower costs and higher speed of rail over road [5]. Irrespective of this, intermodal rail-road transport seems to be the most realistic alternative for reducing the dominance of road transport and helping make the transport system more sustainable.

Intermodal freight transport is a term for describing the movement of goods using one and the same loading unit or vehicle which employs successive and different modes of transport (road, rail, water) without any handling of the goods themselves during transfers between modes [6]. In the intermodal rail-road mode, road transport is used to collect and distribute freight, while rail is also harnessed for the long-haul or terminal-to-terminal trip. Freight forwarders offer consolidation and multimodal services, expertise in trade transactions and influence transport mode

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selection [7]. Significant for intermodal transport is the point-to-point bundling concept that implies that all load units placed on a train at the terminal of origin have the same destination terminal and that only intermodal transport and loading units (containers, swap bodies, and semi-trailers) are used. To promote the intermodal transport, the rail terminals at both ends can be facilitated by consolidation centers [8]. Intermodal transport takes advantage of the combination of rail and road and consists of drayage in the market area of origin, rail haul in the long-haul part of the transport chain, and drayage in the market area of the destination.

On the other side, unimodal road transport is transport carried out exclusively by trucks. It is assumed that trucks are loaded with load units at a single collection area and destined for a single distribution area. The whole transport from door to door is carried out by the same truck and no transshipment is needed. Unimodal road transport entails the collection of cargo in the origin area, transport from the origin to destination area, and distribution of the cargo in the destination area.

Several studies specifically deal with the choice between intermodal and unimodal road transport, yet the results are often based on selected geographical corridors and are inappropriate for generally estimating the competitiveness of intermodal transport. Tsamboulas & Kapros [9] identified three decision patterns regarding the mode-choice decision. The first group comprises already intensive users of intermodal transport, who decide almost solely according to the cost criterion, after ensuring that the basic transport quality requirements are met. The second group encompasses users who engage in intermodal transport only for a minor portion of their total transport volumes; they decide according to both quality and cost criteria. The third group consists of actors whose decisions are influenced by specific logistics needs, beyond the physical transportation activity itself. A thorough review of studies investigating intermodal transport and mode choice was made by Bontekoning et al. [10] and Floden et al. [11]. As noted by Bontekoning et al., who investigated 92 publications in the field of intermodal rail-road freight transport literature, intermodal transport is considered a competing mode and can be used as an alternative to unimodal transport in order to cope with growing transport flows. However, they found that the problems with intermodal transport are complex and require new knowledge to solve them. Floden et al. [11] reviewed studies on the freight transport service choice, focusing on actually mapping real customer attitudes and preferences. They argued the factors in choosing transport services are the cost, transport time, reliability, and transport quality but, after ensuring the basic transport quality requirements, the cost of the transport is the decisive factor. Samimi et al. [12] found that shipment-specific variables (e.g. distance,

weight, and value) and mode-specific variables (e.g. haul time and cost) are key determinants of the mode choice. Many other authors, like Hanssen et al. [13], also consider time as an important transport characteristic as well, yet its importance depends on the time cost of the freight being transported. For particularly time-sensitive goods with a short life cycle and high value/kg ratio, so-called road-affine goods (NSTR 10, 1 + 6), intermodal transport will probably never be used [4, 14].

Macharis & Van Mierlo [15], Janic [16], and Braekers et al. [17] discuss a more general examination of mode choice, concentrating on the impact of the total, external, and internal costs on the mode choice. They developed models for calculating the total costs of given intermodal and road freight transport networks, which may be used to overcome the gap between too general and too specific data. They found that small changes in a parameter can have a large effect on the results and that the total costs of both networks decrease more than proportionally as the door-to-door distance increases, suggesting economies of distance. For the intermodal transport network, the average total costs fall at a decreasing rate as the quantity of loads rises, indicating economies of scale; in the road transport network they are constant.

Travel distance is an important variable in the modal choice estimations. Chalasani & Axhausen [18] calculated crow-fly and network based distances, and assess the accuracy of reported distances. They used travel surveys to collect data for a wide variety of purposes and found out that the spatial dimension of the transport influences different travel parameters such as mode of transport, destination location, time of departure, travel route, etc. Kreutzberger [19] examined transport distance and time as factors of competitiveness of intermodal transport. He compared network distances in alternative bundling networks, but did not incorporate the distance and time results in cost models. Many authors, as Ghosh [20], Stone [21], Gaboune et al. [22], Mathai & Moschopoulos [23], and de Smith [24], examined the distance from a theoretical point of view by proposing different mathematical models to determine the distances between random points in a two dimensional space, as we explain further in Section 2. Reis [25] estimated that the amount of literature concerning mode choice variables is substantial. However, in his opinion, the distance of the transport service is seldom referenced as the factor for the competitiveness of intermodality and that there is still a gap in the literature concerning this area of investigation. The earliest attempts to calculate the transport distances and transport costs between random points in two separated market areas were made by Fowkes et al. [26]. They developed an iterative program to calculate the distances between any two points, both direct (by road) or via an

intermodal service. Kim & Van Wee [27] examined the geometric and costs factors and its influence on the break-even distance of intermodal freight and unimodal road transport, and completed the approach of Fowkes et al. by considering the market boundaries and including the circular shapes of the market areas.

The modeling approach, used in this paper is based on a simulation of a generalized market topography, which enables the calculation of transport distances between random points and underpins the cost and break-even distance calculation for various travel plans. The main hypothesis of this paper is that the distance is a major determinant of transport cost, and thus one of the most important criteria in the freight-mode-choice process. The paper's purpose is to examine this hypothesis and develop a model to determine the mode choice on the basis of the break-even distances, independently of certain specific transport corridors. As the break-even distance is difficult to generalize since it is influenced by several parameters, the main emphasis is given to determining the ranges in which break-even distances can occur. The limits of the ranges depend on the variability of drayage and long-haul distances, as well as on the technical and operational characteristics of transport modes, selected travel plans, and transport costs.

Unfortunately, some assumptions and limitations in such general estimations are inevitable, which provide an opportunity for future exploration of this topic. We did not include all factors that influence the freight-mode choice. Time cost, for instance, is an important transport characteristic that influences the mode choice, yet its importance depends on the time cost of the freight being transported. Accordingly, particularly time-sensitive goods with a short life cycle and high value are excluded from this investigation, so that the findings will not be applicable for this type of cargo. Economies of scale, except for economies of distance, are not considered. Economies of distance exert an important impact on the mode choice. Distance-dependent transport costs were taken into account in this paper, meaning the transport costs are inversely proportional to the distance.

2 Modelling of transport distances

In this section, we describe the model of transport distances that is used to underpin the cost calculation. The model consists of a submodule for calculating drayage distances in a circular market area and another submodule for calculating the distances between two separated market areas, taking different distance metrics into account.

Given that the cost is correlated to the distance travelled, the transport distance therefore determines the mode choice, but differently for each transport mode. The following transport distances need to be considered in this research: drayage distance that is normally performed by truck, rail-haul distance which is performed by train, and unimodal road door-to-door distance. Drayage distance is the distance between shippers or consignees and the intermodal terminal. Despite the relatively short drayage distance compared to rail haul, drayage accounts for 25–40% of origin-to-destination expenses and thus greatly affects intermodal transport's competitiveness [10, 28].

Rail-haul distance is the distance between two terminals located in the centers of the origin and destination market areas. It is the rail-haul segment of the door-to-door intermodal trip. Unimodal road door-to-door distance is the distance performed by a truck between shippers in the origin and consignees in the destination market area.

With regard to the distance metrics, various distances between pairs of points in a two-dimensional space can be distinguished. The most commonly used is the Euclidean distance, which can also be seen as direct distance. Manhattan distance, also known as rectilinear or taxicab distance, is the distance between two points measured along axes at right angles. It is calculated as the sum of the horizontal and vertical components of the pairs of points. The most relevant is the real distance, which is based on the actual transport network. To approximate the real distance, Cooper [29] proposed the use of a factor of the curvature of the road, the so-called detour factor, that can be calculated as the ratio between the real distance d_R and the Euclidean distance d_E, as follows [30]:

$$\alpha = \frac{d_R}{d_E} \tag{1}$$

For UK roads, Cooper determined a value of 1.2, which has subsequently been widely accepted and used in the scientific community [31]. With reference to the results of Perrels et al. [32], Chalasani & Axhausen [18], Domínguez-Caamaño et al. [31] and Kim & Van Wee [27], the detour factors of 1.25 for long haul and 1.30 for an urban drayage area are used.

The distances between random points within a circle, within a square and rectangle and also the distances between randomly and uniformly distributed points in two separated circles or rectangles are dealt with by many authors. Ghosh [20], Stone [21], Gaboune et al. [22], Mathai & Moschopoulos [23], and de Smith [24] consider average distances between a fixed and a random point in a circle or rectangle. More recently, Kim & Van Wee [27] and Olofsson & Andersson [33] proposed calculating the average distance in a circle using probability theory. The average distances between two separate regions (squares, rectangles, and circles) were also examined by Mathai et al. [34]. The proposed formulae are very complex, but acceptable results can also be obtained using simpler

calculations such those taken from Bouwkamp [35], Fowkes et al. [26], and Kim & Van Wee [27]. The latter for the average distances between two separate circles and probability theory for the average distance within a circle are also considered in this paper.

2.1 Drayage distances in a circular market area

Drayage distance depends on the shape of the market area, the terminal's location and the distribution of shippers and consignees in the market area. In this research, the shape of the market area is assumed to be a circle, the intermodal terminal is assumed to lie in the center of the market area, and all shippers and consignees are assumed to be uniformly and randomly distributed in the origin and destination market areas.

Drayage distances are calculated as both Euclidean and Manhattan distances. They are presented in Fig. 1 and calculated in Sections 2.1.1 and 2.1.2.

2.1.1 Calculating the average Euclidean drayage distance

The average or expected drayage distance can be calculated using probability theory. If (X, Y) is a random point in the unit disc, the Euclidean distance d_E from that point to the center of the disc is

$$d_E = \sqrt{X^2 + Y^2}$$

The random variable is thus $g(x, y)$

$$g(x, y) = \sqrt{x^2 + y^2}$$

and the joint pdf of (X, Y) in the unit disc is

$$f(x, y) = \frac{1}{\pi}; x^2 + y^2 \leq 1$$

The expected distance $E[d_E]$ to the center of the unit disc is given by the following equation [33]:

$$E[d_E] = E\left[\sqrt{X^2 + Y^2}\right] = \frac{1}{\pi} \iint_{x^2+y^2 \leq 1} \sqrt{x^2 + y^2} \, dx \, dy$$

By changing x and y to polar coordinates d_E and q

$$x = d_E \cos\vartheta, y = d_E \sin\vartheta$$

and by using the Jacobian matrix for the transformation $(d_E, q) \rightarrow (x, y)$,

$$J = \begin{pmatrix} \dfrac{dx}{dd_E} & \dfrac{dx}{d\vartheta} \\ \dfrac{dy}{dd_E} & \dfrac{dy}{d\vartheta} \end{pmatrix} = \begin{pmatrix} \cos\vartheta & -d_E \sin\vartheta \\ \sin\vartheta & d_E \cos\vartheta \end{pmatrix}$$

the determinant of the Jacobian matrix is

$$|J| = \cos\vartheta d_E \cos\vartheta - (-d_E \sin\vartheta)\sin\vartheta$$
$$= d_E(\cos^2\vartheta + \sin^2\vartheta) = d_E$$

Due to the determinant being equal to d_E, we obtain

$$dx dy = d_E dd_E \, d\vartheta$$

which, by integration into the ranges $0 \leq d_E \leq 1$ and $0 \leq q \leq 2\pi$, gives the expected distance in the unit disc

$$E[d_E] = \frac{1}{\pi} \int_0^{2\pi} d\vartheta \int_0^1 d_E^2 dd_E = \frac{2}{3}$$

The expected distance $E[d_E]$, denoted as the average drayage distance $\bar{d}_E$ in the circle with radius R, is

$$E[d_E] = \frac{2}{3} R = 0.67R = \bar{d}_E \qquad (2)$$

2.1.2 Calculating the average Manhattan drayage distance

The average Manhattan distance can be calculated similarly as the average Euclidean distance in the previous case. If (X, Y) is a random point in the unit disc, the Manhattan distance from that point to the center of the disc is
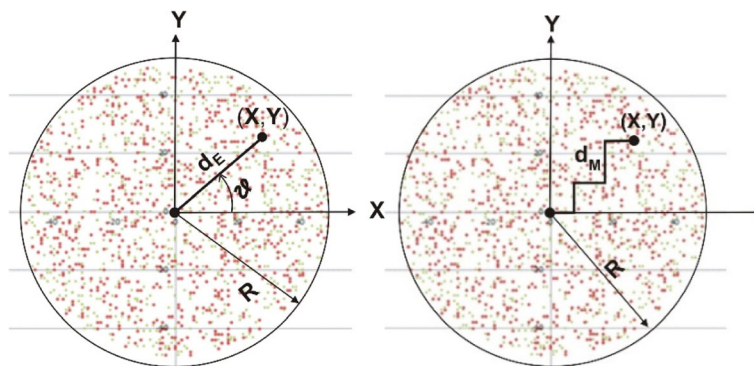

Fig. 1 Euclidean (left) and Manhattan (right) drayage distances

$$d_M = X + Y$$

The random variable is thus

$$g(x, y) = x + y$$

and the joint pdf of *(X, Y)* in the unit disc is

$$f(x, y) = \frac{1}{\pi}; x^2 + y^2 \leq 1$$

The expected Manhattan distance $E[d_M]$ to the center of the unit disc can be expressed by the equation:

$$E[d_M] = E[X + Y] = \frac{1}{\pi} \iint_{x^2 + y^2 \leq 1} (x + y) dx dy$$

Using the same calculation as for the Euclidean distance, the expected Manhattan distance $E[d_M]$ is given by

$$E[d_M] = \frac{1}{\pi} \int_0^{2\pi} \int_0^2 (d_M cos\vartheta + d_M sin\vartheta) d_M dd_M \, d\vartheta$$
$$= \frac{1}{\pi} \int_0^2 d_M{}^2 dd_M = \frac{8}{3\pi}.$$

The expected Manhattan distance $E[d_M]$ denoted as the average Manhattan distance $\bar{d}_M$ in the circle with radius R, is

$$E[d_M] = \frac{8R}{3\pi} = 0.85R = \bar{d}_M \qquad (3)$$

2.1.3 Comparison of various distance metrics
In practice, several studies have compared how Euclidean and Manhattan distances differ from real distance measures, based on actual transport networks. According to Buczkowska et al. [36], Euclidean distance can only be regarded as a proxy for the true physical distance and might not always be the most relevant one depending on the problem at hand. Distance measures based on an actual transport network might be more appropriate because, in reality, goods move along transport networks and rarely go from origin to destination in a straight line. Duranton & Overman [37] indicate that in low-density areas roads are fewer (so actual journey distances are much longer than Euclidean distances) whereas in high density areas they are numerous (making Euclidean distances a good approximation of actual ones). If no other factors are involved, then this shortest Euclidean distance is a reasonable solution to use as the drayage distance in high-density areas. The Manhattan distance can be considered a logical alternative to Euclidean distance where roads are not as developed as in high-density areas.

Land transport networks are notably influenced by the topography so it is reasonable to assume that traffic flows by road and by rail use the same transport corridors. The main land transport infrastructures are typically built where there are the minimal physical impediments, such as on plains, along valleys, or through mountain passes. Highways and railways tend to be impeded by grades higher than 3% and 1%, respectively. In such circumstances, land transport tends to be of a higher density in areas of limited topography. Natural conditions are very difficult constraints to avoid so it is not surprising to find that most networks follow the easiest paths, which generally run along valleys and plains [38]. These facts are considered in the Euclidean and Manhattan exit-entry travel plans presented in Fig. 2. Transport flows by road and by rail between A and B use the same long-haul corridor connecting the shortest path between two market areas. In Fig. 2, the distances of the unimodal road are depicted by the dashed blue lines and the distances of the intermodal rail-road routes are depicted by the black lines. Both routes pass through the same points A and B on the circumference of the market areas.

It is thus unclear which distance is the most appropriate for all cases considered. This research proposes a flexible approach in which various distance measures may be used instead of being systematically opposed. This approach allows us to compare various distance measures with each other.

2.2 Distances between two separated market areas
This section addresses the calculation of distances between two randomly and uniformly distributed points in two separated market areas. The calculation embraces Euclidean, Euclidean exit-entry, and Manhattan exit-entry travel plans, as depicted in Fig. 2. Observe that a general Manhattan travel plan is identical to a Manhattan exit-entry travel plan in terms of costs, as the distances of the two plans are equal. Therefore, only Euclidean, Euclidean exit-entry and Manhattan entry-exit alternative are discussed in sections below. In addition to scenarios with two-sided market areas, a one-sided Euclidean travel plan that consists of a terminal and a drayage area on one side, and a terminal without a drayage area on the other, were considered.

Because the intermodal distances between shippers and consignees are simply calculated as the sum of two drayage distances and the rail-haul distance, the biggest focus in the distance calculation is determining the unimodal road distances.

2.2.1 Unimodal Euclidean travel plan
The distance between origin and destination in a unimodal road Euclidean travel plan is calculated as the Euclidean distance based on the assumption that both market areas are interconnected with extensive road
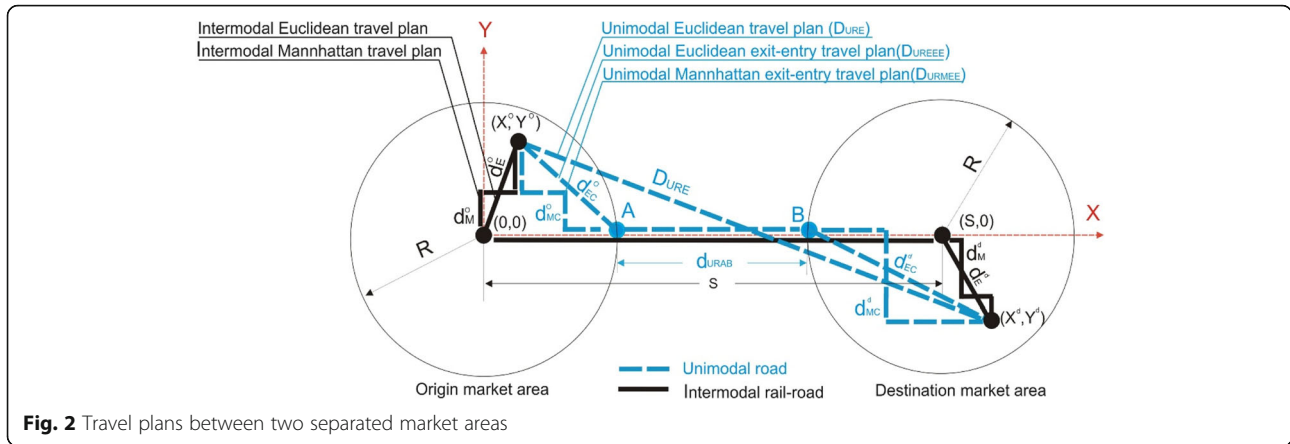
Fig. 2 Travel plans between two separated market areas

systems in which any point in one area is connected to any point in the other. The unimodal road Euclidean distance D_{URE} is the distance on a straight line, given the shortest possible route. It can be expressed by the following trigonometrical equation where variables q and d_E vary from 0 to 2π and 0 to R, respectively.

$$D_{URE} = \sqrt{\left(d_E^o \, sin\vartheta^o - d_E^d \, sin\vartheta^d\right)^2 + \left(-d_E^o \, cos\vartheta^o + s + d_E^d \, cos\vartheta^d\right)^2} \quad (4)$$

Variables d_E^o and d_E^d in (4) are Euclidian distances between origin/destination points and the intermodal terminals and variables ϑ^o and ϑ^d are the angles of the polar coordinates of these points.

Average unimodal road Euclidean distance $\overline{D}_{URE}$, calculated over all origin/destination pairs, generated by a Monte Carlo simulation at certain distance s is determined by the average of all generating points

$$\bar{D}_{URE} = \sum\nolimits_{n=1}^{N} \frac{D_{URE}}{N} \cong s \quad (5)$$

and approximately equals the distance s between two intermodal terminals. Similar results are found in the earliest works by Fowkes et al. [26] and Kim & Van Wee [27] and are consistent with the equation derived by Bouwkamp [35] and de Smith [24], which is

$$\bar{D}_{URE} = s + \frac{R^2}{4s} + \cdots \cong s \quad (6)$$

2.2.2 Unimodal Euclidean exit-entry travel plan

The distance between origin and destination in a unimodal road Euclidean exit-entry travel plan D_{UREEE} is calculated by:

$$D_{UREEE} = d_{EC}^o + d_{EC}^d + d_{URAB,} \quad (7)$$

where d_{EC} is the Euclidian circumferential distance between the origin/destination points and points A and B

on the circumference of the market area, while d_{URAB} is the distance between A and B:

$$d_{URAB} = s{-}2R. \quad (8)$$

The average Euclidean unimodal road distance in a Euclidean exit-entry travel plan consists of the two average Euclidean circumferential distances $\overline{d}_{EC}$ and of the distance d_{URAB}:

$$\overline{D}_{UREEE} = 2\overline{d}_{EC} + d_{URAB.} \quad (9)$$

The average Euclidean circumferential distance $\overline{d}_{EC}$ can be obtained by:

$$\overline{d}_{EC} = \sum_{n=1}^{N} \frac{d_{EC}}{N} = 1.13R, \quad (10)$$

which is consistent with the equation given by de Smith [24]:

$$\bar{d}_{EC} = \frac{32R}{9\pi} = 1.13R. \quad (11)$$

2.2.3 Unimodal Manhattan exit-entry travel plan

Based on Fig. 2 and using the same approach as for the Euclidean exit-entry travel plan, the unimodal road distance in a Manhattan exit-entry travel plan D_{URMEE} is given by

$$D_{URMEE} = d_{MC}^o + d_{MC}^d + d_{URAB}, \quad (12)$$

where d_{MC} is the Manhattan distance between the origin/destination points and points A and B on the circumference of the market area, while d_{URAB} is the distance between A and B.

The average unimodal road distance in the Manhattan exit-entry travel plan $\overline{D}_{URMEE}$ is the sum of the two average Manhattan circumferential distances $\overline{d}_{MC}$ and of the distance d_{URAB}

$$\overline{D}_{URMEE} = 2\overline{d}_{MC} + d_{URAB,} \tag{13}$$

The average Manhattan circumferential distance $\overline{d}_{MC}$ is

$$\overline{d}_{MC} = \sum_{n=1}^{N} \frac{d_{MC}}{N} = 1.44R, \tag{14}$$

which is equal to the expression given by de Smith [24]

$$\overline{d}_{MC} = \frac{128R}{9\pi^2} = 1.44R. \tag{15}$$

3 Transport costs

This section describes the methods for calculating particular cost categories of a given rail and road freight transport. It is assumed that the average load factor of the unimodal road and the intermodal transport is equal and that goods are transported from their randomly distributed origin and destination points, according to different travel plans, either direct by road or via intermodal terminals, using a point-to-point consolidation network.

Transport costs are costs incurred by the various parties responsible for moving a consignment from a shipper (such as a factory) to a consignee (another factory or a distribution warehouse) [39]. These costs embrace the depreciation costs of the rolling stock and trucks, the costs of maintenance and repair, infrastructure charges, the costs of energy consumption, labor costs, and transshipment costs (loading/unloading costs). There are many different methods and models for calculating particular cost categories of a given rail and road freight transport. In this paper, distance-dependent unit costs, as well as elements of the analytical modelling of logistics systems developed by Arnold et al. [40], Daganzo [41], and Janic [16, 42], Santos [43] are used. External costs of transport, which are the costs imposed on society, are not included in this research as these costs are not currently considered as part of the trade-offs made by shippers.

3.1 Road-haul costs

Road-haul costs are charged in the form of drayage truck costs for intermodal rail-road transport or long-distance truck costs for unimodal road transport. To calculate the unit cost per vehicle km of an individual truck $c_R(d)$, we follow the approach by Janic [16] where the following regression equation, based on empirical data, was determined:

$$c_R(d) = 5.46d^{-0.278} \ [€/vehicle \ km] \tag{16}$$

The equation is based on the assumption that each truck is loaded with two Twenty-foot Equivalent Unit - TEU, as a statistical measure of capacity. In average one

TEU weights of 14.3 tons, 12 tons of goods plus 2.3 tons of tare, which is common in Europe [39, 44]. Handling costs of the loading units are included.

Based on (16) unimodal road transport, costs C_{UR} between the origin and the destination are determined by the following equation

$$\begin{aligned} C_{UR}(d) &= 5.46d^{-0.278}d\alpha_l \\ &= 5.46d^{0.722}\alpha_l[€/vehicle]. \end{aligned} \tag{17}$$

In (17), d is the distance between the starting and destination points and α_l is a detour factor for road long haul. Distance d can be the Euclidian distance D_{URE}, Euclidian exit-entry distance D_{UREEE}, or Manhattan exit-entry distance D_{URMEE}, depending on the actual travel plan.

3.2 Rail-haul costs

The distance-dependent equation for rail-haul costs is a function of train gross weight w and the distance of rail-haul s. It is based on the assumption that the reference train has a fixed composition of 26 flat cars, without additional shunting and marshalling during the trip. Each wagon weighs 24 tons and the weight of a locomotive is about 100 tons. The capacity of each wagon is equivalent to three TEU, with an average gross weight of 14.3 tons, such that the gross weight of train w equals 1560 tons. Such a train composition has been used in the works of different authors like Janic [16, 42], Kim N.S. et al. [27], Braekers et al. [17] and Bierwirth et al. [45] and could be considered as common in Europe. Also the STREAM study [44], which is based on data representative for the EU, treats a train capacity of 70 TEU, representative of a medium container train, which approximately corresponds to the selected train in this research.

The costs of each train trip c_T can be calculated using different equations, suggested by different authors. For comparison, the rail-haul costs for the distance $s = 400$ km based on the same input data, have been calculated as shown in Table 1. The Eq. (a) is a function of train gross weight w and rail-haul distance s, giving the cost of a train trip over a certain rail-haul distance. The Eq. (b) assumes rail costs to be 65% of total truck costs over the rail-haul distance. Given that each truck is loaded with 2 TEU, this gives the cost of a train trip for 2 TEU over s. More comprehensive approach in Eq. (c) assumes costs depend on the train's gross weight w, payload q and rail-haul distance s. The equation includes five components, cost of investments in rolling stock, costs of maintenance, infrastructure charges, costs of energy and labor costs, where n_l represents the number of locomotives, n_w the number of wagons, v the commercial speed, d the distance of rail segments, L the number of segments i.e. intermediate stops, n_d the number of drivers and D the anticipated delay of a train running between

Table 1 Comparison of rail-haul costs using different equations on $s = 400$ km

	Authors	Equation	Cost [€/train trip]	Cost [€/2TEU trip]
(a)	Janic [16], Braekers et al. [17], Kim N.S. et al. [27]	$c_T(w,s) = 0.58(ws)^{0.74}$ [€/train trip]	11,268	288
(b)	Arnold et al. [40], Kim N.S. et al. [27]	$c_{T2TEU}(s) = 0.65 \cdot 5.46\ s^{-0.278}s$ [€/2TEU]	10,413	268
(c)	Janic [42]	$c_T(w,s,q) = (4.60n_l + 0.144n_w + 0.3)s +$ $+12.98(n_l + n_w) + 5.6q + 0.0019ws +$ $+\sum_{l=1}^{L}\left[0.227\cdot\frac{10^{-6}v_l^2}{\ln d_l} + 0.000774\right]ws +$ $+33n_d(t_{dp} + \frac{s}{v} + D)$ [€/train trip]	11,659	299
(d)	Janic [42], Santos [43]	$c_T(s) = 0.59325 + 0.019s + 0.001804(\frac{s}{\ln s})$ [€/train trip]	12,969	332

two intermodal terminals in hours. The Eq. (d) is based on the Eq. (c) taking into account the average train parameters and cost components.

As we can see the results do not differ greatly. In this paper we decided to use the model (b) proposed by Arnold et al. [40], used also by Kim N.S. et al. [27], which assumes the estimated rail costs for two TEU are simply 65% of truck costs. Due to the fact that our intention is not to examine the cost models in detail, we decided to use the simplest model, which is still comparable with results given by other equations.

$$c_{T2TEU}(s) = 0.65 \cdot 5.46\ s^{-0.278} \ [\text{€/2 TEU km}] \quad (18)$$

Based on (18) the rail transport, costs $C_T(s)$ for two TEU over a rail-haul distance can be expressed as

$$\begin{aligned}C_T(s) &= 0.65 \cdot 5.46\ s^{-0.278}s \\ &= 0.65 \cdot 5.46 s^{0.722} \ [\text{€/2 TEU}]\end{aligned} \quad (19)$$

3.3 Intermodal rail-road costs

Using road drayage costs and rail-haul cost, the intermodal rail-road costs for two TEU and for the whole trip are calculated by the equation:

$$\begin{aligned}C_{IM} &= 5.46\left(d^o + d^d\right)^{-0.278}\left(d^o + d^d\right)\alpha_d \\ &\quad + 0.65 \cdot 5.46 s^{-0.278}s\alpha_l + 2c_t,\end{aligned} \quad (20)$$

where d^o is the distance between origin and d^d distance between destination and intermodal terminals, respectively. Distances d^o and d^d can be Euclidian distances d_E^o and d_E^d or Manhattan distances d_M^o and d_M^d, depending on the actual travel plan. The other variables in (20) are s as rail-haul distance between two intermodal terminals, $\alpha_l = 1.25$ as a detour factor for road and rail long haul, $\alpha_d = 1.3$ as a detour factor for a drayage area, and c_t as the transshipment cost estimated to be 38 €/container [39].

4 Break-even distance calculations

In transport practice, intermodal transport is considered an alternative to unimodal road transport after a certain distance, called the break-even distance [46]. Macharis et al.

[47] state that such an alternative can only be justified when the costs of transshipment and terminal cartage have been offset, making intermodal transport a competing mode once the break-even distance is reached. As already indicated in the introduction, transport cost is the decisive factor in the choice of freight mode and is therefore used as a relevant criterion for estimating the break-even distance in this research. The break-even distance is thus defined as the door-to-door distance at which unimodal road transport costs C_{UR} equal intermodal rail-road transport costs C_{IM}:

$$C_{UR} = C_{IM} \quad (21)$$

Splitting the costs from (21) into distance-dependent variable costs and distance-independent fixed costs produces:

$$FC_{UR} + VC_{UR}BE = FC_{IM} + VC_{IM}BE, \quad (22)$$

where FC_{UR} and FC_{IM} are fixed and VC_{UR} and VC_{IM} variable costs of a unimodal road and intermodal freight transport, respectively, and BE is the break-even distance.

However, the break-even distance obtained by (22) is neither an accurate nor an unambiguous result as the actual travel route used in the unimodal road transport is not the same as for intermodal road-rail transport. Since the actual travel plan for the two transport options depends on the distance between the two market areas, the shipper/consignee location within market areas, the transport infrastructure conditions and thus the type of travel plan (discussed in Section 2.2), it is unclear what the obtained break-even distance represents. It is noteworthy that previous studies of break-even distances of intermodal and unimodal road transport have not then taken account of different distances entailed in both networks. Rutten [4], for instance, regarded drayage distance and its cost as a partly fixed and not as a variable intermodal cost. Janic [16], who develops a model for calculating comparable combined internal and external costs of intermodal and road freight transport networks, considered the average road door to door as the break-even distance. On the other hand, Kim & Van Wee [27] regarded the break-even distances as break-even market distance, which should be equal to s, or

as the break-even distance of the intermodal system based on the distance actually traveled, which is approximated as $2\bar{d} + s$ or the break-even distance of a unimodal road system based on door-to-door distance, which equals $\overline{D}_{URE}$. As stated by Kim & Van Wee [27], all these distances may be acceptable as break-even distances, but produce different results or should be considered separately only as factors that influence the break-even distance.

In our case, we decided to consider the real distances on each side (D_{UR} on the left and $D_{IM} = d^o + d^d + s$ on the right). By using a Monte Carlo simulation to generate random locations of shipper/consignee pairs in both market areas and by varying the distances between two separated market areas s, the corresponding transport costs for each and every pair of 10,000 randomly distributed origin and destination points, at different s, are calculated for each mode. The equalization of the cost functions of both modes yields the average break-even distance for each travel plan. This break-even distance is the distance between two intermodal terminals s, as it is the most influential distance parameter governing the transport mode choice. Further, a Monte Carlo simulation enables us to determine two extreme settings, where the minimum and the maximum break-even distances can be reached, and provide an insight into the share of competitive unimodal road and intermodal road-rail transport at a certain distances s between two extreme settings.

The radius of the drayage area significantly affects the transport cost structure. Authors like Morlok and Spasovic [48], Janic [16, 42], Niérat [49], Rutten [4], and Kreutzberger [50] assumed 160 km, 70 km, 50 km, and 25 km average drayage distances, respectively. In this paper, the radius of the market area of 50 km was selected, approximately in the middle of distances proposed by other authors. However, we also present the sensitivity for the share of the intermodal transport and the break-even distances where we vary the size of the market area.

4.1 Break-even distances in a Euclidean travel plan

The average break-even distance in a Euclidean travel plan can be found by equalizing average unimodal road $\overline{C}_{URE}(s)$ and average intermodal rail-road cost function $\overline{C}_{IME}(s)$, derived from (6), (17), and (2), (20), respectively:

$$\overline{C}_{URE}(s) = 5.46\left(s + \frac{R^2}{4s}\right)^{0.722}\alpha_l \tag{23}$$

$$\overline{C}_{IME}(s) = 2\cdot5.46\left(\frac{2R}{3}\right)^{0.722}\alpha_d + 0.65\cdot5.46s^{0.722}\alpha_l + 2c_t \tag{24}$$

Both functions are graphically presented in Fig. 3. Average costs of intermodal rail-road transport are depicted by the blue line and average costs of unimodal road transport by the red line. The two lines intersect at the distance between the intermodal terminals $s = 640$ km (point A in Fig. 3). This represents the average break-even distance of intermodal rail-road and unimodal road transport. The thinner lines shown in Fig. 3 represent the lower and upper cost bounds of the two modes. Within the bounds, the intermodal and unimodal transport costs vary according to the shipper/consignee locations and the distance between intermodal terminals. The lower bound of the average intermodal rail-road cost function C_{IME}^{min} can be obtained on the condition that d^o, $d^d = 0$ and the upper bound C_{IME}^{max} on the condition that d^o, $d^d = R$

$$C_{IME}^{min}(s) = 0.65\cdot5.46s^{0.722}\alpha_l + 2c_t \tag{25}$$

$$C_{IME}^{max}(s) = 2\cdot5.46R^{0.722}\alpha_d + 0.65\cdot5.46s^{0.722}\alpha_l + 2c_t \tag{26}$$

The lower bound of the average unimodal road cost function C_{URE}^{min} is calculated on the condition that $D_{URE} = s - 2R$ and the upper bound C_{URE}^{max} on the condition that $D_{URE} = s + 2R$.

$$C_{URE}^{min}(s) = 5.46(s-2R)^{0.722}\alpha_l \tag{27}$$

$$C_{URE}^{max}(s) = 5.46(s+2R)^{0.722}\alpha_l \tag{28}$$

Cost functions (25), (26), (27) and (28) make it possible to determine the interval between points B and C (Fig. 3) in which break-even distances can occur. The minimal break-even distance at $s = 103$ km (point B) is determined by the intersection of the minimal intermodal rail-road and the average unimodal road transport cost functions. This is the minimal distance at which the intermodal rail-road transport is able to compete with unimodal road transport. As Fig. 4 shows, this happens if shippers and consignees are located close to the centers of the market areas, where the costs of the intermodal trips are the lowest. The maximal distance s at which unimodal road transport can compete with intermodal rail-road transport is 1143 km (point C), which is well within the intermodal dominant zone. Point C is determined by the intersection of the minimal unimodal road and the maximal intermodal rail-road transport cost functions, where the two options' costs are equal. As Fig. 4 reveals, this occurs when shippers and consignees are located on the circumference of both market areas, at points closest to one another. Intuitively, such shipper and consignee locations represent the worst case for the intermodal rail-road transport, and the best case for the unimodal road transport.
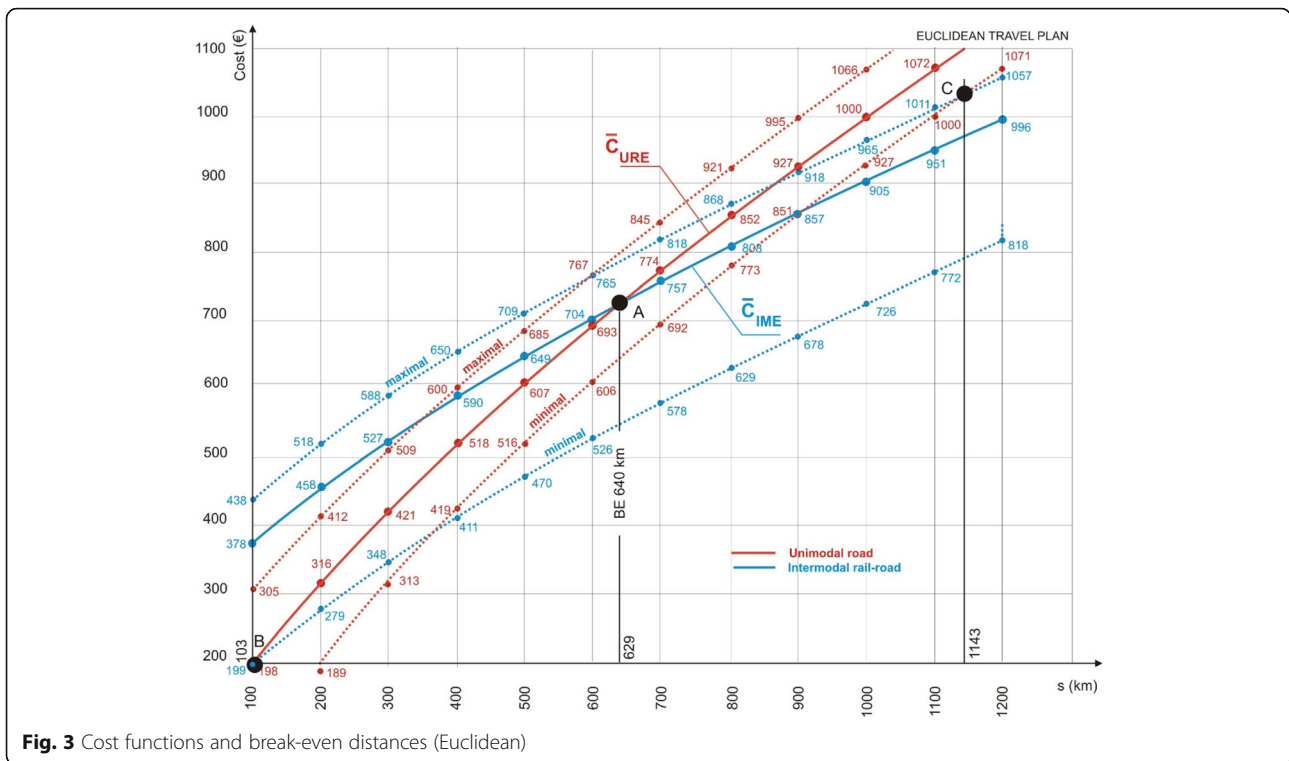
Fig. 3 Cost functions and break-even distances (Euclidean)

Figure 5 shows the envelope of maximal intermodal rail-road costs depicted by the black line, the competitive average unimodal road and intermodal rail-road costs depicted by the red and blue lines, and the competitive shares of modes represented by the vertical red and blue columns. The envelope is determined by the maximal possible intermodal transport costs under the condition that intermodal rail-road cost $C_{IME}(s, d)$ equals unimodal road cost $C_{URE}(s, d)$ for the same pair of trips. The envelope is approximated by the quadratic regression function $f(s) = -0.00068\,s^2 + 1.65\,s + 15.8$ on the interval between points B and X and by the maximal intermodal rail-road cost function (26) between X and C, where the maximal drayage distance equals 50 km.

Looking at average competitive costs, is clear that an increase in distance s tends to raise the shares for intermodal rail-road transport and vice versa. Figure 5 illustrates that the distance elasticity at lower

distances is about 0.75 and is approximately equal for unimodal road and intermodal rail-road transport. At longer distances, from the break-even distance onwards, the distance elasticity of intermodal rail-road transport is lower than unimodal road transport (0.25 vs 0.7), indicating intermodal rail-road transport is less sensitive to a change in distance than unimodal road-only transport. Although the distance elasticities of both modes remain inelastic, it appears that the distance between two market areas has a greater influence on unimodal road than intermodal rail-road transport. This is obviously due to the fact that over greater distances the negative influence of drayage costs is a less and less decisive factor in intermodal rail-road transport competitiveness.

The competitive shares of intermodal rail-road and unimodal road modes expressed in percentage and represented by columns indicate the intervals between maximal and minimal competitive costs.
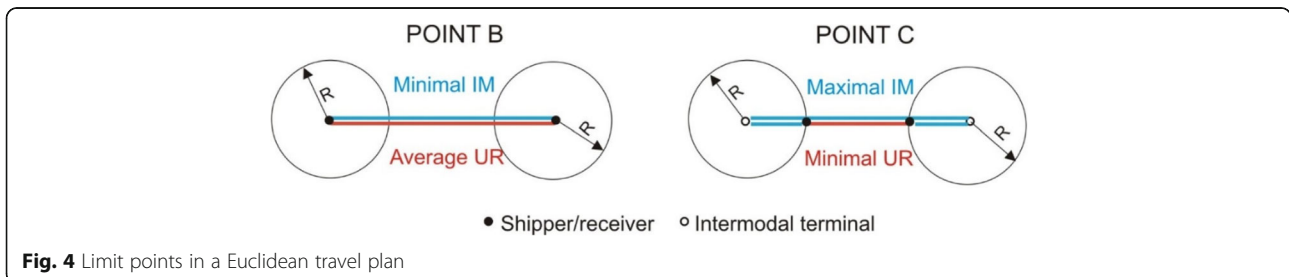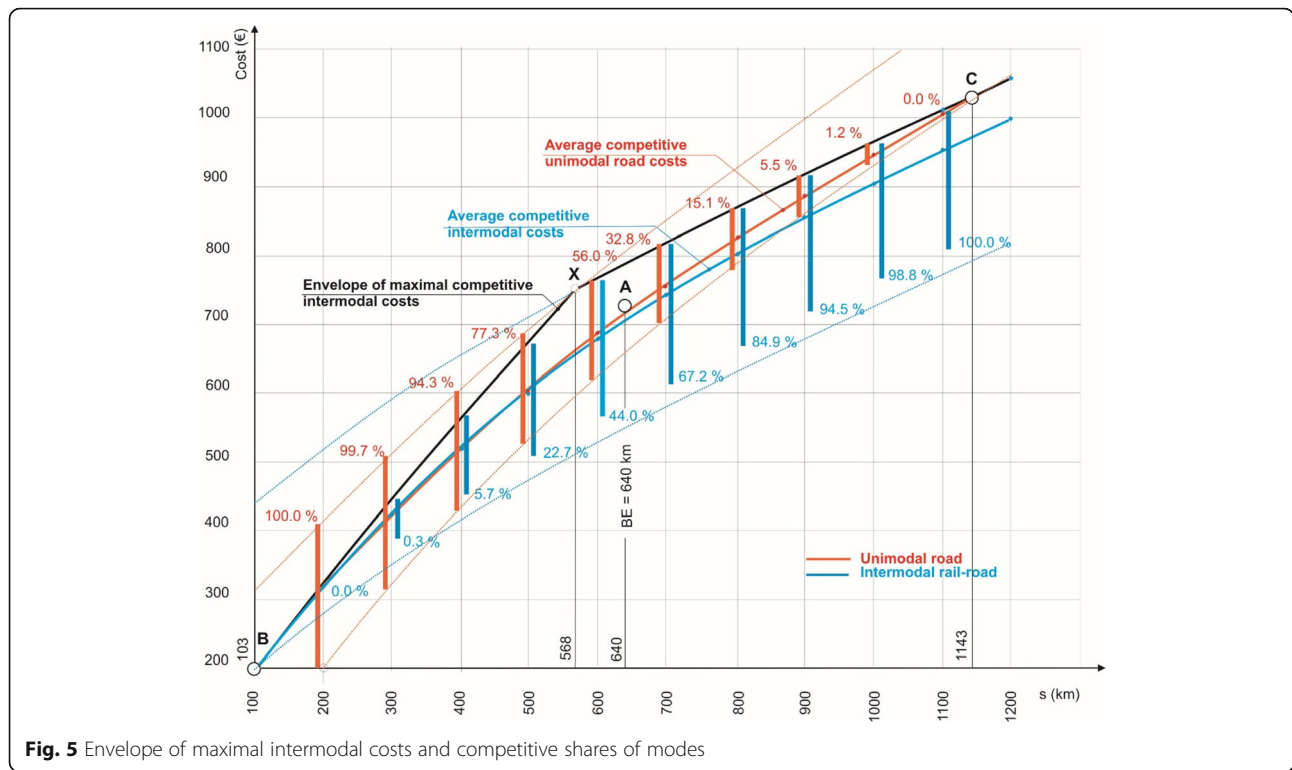

Fig. 4 Limit points in a Euclidean travel plan

Fig. 5 Envelope of maximal intermodal costs and competitive shares of modes

4.2 Sensitivity analysis of the influence of the size of the market area

To further study the effect of the effect of distances on modal split, we perform the sensitivity analysis with which we show the impact of the market area size on the intermodal mode share and the break-even distance. In Tables 2, 3 and 4, we present results for two rail-haul distances, $s = 400$ km and $s = 800$ km, and vary the size of the market area ± 25–50% relative to the reference radius of 50 km.

We can see that the radius of the drayage area significantly affects the intermodal share. A smaller market area and accordingly shorter drayage distance increases the intermodal mode share for the same rail haulage distance. In order to attract 100% of intermodal share the radius of market area should be less than 11.8 km at $s = 400$ km and less than 32.9 km at $s = 800$ km.

To further facilitate a shift to intermodal mode, a smaller effective market area can be realized with an

additional terminal within a market area [51, 52]. Nevertheless, it should be noted that in practice today there are not many origin and/or destination terminals that accommodate or generate enough cargo for cost effective rail freight operations. On the other side, bigger market area attracts more customers, although the intermodal share is relatively smaller. As noted by Duranton & Overman [37], 52% of four-digit industry in UK exhibit localization that takes place mostly within 50 km. Three-digit industry shows a similar pattern of localization at small scales as well as a tendency to localize at medium scales (80–140 km). Based on these findings, we can assume that in such market areas there is sufficient cargo to fill the train completely. As we show, longer rail haulage distances allow for a greater market area and thus can attract the sufficient volume of freight for the intermodal mode.

The positive influence of a shorter drayage distance on the intermodal share can also be seen in Table 5, where

Table 2 Sensitivity analysis of intermodal share with regard to the radius of the market area ($s = 400$ km)

R [km]	Change in R [%]	IM share [%]	Change in IM share [%]
25	− 50	48.8	+ 42.9
37. 5	− 25	16.5	+ 10.9
50 (reference radius)	−	5.9	−
62.5	+ 25	2.6	- 3.3
75	+ 50	1.4	- 4.5

Table 3 Sensitivity analysis of intermodal share with regard to the radius of the market area ($s = 800$ km)

R [km]	Change in R [%]	IM share [%]	Change in IM share [%]
25	- 50	100.0	+ 14.8 (max)
37. 5	- 25	99.1	+ 13.9
50 (reference radius)	–	85.2	–
62.5	+ 25	62.9	- 22.3
75	+ 50	44.1	- 41.1

we present the calculation of the maximal average drayage distance $\overline{d}^{max} = \frac{d^0 + d^d}{2}$ for competitive intermodal rail-road transport at a certain s.

The calculation of maximal average drayage distances is based on the condition the maximal transport costs of both modes C^{max}, are equal for the same pair of trips. It is shown that intermodal rail-road transport can be competitive even over lower distances between intermodal terminals if the drayage does not exceed the maximal values of $\overline{d}^{max}$. For greater drayage distances than those, it becomes more appropriate to organize unimodal road transport directly from the shipper to the consignee. This confirms statements in previous studies that radius of a drayage area is a significant factor in intermodal rail-road transport and that the difference in efficiency with shorter drayage distances is considerable.

To summarize, the results of this section show that it is the ratio of rail-haul distance relative to the market size that influences the share of intermodal transport to a large extent (when s/R increases, % IM increases).

4.3 Simulation of the shape of the actual market area
We represent the shipper/consignee locations within market areas according to the optimality of a particular mode of transport. The shapes of actual market areas after the simulation are shown in Fig. 6. The gray points represent the distribution of shippers/consignees locations for which unimodal road transport is optimal and the red points represent the distribution of competitive intermodal shippers/consignees pairs after simulating 1000 randomly generated trips between origin and destination market areas.

We see that more transport users in the area 'behind' the intermodal terminal (i.e., the opposite direction of the main

haulage) select the intermodal mode due to the longer truck-only distance between these locations, which makes the unimodal option unfavorable. Observe that for a particular location in the origin market area, different shippers can be connected to different consignees in the destination market area, which can result in these shippers having different competitive mode options. The actual market area of competitive pairs of intermodal transport after simulation resembles an ellipse-shaped market area with intermodal terminal that is not located in the center of the market area. Here we point out findings of Kim & Van Wee [27], who study the impact of different shapes of market areas and show that market area shape does not significantly increase the intermodal share. As we show in Section 4.2, the modal split is primarily influenced by the rail-haul distance and the market area size, or, more precisely, their ratio.

4.4 Break-even distance in a Euclidean exit-entry travel plan
Using the same approach as in Section 4.1, the break-even distances in a Euclidean exit-entry travel plan are estimated. With this travel plan, the unimodal road transport route changes as trucks leave the market areas through the points along the highway connecting the two market areas. Correspondingly, the average unimodal road costs are determined by (17) and calculated according to the new distances $\overline{D}_{UREEE} = 2\overline{d}_{EC} + d_{URAB}$. Average unimodal road transport costs are determined by

$$\overline{C}_{URE}(s) = 5.46\left(2\overline{d}_{EC} + d_{URAB}\right)^{0.722}\alpha_l \tag{29}$$

Similarly as in Section 4.1, the maximal and minimal unimodal road costs are obtained on the condition d_{EC}^o, $d_{EC}^d = 2R$ and $d_{EC}^o, d_{EC}^d = 0$, respectively, and the corresponding costs by

Table 4 Sensitivity analysis of the break-even distance with regard to the radius of the market area

R [km]	Change in R [%]	BE distance [km]	Change of BE distance [%]
25	- 50	409.9	- 35.9
50 (reference radius)	–	640.3	–
75	+ 25	860.1	+ 34.3
100	+ 100	1074.9	+ 67.8

Table 5 Maximal average drayage distances $\overline{d}^{max}$

s [km]	C^{max} [€]	$\overline{d}^{max}$ [km]	IM share [%]
200	320	–	0.0
300	446	14.6	0.3
400	566	27, 7	5.7
500	675	40.5	22.7
600	749	45.6	44.0
700	810	47.9	67.2
800	863	48.5	84.9
900	911	48.7	94.5
1000	962	49.2	98.8

$$C_{UREEE}^{max} = 5.46(s + 2R)^{0.722}\alpha_l \tag{30}$$

$$C_{UREEE}^{min} = 5.46(s - 2R)^{0.722}\alpha_l \tag{31}$$

The average, maximal and minimal costs of intermodal rail-road transport are the same as for the Euclidean travel plan.

The results of the analysis are shown in Fig. 7. The average break-even distance lies at 605 km, namely, shorter than with a Euclidean travel plan. The shorter break-even distance is due to the longer unimodal road travel route through points A and B on the circumferences of the market areas. Irrespective of this, the range of possible break-even distances between point B at 82 km and point C at 1143 km only a little longer.

4.5 Break-even distance in a Manhattan exit-entry travel plan

In the same manner as above, the average break-even distances in a Manhattan exit-entry travel plan are calculated. Instead of distance d determined by (17), the distances $D_{URMEE} = 2\overline{d}_{MC} + d_{URAB}$, $\overline{d}_M$ and $\overline{d}_{MC}$ are taken into account. Therefore, the average unimodal road and intermodal rail-road transport costs are

$$\overline{C}_{URMEE}(s) = 2 \cdot 5.46\left(2\overline{d}_{MC} + d_{URAB}\right)^{-0.278}\overline{d}_{MC} \\ + 5.46(d_{URAB})^{-0.278}d_{URAB}\alpha_l \tag{32}$$

$$\overline{C}_{IMMEE} = 2 \cdot 5.46\overline{d}_M^{0.722} + 0.65 \cdot 5.46s^{0.722}\alpha_l \\ + 2c_t \tag{33}$$

The maximal intermodal rail-road and unimodal road costs originate from origin/destination points to be found on the circumference of the market areas under an angle of 135° (and its respective mirrored counterpart in the case of both market areas). Manhattan distances linking the pair of these points in the two market areas are the longest for both the intermodal as well as unimodal transport route. The former are determined on the condition that d_M^{omax}, $d_M^{dmax}, d_M^{max} = R \mid \cos 135^0 \mid + R \mid \sin 135^0 \mid = 70.7\ km$ and the latter on the condition that $d_{MC}^{omax}, d_{MC}^{dmax}, d_{MC}^{max} = R + R \mid \cos 135^0 \mid + R \mid \sin 135^0 \mid = 120.7\ km$ for $R = 50$ km.

$$C_{IMMEE}^{max} = 2 \cdot 5.46d_M^{max 0.722} + 0.65 \cdot 5.46s^{0.722}\alpha_l \\ + 2c_t \tag{34}$$

$$C_{URMEE}^{max} = 2 \cdot 5.46d_{MC}^{max 0.722} + 5.46(s - 2R)^{0.722}\alpha_l \tag{35}$$

C_{IMMEE}^{min} and C_{URMEE}^{min} are the same for all travel plans and equal to the Euclidean travel plan. In the Manhattan travel plan, the detour factor is not taken into account in the drayage areas.

As shown in Fig. 8, the average break-even distance at 578 km is the shortest of all previous travel plans, while the range of possible break-even distances is nearly the same.

Obviously, the more detailed transport infrastructure conditions of the network infrastructure influence the position of the average break-even point but do not heavily affect the range of possible break-even distances. The position of the average break-even point is chiefly the result of the interplay of the drayage distance, the distance between two market areas and the transport cost of a particular transport mode, while the range of possible break-even distances depends on intersections with the minimal intermodal costs function, which is the same for all travel plans and average unimodal
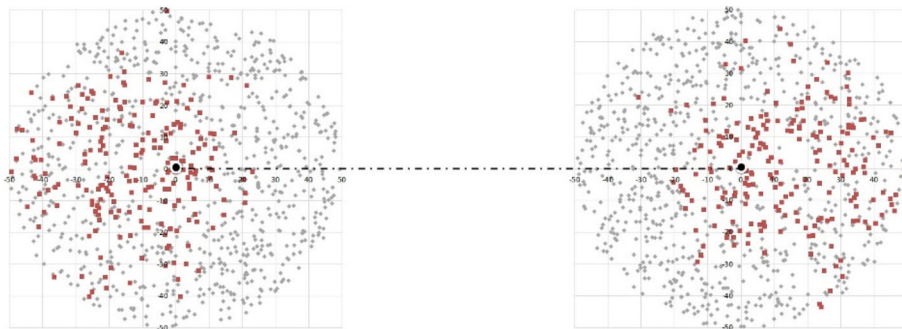

Fig. 6 The distribution of all shippers/consignees points after simulation

Fig. 7 Cost functions and break-even distances (Euclidean EE)

Fig. 8 Cost functions and break-even distances (Manhattan EE)

road costs function on one side, and the maximal intermodal and minimal unimodal road costs functions on the other.

Because the Euclidean distance can only be regarded as a proxy for the actual physical distance, it should be corrected with detour factors or replaced with the Manhattan distance. We show that when Manhattan distances are considered for drayage areas, the average break-even distances in the Euclidean exit-entry travel plan with a detour factor applied and Manhattan exit-entry travel plan give similar results. However, in the case of a real-life transport network, one would simulate actual travel plans that fit the network topology best.

4.6 Break-even distances in a Euclidean travel plan with a one-sided drayage area

Here we examine a special travel plan denoted as a one-sided Euclidean travel plan. This travel plan consists of a terminal and drayage area on one side, and a terminal without a drayage area on the other. The terminal without a drayage area could be a port terminal, a terminal in a big industrial undertaking with industrial sidings, a terminal in a factory or in a distribution warehouse with private sidings. Port terminals are the most substantial intermodal facilities to which inland transport systems, particularly rail, extend. Such maritime terminals are bounded by sea access and located in the port area where containers move directly from the dock or the storage areas to a railcar using the terminal's own equipment.

For the break-even calculation, the same equations as for a Euclidean travel plan, considering only one drayage area, can be used. The cost functions in this travel plan are presented in Fig. 9.

As shown in Fig. 9, the average break-even distance in this travel plan is much shorter at 248 km, meaning this plan offers the highest level of competitiveness of intermodal rail-road transport compared to unimodal road transport. The break-even distance interval lies between 60 km (point B) and 478 km (point C), thereby indicating that intermodal transport is competitive even over very short distances on the condition that the shippers/consignees are located close to the intermodal terminal (point B in Fig. 10).

We limit our analysis of the one-sided drayage area to Euclidean travel plan based on the observation in Section 4.5, where we show that results of the Manhattan travel plan are approximately equal to those of Euclidian travel plan when an appropriate detour factor is applied.

5 Conclusions

The purpose of this paper was to give a general answer about the competitiveness of intermodal rail-road transport based on the transport distance as the decisive cost component in freight land transport. The key finding is that distance is one of the important modal choice criteria in the freight-mode choice process and that there are many break-even distances, which vary over certain

Fig. 9 Cost functions and break-even distances (Euclidean one-sided)

Fig. 10 Limit points in the one-sided drayage area
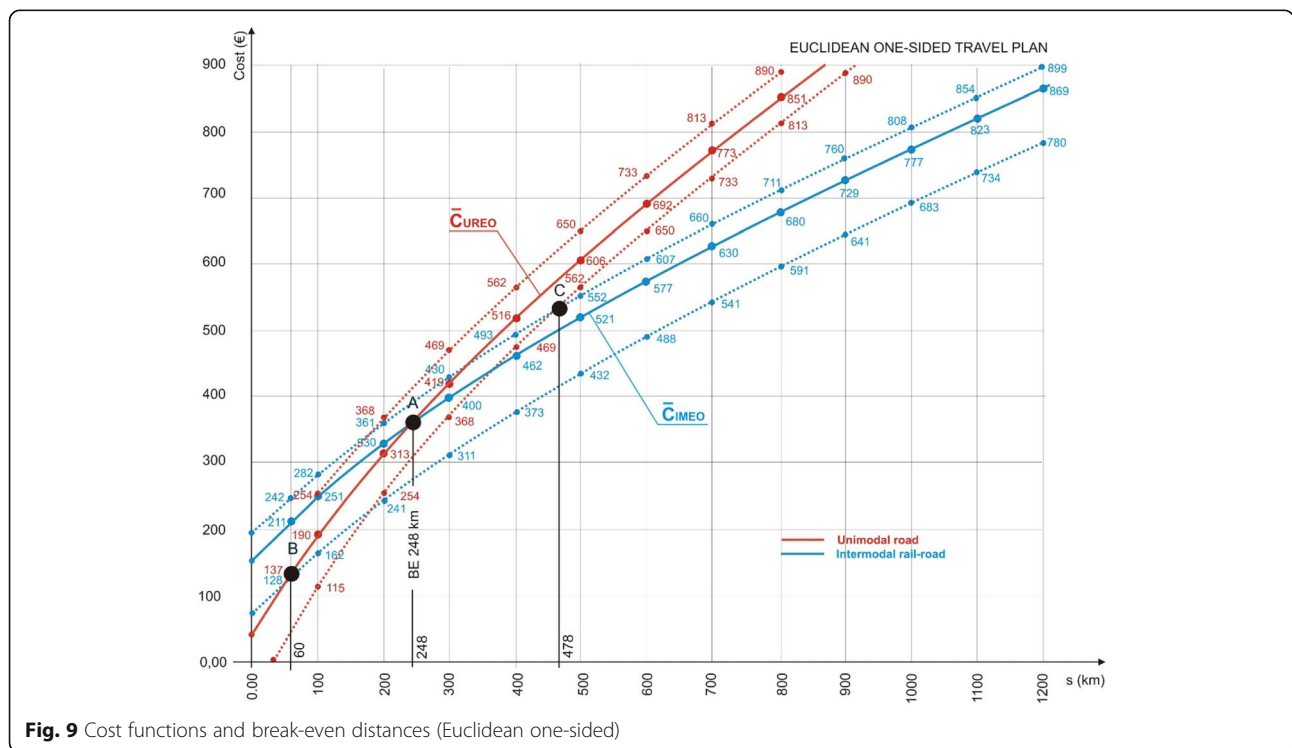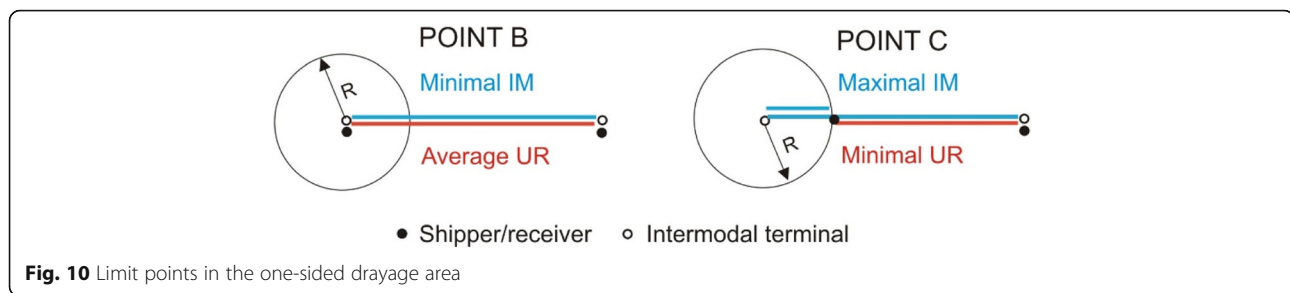
intervals, depending on different travel plans, shipper/consignee locations and cost components.

The break-even distances between intermodal rail-road and unimodal road transport in two-sided drayage areas are estimated to lie in the interval from 104 km (point B in Manhattan EE travel plan) to 1143 km (point C in the Euclidean travel plan), while average break-even distances are estimated to be at 578, 605 or 640 km, depending of the travel plan under scrutiny. As shown, intermodal rail-road transport can be competitive over all distances where the minimal transport costs involved are below the average unimodal road transport costs. On the other hand, unimodal road transport can be competitive so long as its minimal transport costs are less than the maximal intermodal transport costs. Irrespective of this, the costs of the competitive mode should be lower than those represented by the envelope of maximal competitive cost.

In the case of a one-sided drayage area, the average break-even distance is much shorter, namely at 248 km, and the range of possible break-even distances lies between 60 km and 478 km, which is very much in favor of intermodal transport. It is clear that by eliminating pre- or post-haulage intermodal transport could be a good alternative to unimodal road transport, also on short- and medium-distance trips.

The results confirm the conclusions of other authors that there are many, not just a single, break-even distances and that break-even distances depend on different factors and travel plans. It is worth noting that similar previous studies did not take account of the different distances in both networks. Rutten [4], for instance, regarded drayage distance and its cost as a partly fixed and not a variable intermodal cost. Janic [16] considered the average road door to door as the break-even distance. On the other hand, Kim & Van Wee [27] categorized three different break-even distances, such as break-even distance as market distance, break-even distance as distance actually traveled, or break-even distance as door-to-door distance. All these distances are considered separately but only as factors influencing the break-even distance. In this research, the distances and corresponding transport costs for each and every pair of 10,000 randomly distributed origin and destination points were calculated separately for each transport mode. In addition, by examining different travel plans, the costs of each mode were obtained. This helped us avoid the problem of different distances, thereby significantly contributing to more accurate results. This enabled us to obtain the sensitivity results for the influence of the market size area and the rail-haul distance on the modal split. More precisely, we show that it is the ratio of rail-haul distance to the size of the market area that majorly determines the share of the intermodal transport.

The results give a general insight into the impact of distance on the competitiveness of unimodal rail-road transport and show that intermodal transport can be competitive, even over relatively very short distances if the drayage costs are not too high. Drayage costs are thus potentially one of the major barriers to the intermodal rail-road service. The findings are quite promising for the development of intermodal rail-road transport, particularly if in the future the external costs are included in transport prices. The inclusion of external costs would potentially significantly alter the results to the benefit of intermodal rail-road transport in the future, yet they are currently not part of the trade-off considered by shippers. Despite the assumptions inevitable in such general analysis, we believe the obtained results can help better understand the competitiveness of land freight transport and be used by policy- and other decision-makers to better evaluate the opportunities, competitiveness, and attractiveness of intermodal rail-road transport. Future analysis in the field of distance-dependent transport costs that would include external costs, minimum requirements on maximum daily and weekly driving times in the road sector and the results of implementing the TEN-T green freight transport corridors would be needed in order to contribute to fair competition among operators and to a more sustainable transport policy in the future.

Publisher's Note

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