Long-distance, multi-modal freight in a continental transportation model

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Abstract:

This paper proposes a model of long-distance freight traffic which is suitable for transportation models covering very large areas. Three challenges are discussed in turn. First, the geographic distribution of trips not only depends on locations of production and consumption, but also on the choice between alternative logistic distribution chains and the locations of intermediate distribution centers. Second, any stage of the distribution chain may combine several modes into a multi-leg transport. Third, the large scale of the model leads to large zones, implying a significant share of intra-zonal traffic. The proposed approach adapts the four-stage model by generalizing destination choice into a distribution channel model and by introducing a mode sequence choice model for multimodal transport. A simplified distance-band model is applied to intra-zonal traffic.

Keywords:

Freight modelling, distribution logistics, intermodal assignment, long-distance traffic

INTRODUCTION

TRIMODE is a strategic transport network model simulating passenger and freight transport activity and covering all mobility – urban, regional, national, international and intercontinental – for the European Union and neighbouring countries, fully integrated with an economy and an energy model. The tool is being developed to provide the European Commission with a usable and reliable tool to support the assessment of transport policies and infrastructure investments.

Even though its focus is on mobility at the European national and international level, TRIMODE is targeted at simulating the whole transport demand, from local to inter-continental, for both passenger and freight. To deliver good quality forecasts and responses to policy simulation, TRIMODE aims to provide a realistic representation of how transport activity is generated and occurs on to the European territory. Freight transport activity is rooted in inter-regional trade but its pattern is heavily influenced by logistic operations. Economic transactions between zones give rise to movements of goods, which are transported through various distribution chains, from the original producer to the final consumer. In many cases, different transport modes are used to move goods within a specific distribution chain, so that multimodality is a common feature of freight transport. In many distribution chains the final leg consists of delivering relatively small amounts of products to retailers. A large share of these movements occurs at distances that, given the spatial granularity of a model like TRIMODE, are internal to each zone.

Accordingly, many extra challenges arise when developing operational, comprehensive models that represent all freight movements on all modes across a large number of countries. To address these in TRIMODE, distribution chains are explicitly represented in the modelling of freight demand patterns, while multi-modal assignment is used to estimate freight movements within each chain. Furthermore, local distribution movements occurring within zones, even though they are not assigned to the network, are modelled in detail by means of a distance band approach.

This paper presents how these three aspects are implemented in TRIMODE, starting in the next section with the modelling of freight distribution chains, then the description of multi-modal assignment and finally, the treatment of intra-zonal movements. A final section presents some conclusions.

FREIGHT DISTRIBUTION CHANNEL MODELLING

When examining wide-ranging transport policy measures at the European scale it is important to ensure that freight is represented as a derived demand. The pattern of goods movement arises from the interplay between:

- the spatial pattern of the supply (production) and demand (consumption) and of the cost of goods; and
- the logistics structures that are in place to ship goods from producers (supply) to consumers (demand), via Distribution Centres (DCs), using the most suitable combination of modes.

The *economic transactions* between suppliers and consumers, and the *logistics operations* that actually deliver the physical goods, are the two main drivers behind the observed pattern of freight movements. Accordingly, we draw a distinction between two separate matrices of movements that are used conceptually in demand analysis for freight transport:

- **The pattern of economic trade in goods** from their initial producer to their ultimate consumer; this is called the **Production-Consumption (P-C) matrix of trade**. Changes in this matrix are strongly influenced by economic changes *outside* the transport and distribution sectors. This matrix is forecast within the TRIMODE Economy Model component and is not further discussed in this paper.

- **The actual set of physical transport movements** generated by the logistics structure that distributes and transports these P-C trades in practice; this is called the **Origin-Destination (O-D) matrix of shipments** and it is forecast within the TRIMODE freight demand model using the distribution channel choice methodology described below. Changes in this matrix are strongly influenced by changes *within* the freight transport and the distribution industry sectors.

Representing logistics and distribution channels

The formulation of the distribution channel choice mechanism within the freight demand model use two distinct but intertwined structures that are solved simultaneously within its mathematical formulation:

- a *spatial structure* generating transport movements for traded goods from production zones to consumption zones. This is a conventional component of standard transport models. The corresponding monetary flow to pay for the goods transported passes in the reverse direction: from the consumption zone to the production zone.
- a *distribution channel* connecting a specific type of good from its original zone of production through DCs to its ultimate zone of consumption, being transported via various types of intermediate logistic legs.

The distribution channel representation that is used was originally developed in 1978 for a freight model for the state of Sao Paulo in Brazil *(1)*, then refined in UK government funded research studies *(23)* and was subsequently successfully implemented at a large scale in 2010 in the Base Year Freight Matrix (BYFM) model for all domestic freight transport movements on road and rail within Great Britain *(34)*. The distribution channel choice mechanism in TRIMODE refines and simplifies that used previously in BYFM.

We start by introducing some terminology and context.

- The **ultimate consumption zone *c*** in this distribution channel context denotes the zone, at the end of a particular distribution channel, in which either the *intermediate or final consumption* of that good takes place.
- The **original production zone *p*** is the zone at the start of a particular distribution channel. It is **not** one of the DC zones at which goods may be transferred or stored along the distribution channel prior to reaching their ultimate consumption zone.

The equations which estimate the transport flow T_{pc}^{r} from the production zone *p* to the consumption zone *c* for type of freight *r*, take explicit account of intermediate distribution activities. FIGURE 1FIGURE 1 illustrates this conceptual shift from the left hand box (the Production – Consumption presentation) to the middle box, which represents the actual freight movements on a logistic leg by leg basis, through the stages of the **distribution chain**. The transport flow T_{pc}^{r} is replaced by a more general procedure that adds a further layer to the model formulation. This extra layer builds up the transport flow in a manner that reflects the logistics options that are available at each distribution stage, connecting the original production zone through to the ultimate consumption zone for a specific commodity, through use of a succession of intermediate logistic legs along the distribution chain as illustrated in FIGURE 1FIGURE 1. The right hand box is the equivalent channel-based representation of the leg-based middle box. It illustrates the three separate **distribution channels** that a consignment could take through this example distribution chain.

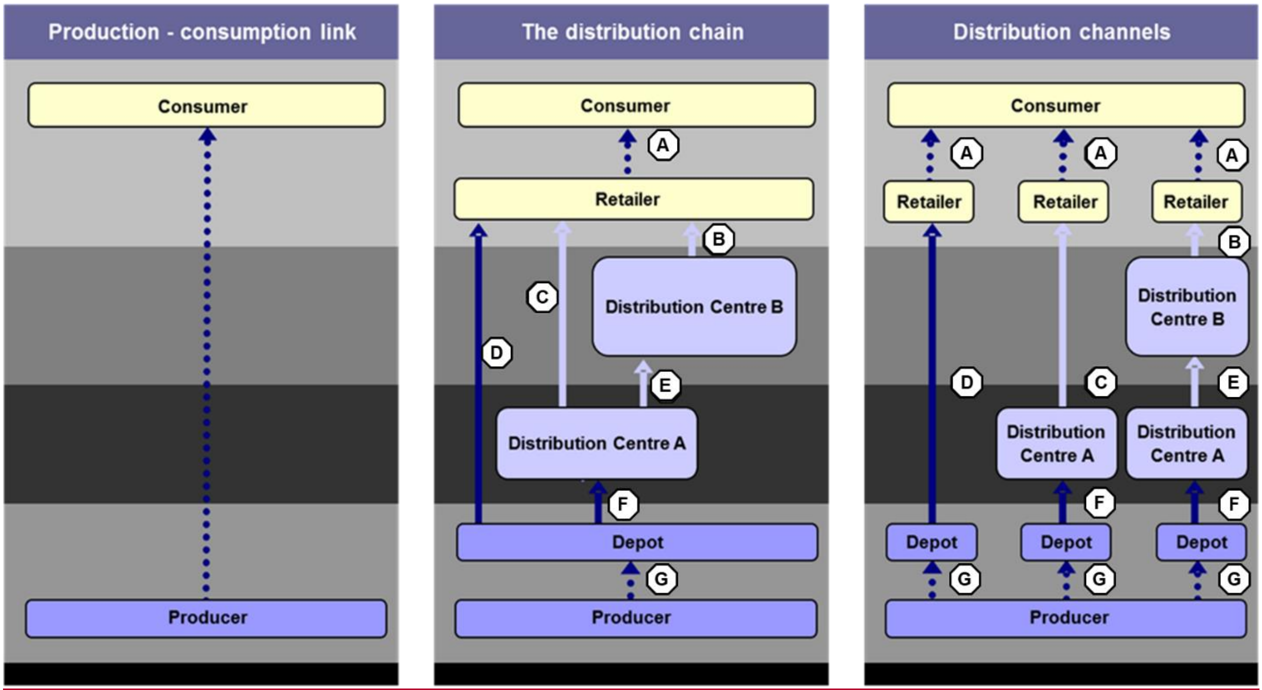

FIGURE 1 The production-consumption, distribution chain and distribution channels.

The logic behind this approach is now illustrated in the context of the example in FIGURE 1~~FIGURE 1~~.

- The ultimate demand for consumption of a good of type *r* by households in zone *c* is satisfied by receiving these goods via some local retailer, denoted by logistic leg (~~1~~A).
- These goods arrive to the retailer through a number of different types of logistic legs:
  - either *directly from a producing factory* - denoted by logistic leg type (~~4~~D).
  - or else *indirectly from a distribution centre* in which the goods have been warehoused or cross-docked between logistic legs - denoted by logistic legs type (~~2~~B) and (~~3~~C).
- For those goods that are output from the DC B, they will first have needed to be delivered there from DC A, using logistic leg type (~~5~~E).
- The solution algorithm continues moving up the distribution chain through the sets of distribution centres for all zones until all distribution chain legs (in this particular example just the further logistic leg type (~~6~~F)) have been traversed back to the original production zones (the blue box denoting the depot of the factory at which the goods were first produced).

This approach is generalised into a procedure for a given type of good that commences with the set of ultimate consumption zones at the top of the right-hand box in FIGURE 1~~FIGURE 1~~ and then successively satisfies their demands by moving down each of the distribution channels, transporting goods from producers or DCs, via the appropriate logistic leg type and intermediate zone. The procedure continues until all demand for goods has been satisfied by the output from production or from import zones at the bottom of the box.

In practice the computation is more complex because for each type of distribution chain in FIGURE 1~~FIGURE 1~~ there will be many DCs and producers competing in different zones, so that the range of distinct options increases greatly. However, the dimensional scale of this solution algorithm is not overwhelming, provided that within a DC the goods are pooled and that the exact consumption zones of each output shipment further up the distribution chain do not need to be remembered within the solution algorithm when selecting DCs or production zones lower down in the chain.

Formulation of the distribution channel choice model

The mathematical formulation below specifies the integration of the spatial distribution channel choice and its associated logistic leg choice within the TRIMODE Freight Demand model component.

The solution algorithm adopted is the distribution channel choice approach shown in the right hand box in FIGURE 1~~FIGURE 1~~ rather than the distribution chain (leg choice) approach. It commences at the consumer end and traces back through each distribution activity along the distribution channel to end at the producer. The channel stages and logistic leg types at the top and bottom of each distribution channel are predominantly local short distance trips that will be represented as intra-zonal movements (see separate section below).

The starting point for the calculations of the amount moved on each logistic leg is:

D_c^r denotes the total ultimate amount of consumption of freight type *r* within the consumption zone c. It is based on forecasts from the TRIMODE Economy Model.

X_{jk}^{rh} denotes the amount of the freight type *r* delivered to zone *j* via the distribution channel of type *h* in the k^{th} stage back from the ultimate destination. It is calculated at stage *k=1* as:

$$X_{j1}^{rh} = p_{h|rj} D_c^r \quad \forall j = C, r \tag{1}$$

In this ultimate consumption zone only, implement a discrete choice model that is to be calibrated to match the handling factor value[1] that is exogenously specified for each specific freight type. This probabilistic choice is between competing distribution channel types *h* and is based on their relative costs of moving goods through to that consumption zone from all of the various available original production zones.

$$p_{h|rj} = e^{-\lambda^r\left(\tilde{u}_{j1}^{rh} + r_j^{rh}\right)} \Big/ \sum_{h'} e^{-\lambda^r\left(\tilde{u}_{j1}^{rh'} + r_j^{rh'}\right)} \quad \forall j = C, r \tag{2}$$

Each of these distribution channel types *h* has its own exogenously specified:

- Total number of logistic stages, each representing one of a succession of intermediate DCs or other facilities that needs to be traversed;
- Sequence of the type of storage facility used in each successive stage *k*, starting with *k=1* from the ultimate consumption zone end and increasing the stage count when traversing the distribution channel in the direction back to the original production zone;
- Logistic leg type *l* (e.g. primary, secondary or tertiary, etc.) associated with each movement stage *k*, between each of its successive pairs of facilities.

r_C^{rh} denotes the unit residual disutility, if any, within the ultimate consumption zone c. If there is insufficient data to calibrate these values zonally using observed totals as constraints to be matched, the zonal subscript is dropped and the term acts as an exogenously input alternative specific constant for each distribution channel.

λ^r is a calibrated parameter that denotes the extent to which deliveries of freight type *r* concentrate on those distribution chains that can deliver goods with the lowest generalised cost of sourcing.

$\tilde{u}_{j1}^{rh}$ see equation (12)~~(12)~~.

The next component of the model is the spatial distribution of the leg *l* among the competing origin zones.

D_{jk}^{rhld} denotes the amount of the freight type *r* delivered to the distribution activity *d* in zone *j*, via the logistic leg of type *l* in the k^{th} stage back from the ultimate destination on the distribution channel of type *h*:

[1] Handling factor denotes the average number of logistic legs for that freight type.

$$D_{jk}^{rhl(d)} = a_k^{rhld} X_{jk}^{rh} \quad \forall d, j, h, k, l, r \tag{3}$$

a_k^{rhld} is an (I-O) coefficient which takes a value 1, iff the logistic leg type *l* is used on the stage *k* of the distribution channel *h*, otherwise it takes the value 0. It denotes the type of incoming logistic leg type *l* arriving at distribution activity type *d*, that was used to deliver this freight type *r* from its previous production or distribution stage.

For any given type of distribution activity *d*, only a subset of all logistic leg types *l* can deliver to it.

X_{ik}^{rh} denotes the total volume of the freight type *r* that is transported out from the DC or factory in zone *i* via the *k-1*st stage of distribution channel h, to meet all of the demands for delivery elsewhere. It is calculated for $k>1$ as

$$X_{ik}^{rh} = \sum_{jld} T_{ijk-1}^{rhl} \quad \forall i, h, k, r \tag{4}$$

T_{ijk}^{rhl} denotes the volume of the freight type *r* that is delivered on a logistic leg of type *l* in stage *k* of distribution channel *h*, from a DC or production factory in the zone *i* to meet the demand for consumption within the distribution activity *d* in zone *j*.

In principle, this is an O-D matrix, rather than a P-C matrix, though those movements that go directly from a producer activity (i.e. zone $i=p$) to an ultimate consumer activity (zone $j=c$) will be common to both the O-D and P-C matrices:

$$T_{ijk}^{rhl} = D_{jk}^{rhl(d)} p_{i|rjhkl} \quad \forall i, j, h, k, l, r \tag{5}$$

$p_{i|rjhkl}$ denotes the probability that a consignment of the freight type *r* that arrives at the zone *j* will have been delivered there from the zone *i*. This origin zone choice probability is calculated using a standard logit type discrete choice model as

$$p_{i|rjhkl} = S_i^{rl} e^{-\lambda^{rl} u_{ijk}^{rhl}} \Big/ \sum_{i\prime} S_{i\prime}^{rl} e^{-\lambda^{rl} u_{i\prime jk}^{rhl}} \quad \forall i, j, h, k, l, r \tag{6}$$

S_i^{rl} is a zonal size term that denotes the capacity of the origin zone *i* for the delivery of the freight type *r*. Depending on the type of logistic leg *l*, it will represent either the size of the relevant warehousing in the DCs in the zone, or the production capacity of the factories producing the good there.

u_{ijk}^{rhl} is the cumulative disutility, equation (9)~~(9)~~, of delivering a unit of freight type *r* to zone *j* on logistic leg type *l* in stage *k* of distribution channel *h* that has been sourced from the origin zone *i*.

λ^{rl} is a calibrated parameter that denotes the extent to which deliveries of freight type *r* on logistic leg type *l* concentrate from those origin zones that can deliver goods with the lowest generalised cost of sourcing. It is calibrated to match the observed pattern of lengths of haul.

This market clearing equation completes the representation of distribution channels:

$$\sum_p X_p^n = \sum_{ce} D_c^{ne} \quad \forall n \tag{7}$$

The aggregate totals of the P-C matrix are calculated by accumulating the successive O-D delivery legs across the set of distribution channels h, the different combinations of intermediate logistic legs of type *l* that may be used to travel between a variety of intermediate pairs of zones.

$$T_{pc}^{r*} = T_{pc1}^{ru4} + \sum_{j}\left(T_{jc1}^{rv3} p_{p|rjv21}\right) + \sum_{j}\left(T_{jc1}^{rw2} \sum_{i} p_{i|rjw22} p_{p|riw31}\right) \forall c,p,r \tag{8}$$

Here the terms on the right hand side of equation (8)~~(8)~~ denote that there are three competing distribution channels as in FIGURE 1~~FIGURE 1~~ above. It can be extended to represent longer distribution channels. Transport disutilities (generalised costs) within distribution channels, are specified as:

u_{ijk}^{rhl} denotes the cumulative *zone pair consumption disutility* (generalised cost) of sourcing from the origin zone *i* one unit of the freight type *r* for delivery to the zone *j*, within the stage *k* of the distribution channel *h*. This comprises: the disutility of the previous delivery to the origin zone *i*, plus the cost of production or of storage at the DC within the zone *i*, plus the subsequent disutility of transporting the goods using a logistic leg of type *l* through to the destination zone *j*. It is represented as

$$u_{ijk}^{rhl} = w_{ik+1}^{rh} + \hat{u}_{ij}^{rl} \quad \forall i,j,h,k,l,r \tag{9}$$

$\hat{u}_{ij}^{rl}$ denotes the *transport disutility* associated with transporting one unit of the freight type *r* from a DC or a factory in zone *i* to the delivery zone *j* on a logistic leg of type *l*. This transport disutility is a function of the monetary cost, time, quality of service and residual disutility for the modes between the pair of zones. It is output from a standard hierarchical logit mode choice model as a composite log-sum across the set of competing main modes for the zone pair along their equilibrium paths through their multi-modal network computed as described in the next section. For intra-zonal legs, transport disutility depends on the distribution of demand among different distance bands as explained in the penultimate section below.

The zonal *distribution disutility* (at the factory or origin warehouse gate) of one unit of the freight type *r* that is available in the zone *i* for delivery using stage *k* of the distribution channel of type *h*, is:

$$\begin{aligned} w_{ik}^{rh} &= \hat{c}_i^{rd'} + \hat{r}_i^{rd'} \quad \forall\, i = p,h,l(d'),k,r \quad \text{for initial production zones} \\ w_{ik}^{rh} &= \hat{c}_i^{rd'} + \hat{r}_i^{rd'} + a_k^{rhld'} \tilde{u}_{ik}^{rh} \quad \forall i,h,l(d'),k,r \quad \text{for other DC zones} \end{aligned} \tag{10}$$

Here the notation *l(d)* denotes the particular distribution activity of type *d'* at which the logistic leg of type *l* terminates.

$\hat{c}_i^{rd\prime}$ denotes the input factory gate price of the good if it is the starting logistic leg, i.e. from the original production zone, *i*=*p*. Otherwise it denotes the input unit cost of warehousing the good for the distribution activity of type *d'* within dispatch zone *i*.

$\hat{r}_i^{rd\prime}$ denotes the unit residual disutility, if any, of the good, either at the factory gate if it is in the starting logistic leg; or otherwise for warehousing the good.

In all base year and forecasting scenario runs, the total production in each zone is applied as an aggregate production constraint that needs to be matched within the converged solution. This constraint is matched through use of equation (11)~~(11)~~ to calculate the required disutility value that is then passed up through the distribution channels so as to adjust the allocation of supply by zone. The notation "$hk \in p$" indicates summation over all of the distribution stages that emanate from that original production zone *p* for the freight type *r*.

$$\hat{r}_{ps}^{rd\prime} = \hat{r}_{ps-1}^{rd\prime} + \left(\frac{1}{\lambda^r}\right) \ln\left(\sum_{ehk\in p} \frac{X_{pks}^{reh}}{X_p^r}\right) \quad \forall p,r,\ \text{d'=producer/factory} \tag{11}$$

$$\hat{r}_{p0}^{rd} = 0$$

The model is solved iteratively, as indicated by the iteration subscript *s* that has been explicitly included in the relevant terms in equation (11)~~(11)~~. The endogenously calculated variables in all of the other equations above should equally include this model iteration subscript *s* but to avoid representation complexity it has not been explicitly presented within them.

An analogous residual disutility procedure is used to ensure that the input P-C tonnages by freight type and zone pair are also matched.

Each of the logistic legs of type *l* that is used to replenish the stocks of the good in a DC in zone *i*, needs to be sourced from a set of origin zones *q*, each with the corresponding cumulative zone pair consumption disutility: u_{qik}^{rhl}. The expected minimum disutility over all possible origin zones *q*, is given by the following logsum calculation

$$\tilde{u}_{ik}^{rh} = \left(-\frac{1}{\lambda^{rl}}\right) \ln\left(\sum_{q} S_q^{rl} e^{-\lambda^{rl} u_{qik}^{rhl}}\right) \quad \forall i, h, k, l \in (h, k), r \qquad (12)$$

In summary, this delivery disutility at the destination point of distribution includes:

- the initial production disutility (the factory gate disutility in its original production zone) of the good;
- the cumulative disutility of all upstream stages of transporting the good via any intermediate DCs, through to the current DC;
- the cumulative disutility, of all associated operations in all the upstream DCs through which the goods have passed, prior to this current distribution stage.

MULTI-MODAL ASSIGNMENT

Motivation

The specific challenge for traffic assignment in a wide-area model is the presence of long-distance trips for both passengers and freight. Any long-distance trip may combine multiple modes from door to door. TRIMODE mode choice abstracts from this level of detail and adopts a main mode approach: each member of the choice set (Car, Coach, Rail, Air, Ship, …) represents the choice of the dominant mode (or: *main mode*) for the journey. Each main mode is associated with a set of *feeder modes,* which can be used in addition to the main mode.

TABLE 1~~Table 1~~ lists some main modes in the TRIMODE model, with associated feeders.

TABLE 1 Selected passenger and freight main modes with feeder modes in TRIMODE

Main mode	Feeder modes in hierarchical order
Car	-
Rail	1: Coach, 2: Car
Air	1: Rail, 2: Coach, 3: Car
Ship Container	1: Rail Intermodal, 2: Truck
Rail Intermodal	1: Truck
Truck	-

Example: Air may be available as a main mode alternative, even though neither origin nor destination zone has an airport, because a combined Car – Air – Rail trip still counts as a journey of main mode Air. Each contiguous portion (*u*, *v*, *m*) of a trip using a single mode *m* from location *u* to location *v* is called a *mode leg*. The example trip comprises three mode legs (of modes Car, Air, Rail). The *mode sequence* of a trip is the ordered set of its mode legs. In contrast to main modes, each mode (main or feeder) viewed in isolation is called a *single mode*.

Related work

Combining multiple modes for a single trip is not novel. In the most common case multiple public transport submodes are combined in one door-to-door journey. Two modelling approaches exist for this problem: either submode choice is treated as part of route choice in a super-network for all submodes (e.g. in *(4)*, *(5)*) or mode choice is nested for the submodes (e.g. the two case studies in *(6)*). These approaches fail when modes from public and private transport are combined, e.g. in Park & Ride, because commonly available assignment procedures do not treat both simultaneously. The standard approach in this case involves matrix convolution on the costs skimmed from separate assignments, as described in *(7)*. Applications with longer sequences of modes arise in tour-based demand models where the concept of filter constraints on a reasonable order of the modes was first developed (e.g. in *(8)* and *(9)*).

Formulation as a bi-level problem

The approach presented here solves a generalized form of the Park & Ride assignment problem. Demand for a main mode from an origin to a destination is assigned to path alternatives where each path is composed of one or more modal legs, using at minimum the main mode, possibly in combination with feeder modes.

The multi-modal assignment is formulated as a bi-level problem (FIGURE 2~~FIGURE 2~~):

- At the upper level (mode sequence choice) the choice is between mode sequences for a given main mode. O-D demand for the main mode is received from the main mode choice (part of the demand model). The choice set for each O-D pair consists of feasible and efficient (defined below) mode sequences. Generalized costs for each alternative are computed based on single-mode specific costs skimmed from the single mode assignments (lower level). Total demand for the O-D pair is distributed over these alternatives, using a discrete choice model. Finally, for each single mode demand is summed over all O-D pairs and over all mode legs that use this mode. This leg-wise single mode demand is passed to the lower level. The volume-weighted average generalized cost of the mode sequences is passed as main mode generalized cost to the main mode choice.
- At the lower level the leg-wise demand is assigned separately for each single mode (*single mode assignments*). Link volumes and paths are stored for each assignment. Generalized cost components are skimmed off each single mode assignment and passed to the upper level.

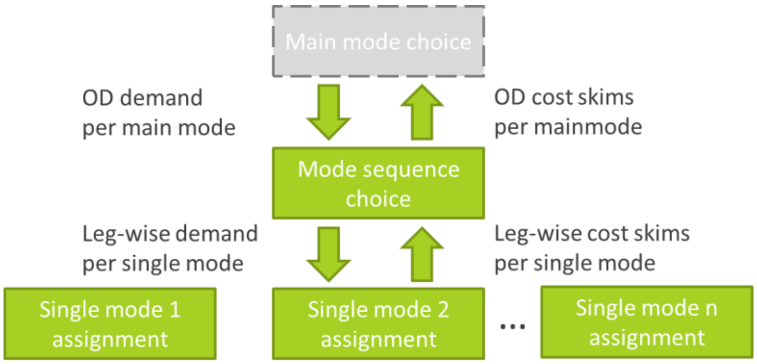

FIGURE 2 Bi-level formulation of TRIMODE assignment.

Since some of the cost components fed back from the lower to the upper level are flow-dependent, the bi-level problem is solved iteratively until a termination condition is met. Costs are suitably smoothed before being fed back, in order to improve convergence.

Mode sequence choice

Mode sequence choice is carried out on a graph that uses the same zoning structure as for the lower level, but abstracts from any link network detail. Mode sequence choice involves five steps:

1. Mode sequence search
2. Mode sequence utility calculation
3. Demand split across alternative mode sequences
4. Extraction of leg-wise single mode demand
5. Extraction of main mode generalized cost skims

Mode sequence search is carried out on a multi-graph $G = (Z, E), E \subseteq Z \times Z \times M$. Let e-, e+, m(e) denote the first, second, third component of edge e. *Z* denotes the set of all zones. Zone indices *o*,*d* refer to the origin and destination zone of a complete trip. Indices *u*,*v* refer to the start and end zone of a mode leg. *M* denotes the set of all single modes, $\widehat{M}$ the set of main modes. The procedure described below is applied to each main mode and each user class, but for brevity their indices are omitted in the equations. Two important simplifications are introduced:

- Transfer locations between mode legs are also represented by zones.
- Mode legs within a mode sequence must join up at the transfer zones, but are implicitly assumed to fit together in time. Expected transfer waiting times and costs (if any) are assumed to be included in the leg-wise costs.

With these simplifications, any edge in *G* corresponds to a mode leg, and any path corresponds to a mode sequence.

From the single-mode assignments skims ${}_hc_{e-,e+}^{m(e)}$ are available for each mode m and cost type $h \in H$, the set of all cost types (time, distance, monetary cost etc.). They induce edge costs ${}_hc(e)$:

$$ {}_hc(e) = {}_hc_{e-,e+}^{m(e)} \tag{13} $$

For path $p = (e_1, \dots, e_n)$ we define

$$ {}_hc(p) = \sum_{i=1}^{n} {}_hc(e_i) \tag{14} $$

by summing mode specific cost over all mode legs.

From the individual cost types generalised costs are defined:

$$c(p) = \sum_{h} {}_{h}\beta \;\, {}_{h}c(p) \tag{15}$$

Only edges e with $c(e) < \infty$ belong to E. In other words, the edge from zone *u* to zone *v* using *m* exists if single mode *m* uni-modally serves *u*-*v*.

FIGURE 3~~FIGURE 3~~ displays an example of the multi-graph and one mode sequence. The mode label is shown for some edges only. All nodes represent zones. In the example the circles take the role of origins and destinations, boxes represent transfers.

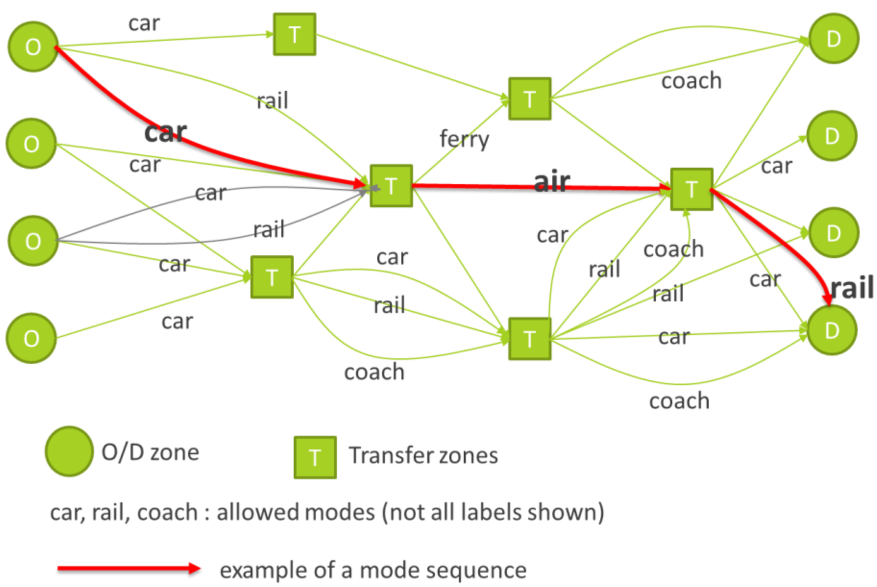

FIGURE 3 Example of a multi-graph for mode sequence search, one mode sequence highlighted.

Not all paths in *G* are realistic mode sequences. Unconstrained path search generates e.g. paths with many repetitions of Rail – Car – Rail – Car – Rail – Car - …. Even if most of these unrealistic choice alternatives carried unattractive generalised cost and therefore attracted zero demand, they would greatly increase computational burden.

Constraints are therefore specified on the order in which feeder modes appear in a mode sequence. TABLE 1~~TABLE 1~~ lists the feeder modes in hierarchical order. Example: for main mode Air the highest-ranking feeder mode is Rail, the lowest-ranking feeder mode is Car.
The following constraints apply:

1) The main mode must appear exactly once in a mode sequence.
2) Any feeder mode must appear at most once before the main mode and at most once after the main mode. This mode leg may contain transfers.
3) If a feeder mode appears *before* the main mode, it does so *after* all lower-ranking and *before* all higher-ranking feeders.
4) If a feeder mode appears *after* the main mode, it does so *before* all lower-ranking and *after* all higher-ranking feeders.

Example: mode sequence Rail – Air – Rail – Car satisfies the mode order constraint for main mode Air, while Rail – Car – Air does not. Rationale: It is considered unlikely that Rail is used to access a rental location for a Car that is then driven to the airport, so this sequence is ruled out.

A path $p = (e_1, \dots, e_n)$ from o to d in G is *feasible* for main mode $\hat{m}$, if the mode sequence $(m(e_1), \dots, m(e_n))$ of p satisfies the mode order constraint for $\hat{m}$.

A path $p = (e_1, \dots, e_n)$ from *o* to *d* in *G* is *reasonable* for main mode $\hat{m}$, if conditions (16(16) and (17(17) apply:

$$ {}_{\hat{d}}c(p) \leq a \cdot {}_{\hat{d}}c(p^0) + b \tag{16} $$

where $a, b \geq 0$ are parameters and p^0 is a least-cost path from *o* to *d* using $\hat{m}$. Typically *a* is in 1.1 .. 1.5.

$$ \sum_{\substack{i=1 \\ m(e_i) \neq \hat{m}}}^{n} dd_{e_i-, e_i+} < \theta \cdot dd_{od} \tag{17} $$

where dd_{ij} is the straight-line (direct) distance between zones *i* and *j*.

Dominance criterion (16(16) is used to prune path alternatives that are too inferior to other alternatives. Condition (17(17) eliminates path sequences where the main mode is only used for an insignificant portion of the whole trip. Realistic results were obtained in numerical experiments with a threshold factor $\theta = 0.3 \,..\, 0.5$.

Complete enumeration of all mode sequences is impractical due to combinatorial explosion. Instead branch-and-bound search is run from each origin zone to all destination zones, keeping multiple paths as long as they are feasible and reasonable. The search is implemented using the approach described in *(4)* for connection search in schedule-based public transport assignment, except that here the time dimension is not considered.

Once the path choice set $P_{od}^{\hat{m}}$ from *o* to *d* for main mode $\hat{m}$ is constructed, total demand $OD_{od}^{\hat{m}}$ for the main mode is split across the alternatives. A logit model is used.

$$ \pi_{od}^{\hat{m}}(p) = \frac{e^{\lambda c_{od}^{\hat{m}}(p)}}{\sum_{r \in P_{od}^{\hat{m}}} e^{\lambda c_{od}^{\hat{m}}(r)}} \tag{18} $$

$$ OD_{od}^{\hat{m}}(p) = \pi_{od}^{\hat{m}}(p) \cdot OD_{od}^{\hat{m}} \tag{19} $$

Leg-wise demand is aggregated by single mode *m* by summing demand over all loaded mode sequences of all main modes which contain a leg of mode *m*. OD_{uv}^{m} is passed to the single mode assignments at the lower level.

$$ OD_{uv}^{m} = \sum_{\hat{m}} \sum_{\substack{p \in P_{od}^{\hat{m}} \\ (u,v,m) \in p}} OD_{od}^{\hat{m}}(p) \tag{20} $$

Finally, main mode costs ${}_{h}c_{od}^{\hat{m}}$ for all cost types *h* are computed as volume-weighted averages over all mode sequences for a given O-D pair. They are fed back to main mode choice within the demand model.

$$ {}_{h}c_{od}^{\hat{m}} = \sum_{p \in P_{od}^{\hat{m}}} \pi_{od}^{\hat{m}}(p) \; {}_{h}c(p) \tag{21} $$

Single mode assignments

After mode sequence choice, separate assignments for each single mode are run, all in parallel. The assignment method for each mode can be chosen independently, based on the characteristics of the mode, in particular drawing from both public and private transport assignment methods.

For all road-based single modes one multi-class equilibrium assignment is computed. For most discontinuous transport modes some form of public transport assignment is applied. The choice between schedule-based and frequency-based assignment depends on the frequency and regularity of the supply.

Where no explicit link network exists (e.g. bulk shipping services), only the resulting single-mode demand is stored in matrix form, without assignment to a network.

INTRA-ZONAL MOVEMENTS MODELLING

The spatial distribution task within the freight distribution channel choice model allocates the demand consumed in each destination NUTS-III zone among the available origin zones for a particular logistic leg type. One potential origin is the destination zone itself and for some tertiary logistic legs it is expected that such intra-zonal movements will be the majority of total movements. At the same time, for passenger demand a large share of trips is intra-zonal. Given the size of NUTS-III regions[2], the length of intra-zonal movements can be of a few kilometres as well as of 20 kilometres or more. In order to represent intra-zonal transport disutility more accurately and, at least as far as passenger demand is concerned, also to model availability and competitiveness of transport alternatives, intra-zonal movements are further distributed among different distance bands, namely:

< 1.5 km
1.5 – 3 km
3 – 5 km
5 – 10 km
10 – 20 km
> 20 km

Depending on the zone size, it may be the case that the longest distance bands are not deemed to be available in the smaller sized zones.

This distance band approach to intra-zonal modelling was originally developed for use in the SCENES model *(10)* of Europe to ensure that it represented all freight and passenger travel demand on all modes, despite SCENES being implemented with a NUTS II level of zoning. This methodology has since been refined by combining it together with an area type based zoning system to provide the core functionality underpinning the policy model component of the national passenger transport model (NTMUK) of Great Britain, which has been used intensively for policy assessment by the UK Department for Transport from 2002 through to the present.

The algorithm used for the intra-zonal distribution among distance bands within a zone is very similar to that used for the distribution of movements between zones. Basically, the distance bands represent a set of fictitious zones. Both for freight and passenger it applies:

$$ {}_S p_{id} = \frac{e^{-\psi^S \, {}_S U_{id}}}{\sum_{\mathrm{d}} e^{-\psi^S \, {}_S U_{id}}} \tag{22} $$

where:

${}_S U_{id}$ is the disutility of travelling within distance band *d* of zone *i* or of delivering a unit of freight along distance band *d* within an intra-zonal movement in zone *i* for demand segment *S* (trip purpose and population group for passenger, freight type and logistic leg for freight). It includes attraction factors and calibration parameters.

ψ^S is a calibrated parameter that denotes the extent to which intra-zonal trips or deliveries of segment *S* concentrate within those distance bands with the lowest total disutility of delivery/travel

[2] The EU-28 countries contain 1342 NUTS-III regions.

For passenger, where several transport modes are available in each distance band, the disutility is estimated as the logsum of that by mode of transport:

$$ {}_{s}U_{id} = -\frac{1}{\eta} * \ln\left[\sum_{m} e^{-\eta(\,{}_{s}U_{id}^{m})}\right] \quad (23) $$

The modal transport costs and speeds that are applied to each distance band are an exogenous input, differentiated by the area type of the zone. In congested metropolitan areas: road speeds will be slow; parking costs may be high; while public transport services will be widely available. In contrast in low density rural areas, road speeds will be higher but public transport may be sparse.

The reason for developing this distance band methodology is to enable the supply characteristics of short distance passenger and freight trips to be represented adequately, while avoiding excessive computing costs. Model run times generally increase in proportion to the square of the total number of zones. However, this distance band approach alleviates the need to introduce a much larger number of small zones and so generates minimal extra computing burden, while providing a complete representation of total travel. In particular, it ensures that: some trips will switch from shorter intra-zonal bands to longer intra-zonal bands or to inter-zonal trips if either transport costs reduce or if incomes increase; and vice-versa. This avoids the unrealistic cut-offs that can arise within large scale models that represent only the "long distance" component of passenger or freight trips.

CONCLUSIONS

The methodological developments introduced above have been designed to improve the realism and performance of comprehensive operational freight modelling procedures for large study areas.

The impact of trends in logistics and of the responsiveness of logistics to policy initiatives can best be understood realistically, if these impacts are considered within the context of both their underlying P-C and O-D matrices. The cost-effectiveness of individual distribution channels is highly sensitive to transport and logistics cost structures so the resulting spatial pattern of O-D movements should take major account of this sensitivity. The distribution channel choice procedure provides a computationally efficient method for representing the complexity of the operation of logistics and for representing how the distribution structure varies greatly across broad types of goods and for representing how it will evolve in response to cost changes.

The greatest challenge in the implementation of the distribution channel choice lies in obtaining access to comprehensive data that describes the actual scale of usage of competing distribution channels. The residual disutility based methods for constraint matching have been developed in part to ensure that flexible and effective use can be made of whatever aggregate data does become available.

The ability to provide a consistent representation of the door-to-door costs for the choice set of multi-modal options available for each O-D pair is important in ensuring that appropriate transport costs are input into the distribution choice procedure. To achieve this, the bi-level formulation for multi-modal assignment presented here has a number of advantages in practical application:

- Mode sequence choice for all main modes can run in parallel, as can all single mode assignments, reducing execution time and allowing distributed computation.
- Once leg-wise single mode demand has been calculated for all road-based single modes (e.g. Car and Truck), it is passed into a single multi-class highway assignment at the lower level. Equilibration between Car and Truck is achieved without further outer loops.
- The simplifying assumption that transfer locations are represented by zones reduces network coding effort, as there is no need to create transfer links between single-mode networks.

Some limitations should, however, be noted for the formulation presented here:

- Large zones may connect to different network nodes for different modes, in which case inter-mode transfer costs at such a zone may be incorrectly represented.
- In a wide-area model like TRIMODE it may be justified to neglect the question whether mode legs join up in time. The same would not be true in urban applications, e.g. for the combination of shared mobility services with conventional public transport. Adding the time dimension would increase the computational burden, however, and needs to be investigated further.

The use of distance bands for intra-zonal movements adds flexibility and ensures that the average travel length of local distribution consignments can depend on zonal features like density. It enables the characteristics and responsiveness of shorter freight trips to be represented in a realistic fashion without requiring the adoption of a much larger number of small zones that would in turn generate infeasible computing run times. The approach is even more useful for passenger demand because the competitiveness of alternative passenger transport modes varies with distance.

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