

# Network Data Model and BerlinMOD Benchmark

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## Abstract

In the past, several data models for the representation of histories of spatio-temporal data objects have been developed. We can categorize these data models into data models for objects moving freely in the two dimensional space and data models for network constrained moving objects. In this paper we select two representatives, one for each data model category, which are both implemented in the SECONDO DBMS, and compare their capabilities with the BerlinMOD Benchmark. We describe our implementation of the used network constrained data model, and the translation from the BerlinMOD Benchmark into the network constrained data model and show that in our experiments the network constrained data model outperforms the data model of free movement in the two dimensional space by orders of magnitude.

## 1 Introduction

In the past, several data models for the representation of spatio-temporal data objects have been developed. We can categorize them into data models for objects moving freely in two dimensional space and data models for network constrained objects. For both categories several different data models have been presented like [11, 14, 24, 25] for spatio-temporal data objects moving freely in two dimensional space (DMFS) and [7, 15, 31, 34] for spatio-temporal data objects that are constrained by given networks (NCDM), to name just a few. Objects which are restricted to use existing networks, like cars are restricted to use road networks, can be represented as moving point objects in both data models, whereas objects, which are not restricted by a given network, like people, can be represented as moving point objects only in DMFS.

Why do we spend time on NCDM, if everything can be represented by a DMFS? Now, it is natural to give positions related to the street network instead of x,y-coordinates. NCDM are expected to use less storage space, because geographical informations about street curves are stored only once in the network, whereas in DMFS each street curve is stored in each moving point object using this street. NCDM can support query processing with specialized indexes, because of the knowledge of the underlying network. And it is much easier to formulate queries about the relationships between moving objects and the network in the NCDM. And last but not least the results of our experiments show that our network data model outperforms our data model of free movement in two dimensional space by orders of magnitude. The network constrained data model uses less than 60% of the storage space and less than 50% of the total query run time of the data model of free movement in space we used in our experiments. We think that these results show that it is useful to develop specialised data models for specialized data structures like NCDM for network constrained moving objects to save storage space and reduce query run times.

For our benchmark experiments, presented in this paper, we chose two data models one for each data model category. Both data models use the same temporal representation and are available in SECONDO DBMS [6, 13]. So we can exclude that different DBMS or temporal representation

issues bias the results of our data model comparison with the BerlinMOD Benchmark [4]. The DMFS we use is the data model presented in [11] (SPACE for short). And the NCDM we use is the data model presented in [15] (NET for short). Our implementation of NET is described first in this paper (Section 3 and provides some further concepts which were only sketched in [15].

We used the BerlinMOD Benchmark [4] to compare the capabilities of the two data models, because the BerlinMOD Benchmark is to the best of our knowledge the first benchmark for complete spatio-temporal database systems. It is developed and available in SECONDO DBMS. And the data generated by the BerlinMOD Benchmark data generator are restricted to the streets of the German capital Berlin, such that they can be translated into a network constrained environment. And last but not least, the data model used in the BerlinMOD Benchmark is SPACE that we use for our comparison. So we only have to translate the spatial and spatio-temporal data types of the BerlinMOD Benchmark once into our NET representation. This simplifies the control of the query results and avoids errors caused by translation. The translation of the spatial and spatio-temporal data types of the BerlinMOD Benchmark data into the NET representation described in this paper 4 can be seen as an example for the usage of the BerlinMOD Benchmark with other compatible data representations or DBMS.

The rest of the paper is organised as follows: Related Work is presented in Section 2, including short reviews of the underlying SECONDO DBMS (Section 2.1), the two data models (SPACE Section 2.2 and NET Section 2.3) we chose for our comparison, and the BerlinMOD Benchmark (Section 2.4). In Section 3 we give some informations about our implementation of NET, the used operations and indexes. The translation of the BerlinMOD Benchmark data and query set into the NET representation is described in Section 4. The resulting experimental benchmark setup is described in Section 5 followed by the results of our experiments in Section 6. We conclude our work in Section 7.

## 2 Related Work

In the past many different spatio-temporal data models have been presented. Many of them support only discrete spatio-temporal changes [3, 20, 22, 23, 28] or deal only with current and future positions of continuously moving objects [30]. Reviews of several different spatio-temporal data models are given in [27]. In this paper we will focus on spatio-temporal data models for complete histories of continuously moving objects. These can be categorized into data models for objects moving freely in two dimensional space (DMFS) and data models for network constrained moving objects (NCDM).

We will start with a few DMFS. [32] proposes the basic ideas of an DMFS based on differential geometry and the linear constraints approach of modeling spatial and spatio-temporal data. Spatial and spatio-temporal objects are defined by linear constraints, and the queries use formulas from differential geometry. The paper proposes only an incomplete abstract model without any usability.

[24] and [11] use both the idea of time sliced representation of moving objects first presented in [14]. [11] supports only linear interpolation of movement, whereas [24] also supports arc interpolation. [24] uses only one spatial object containing all spatial geometries and one moving object for the representation of the different moving object data types, whereas [11] uses different spatial and moving objects for the representation of the different data types. Therefore [24] provides only a single operator that distinguishes between the different topological relationships via a parameter, whereas [11] uses different operations to estimate topological relationships. Altogether [24] offers a more flexible object oriented design than [11].

The spatio-temporal framework proposed by [11, 14] is extended by [15] to be also usable in network constrained environments. Similar to the most other NCDM in this section [15] depends

on a fixed network representation. That means that the old network informations are lost when a update of the network data structure occurs. Only [7] can handle such updates without loss of information.

[34] proposes an edge based NCDM. With an relation holding the edges and their attributes. The edge relation represents a undirected graph. Moving objects are assumed to drive always on the path with the lowest cost (distance or travel-time) from the source to the target point from a given starting time. The trajectory is computed by this assumption using the length and speed attributes of the graph edges within the shortest / fastest path computation. These assumptions will not always hold in real world environments. Such that the moving object representation does not suffice real world requirements.

[31] uses also an edge based network representation. The paper proposes a combination of an 2D geometrical edge representation with an directed graph representation of the network. Where as the 2D geometrical representation handles the spatial information the connectivity information is mostly embedded in the directed graph representation. The both representations are connected by transition policies. Moving objects are represented by sets of 5 tuples. Each 5 tuple contains an edge identifier, the position of moving point on the edge in terms of weight and length, the speed and direction of the movement, and the time instant of this information.

Different from all other NCDM in this section [7] proposes a dynamic transportation network model. This means that the attributes of the network parts are modelled by time depending dynamic attributes, such that changes in the network environment can be handled without loss of information. Similar to [15] the idea of the network model bases on routes and junctions. The authors propose a two-layer network representation data structure, which combines the advantages of dynamic edge based [9] and route based [8] NCDM approach. The route based environment reduces the update intervals and used storage space for moving objects, whereas the edge-based environment supports a more detailed view on the traffic conditions of the different edges belonging to the same route. Moving objects are represented by a set of pairs of motion vectors together with a boolean flag telling if the motion vector contains actual or historical information. Each motion vector consists, in parts similar to [31], of a time stamp, a network position, and a speed vector.

To the best of our knowledge only a few of these data models have been completely implemented into different database management systems:

1. [24] is implemented as data cartridge [25, 26] for the commercial Oracle®ORDBMS [?].
2. [7] is implemented as extension of the open source database project PostgreSQL [12].
3. [11] and [15] are implemented in the freely available extensible SECONDO DBMS [13].

Although [24] for the DMFS and [7] for the NCDM provide greater flexibility we decided to use [11] and [15] in our experiments, because both are available in the freely available SECONDO DBMS. And not at least SECONDO is the DBMS with which the BerlinMOD Benchmark [4] was developed.

Other benchmarks for spatio-temporal databases provide only well defined query sets [?] and a database description without data. Or they come with well defined data generation, workload sets and experiments but only to evaluate the capabilities of indexes for current and near future positions [21]. Or they focus on time-evolving regional data and associated index methods like [33].

The BerlinMOD Benchmark is to the best of our knowledge the only benchmark testing the capabilities of complete spatio-temporal database systems. Coming with well defined data and query sets feasible for moving objects in space and network constrained moving objects.

In the next sequel we give short reviews of the SECONDO database system (Section 2.1), the both data models (Section 2.2, Section 2.3) we used in our experiments, and the BerlinMOD Benchmark (Section 2.4).

## 2.1 Secondo DBMS

The extensible SECONDO DBMS presented in [6, 13] provides a platform for implementing various kinds of data models. It provides a clean interface between the data model independent system frame and the content of the single data models. Hence SECONDO can be easily extended by the user implementing algebra modules to introduce new data types and operations on these data types. The user may define additional viewers for the graphical user interface or write additional optimization rules or cost functions to extend the the optimizer. Since SECONDO version 2.9 the users may publish their extensions as a SECONDO plugin such that other users can use these plugins to extend their own SECONDO system. They may use the newly provided functionalities or repeat the published experiments. SECONDO is freely available on the web [18]. It comes with a number of already implemented spatial and spatio-temporal data types and operations including the DMFS (Section 2.2) and the NCDM (Section 2.3) used in this paper. Furthermore, the BerlinMOD Benchmark described in Section 2.4 has been developed in the SECONDO DBMS. For our experiments we used the SECONDO version 2.9.x.

## 2.2 Data Model of Free Movement in Two Dimensional Space

[10] presents the basic idea of the new spatio-temporal data model that we will use as DMFS in our experiments. Besides the general idea it discusses related work and the advantages of having abstract and discrete data models. Abstract data models allow us to make definitions in terms of infinite sets, without worrying whether finite representations exist. They are useful as conceptual model, but they cannot be implemented, because computers can only use finite sets. Data structures and algorithms have to work with finite representations of the data types. Therefore we also need a discrete algebra representation. The abstract definition of our data model has been published in [14], whereas an associated discrete data model was presented in [11].

The basic idea of [14] is to define type constructors that create new data types if they are applied to an data type of a given set of base types. The type system is defined using the techniques presented in [16]. Base types are the standard data types like integer, real, and Boolean; the spatial data types like point, line, and region; and the temporal type instant. The most important introduced type constructor is “moving”. Moving maps each standard and spatial data type  $\alpha$  into an time dependend spatio-temporal moving data type  $\text{moving}(\alpha)$ .

The standard data types are defined as usual, but their carrier sets are extended by  $\{\perp\}$  (undefined). The spatial data types are *point* (carrier set  $\mathbb{R} \cup \{\perp\}$ ).

Spatial positions are assumed to be located in a two dimensional space.

A single spatial position is represented by the data type point. A point consists of a pair of real values interpreted as x,y-coordinates in the assumed two dimensional plane.

Streets are represented by line values. A line value consists of a set of HalfSegments representing the geometry of the line in the two dimensional space. Each HalfSegment consists of two point values and a Boolean flag telling us if the left or the right point is the dominating point of the HalfSegment.

Regions are represented by the data type region. A region consists of a set of HalfSegments defining the outer border of the region in the two dimensional space. If a region contains wholes the inner border is also formed by the HalfSegments.

In SECONDO all these spatial data types and many standard data types can be “lifted” to become time dependent moving values. For all data types  $\alpha$  the constructor moving creates a new data type moving( $\alpha$ ) (short form m $\alpha$ ).

A car may be represented by a moving(point), short mpoint. An mpoint consists of a set of units called unit(point) (short form upoint). Each upoint consists of a time interval and two point values. The first point value represents the position of the mpoint at the start of the time interval

and the second *point* value represents the position of the *mpoint* at the end of the time interval. It is assumed that the object represented by the *mpoint* moves on the straight line between these two points with constant speed within the given time interval. The velocity of the object is given by the ratio from the distance of the two points and the length of the time interval of the unit. All units of an *mpoint* must have disjoint time intervals, because a car cannot be at two different positions at the same time. The units are sorted by ascending time intervals.

This spatio-temporal data model of *moving* allows us to compute the position of an *mpoint* at every time instant within its definition time. We can also compute the time instant the point passed a given position assuming the *mpoint* ever passes this position. The position of a *point* at a given time instant is represented by an *intime(point)* (short form *ipoint*). An *ipoint* consists of a time instant and a *point* value.

Some other data types of SECONDO which are used in the BerlinMOD Benchmark are shown in Table 1.

Data Type	Description
<i>bool</i>	Usual boolean data type
<i>int</i>	Usual integer number
<i>real</i>	Usual real number
<i>instant</i>	A point in time
<i>periods</i>	A set of disjoint and not connected time interval
<i>mbool</i>	A time dependent boolean value, which is constant <i>TRUE</i> or <i>FALSE</i> within each <i>ubool</i>
<i>mreal</i>	Time dependent real number. Each unit is defined by a function of time representing the <i>real</i> value at each time instant.

Table 1: Other Data Types of BerlinMOD Benchmark

### 2.3 Network Data Model(NET)

The central idea of the NDM presented in [15] is that every movement is constrained by a given network and every position can be described relative to this network. The data type *network* is the central data type in the NDM. All other data types of the NDM are related to a given *network* object by the unique network identifier that is part of each *network* object.

The *network* object contains all spatial information of the represented network. The *network* consists of three main relations (*routes*, *junctions*, and *sections*), two arrays providing fast access to adjacent network sections, and some B-Tree and R-Tree indexes to supporting faster access to the main relations.

The relation *routes* of the *network* contains the attributes of the streets like *id*, *routecurve*, *routelength*, and two Boolean flags. The first flag indicates if the route starts at the lexicographically smaller end point or not. The second flag indicates if the lanes of the street are separated like on German Highways or not.

The *junctions* relation of the *network* contains all attributes of the street crossings like the two route identifiers of the first and second street meeting at the crossing, the distance of the crossing from the start of the first respectively second street, tuple identifiers of the both streets in the routes relation, tuple identifiers of the sections connected by this junction in the sections relation, and a connectivity code telling us which lanes of the two streets are connected by the crossing.

The *sections* relation of the *network* object contains the attributes of the street parts between two crossings or a crossing and the end of the street. These are the route identifier of the street the section belongs to, the tuple identifier of this street in the routes relation, the start position and end position of the section on the street, the section curve, and again two Boolean flags with the same meaning as in the routes relation.

Furthermore there are two arrays in the network object providing a fast access from each section to their adjacent sections with respect to the driving direction. Two sections are adjacent if their lanes are connected by a junction.

We created four B-Tree indexes for the route identifier attributes in the *routes*, *junctions* and *sections* relation, and an R-Tree index over the curve attribute of the *routes* relation to support faster execution of operations dealing with the relations of the network object.

The data type gpoint represents single positions in a given network. Besides the network identifier a gpoint consists of a route identifier, a distance from the start of the route to the position of the gpoint and a *side* value (*up*, *down*, *none*) telling us if the position is reachable from the *up* or the *down* side of the route in case of separated lanes. For simple streets or positions which are reachable from both sides of the route, the side value is always *none*.

Parts of the network, regardless if they represent paths or regions, are given as gline values. Besides the network identifier, a gline consists of a set of RouteIntervals, and two Boolean flags. The Boolean flags tell us if the gline is defined and if the set of RouteIntervals is sorted.

Each RouteInterval consists of a route identifier identifying the route that the route interval belongs to, and the start and the end position of the route interval on this route <sup>1</sup>. We call a set of RouteIntervals sorted if the following conditions are fulfilled:

- all RouteIntervals are disjoint
- the RouteIntervals are stored in ascending order of their route identifiers
- if two disjoint RouteIntervals have the same route identifier, the RouteInterval with the smaller start position is stored first
- for all RouteIntervals, the *start position*  $\leq$  *end position*

Many algorithms take profit from sorted gline values. For example: If  $n$  is the number of the route intervals in a gline, the decision, if a gpoint is inside the gline needs  $O(n)$  time for unsorted and  $O(\log n)$  time for sorted gline values.

Unfortunately not all gline values can be stored sorted. If a gline value represents a path between two gpoint in the network, we need the route intervals exactly in the sequence they are used in the path. This will nearly never be a sorted set like defined before. We store gline values sorted whenever this is possible to support faster query execution, and introduced a Boolean sorted flag. Every algorithm which deals with gline values checks this flag and uses the corresponding code.

Mostly similar to the mpoint of the other data model there is an mgpoint in the NDM. An mgpoint consists of a set of ugpoint with disjoint time intervals. Each ugpoint consists of a time interval and two gpoint values. Every time the mgpoint changes the route or the speed, a new ugpoint is written. Each ugpoint is assumed to follow the same route from the start to the end position at the same speed. So accordingly to the mpoint we can compute the network position of the mgpoint at every time instant within the definition time of the mgpoint as intime(gpoint).

In deviation from the original NDM we extended the implementation of the mgpoint with four additional attributes to support faster query execution:

1. The total driven distance
2. A sorted set of RouteIntervals representing the positions ever traversed by the mgpoint
3. A Boolean defined flag for the set of RouteIntervals

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<sup>1</sup>In the original paper the RouteInterval includes a *side* value analogous to the gpoint. But this parameter is not yet part of the implementation.



#### 4. A spatio-temporal minimum bounding box

The sorted set of RouteIntervals was introduced, because analogous to sorted gline values it makes it much faster to decide whether an mgpoint ever passed a given network position or not. Instead of a linear check of all  $m$  ugpoints of an mgpoint we can perform a binary scan on the much smaller number  $r$  of the passed RouteIntervals. This reduces the time complexity from  $O(m)$  to  $O(\log r)$  for the **passes** operation.

The spatio-temporal minimum bounding box was introduced as an parameter to the mgpoint because the computation of this value is very expensive in the NDM. Although each unit of an mgpoint stays on the same route at the same speed it may follow different spatial directions. For example, a route may lead uphill in serpentine. A spatial bounding box only computed from the spatial start and end position may not enclose all spatial positions of the car within the unit. Therefore we always have to examine the spatial dimensions of the RouteInterval passed within a unit to compute the units bounding box. This needs an access to the route curve in the routes relation of the corresponding network object. If  $r$  is the number of routes of the network and  $h$  the number of HalfSegments belonging to the RouteInterval passed in a unit, we need  $O(h + \log r)$  time to compute the bounding box for a single unit. The bounding box of the mgpoint is the union of the bounding boxes of its  $m$  units. So the computation of the spatio-temporal respectively spatial bounding box of an mgpoint needs  $O(H + m \log r)$  time, with  $H = \sum_{i=1}^m h_i$  if  $h_i$  is the number of the half segments for unit  $i$ ,  $1 \leq i \leq m$  of the mgpoint. This very expensive computation is only done on demand or if we can get the bounding box for free. For example we can copy the bounding box of an mpoint at the translation time into an mgpoint without big computational costs. The bounding box attribute is not maintained. If the mgpoint value changes, the bounding box attribute is set to be undefined until recomputing is necessary.

## 2.4 BerlinMOD Benchmark

The BerlinMOD Benchmark was presented in [?] and the provided scripts for the data generator are implemented as SECONDO DBMS operations. The BerlinMOD Benchmark is available on the web [17] and provides a well defined data-set and queries for the experimental evaluation of the capabilities of spatial and spatio-temporal database systems dealing with histories of moving objects. The BerlinMOD Benchmark emphasises the development of complete systems and simplifies experimental repeatability pointing out the capabilities and the weaknesses of the benchmarked systems.

The data-sets of the BerlinMOD Benchmark are created using the street map of the German capital Berlin [29] and statistical data about the regions of Berlin [1, 2] as input relations. The created moving objects represent cars driving in the streets of Berlin, simulating the behaviour of people living and working in Berlin. Every moving object has a home node and a work node. Every weekday each car will do a trip from the home node to the work node in the morning and vice versa in the late afternoon. Beside this, randomly chosen cars will make additional trips in the evening and up to six times at the weekend to randomly chosen targets in Berlin and back home. The BerlinMOD Benchmark uses the data model of free movement in two dimensional space described in Section 2.2. Because the BerlinMOD Benchmark generates all data sets restricted to the street map of Berlin, the BerlinMOD Benchmark can also be used for network constrained data models, if the spatial and spatio-temporal data types are translated into a corresponding NDM, like we did for our experiments.

The number of observed cars and the duration of the observation period can be influenced by the user setting the *scalefactor* to different values in the data generation script of the BerlinMOD Benchmark. For example at *scalefactor* 1.0 the data generator creates 2000 moving point objects observed for 28 days, each of them sending a GPS-signal every 2 seconds. These simulated signals

are simplified such that time intervals when a car does not move or moves in the same direction at the same speed are merged into one single time interval. For example: If a car is parked in front of the work node for 8 hours, there will be only one entry in the history of the cars movement with a time interval of 8 hours instead of 14.400 entries, one for each GPS time interval.

The BerlinMOD Benchmark provides two different approaches to store the histories of moving objects, called the object-based approach (OBA) and the trip based approach (TBA), respectively.

In the OBA, the complete history for each moving object is kept together in one single entry. There is only one relation *dataScar* containing one tuple for each object consisting of the spatio-temporal data of the object *journey*, the *licence*, the *type*, and the *model* of the object.

In the TBA, we have two relations *dataMcar* and *dataMtrip*. *dataMcar* contains the static data for each object like *licence*, *type*, and *model* together with an object identifier *moid*. *dataMtrip* contains for each *moid* several tuples, each of them containing all units of a single trip of the moving object, or a single unit for a longer stop. For example, each time the car drives from home node to work node is a single trip, and each time the car is parked in front of the office is also a single trip.

Besides the moving point objects, the BerlinMOD Benchmark provides several data sets, each of them containing 100 pseudo randomly generated data objects, which are used in the benchmark queries. Table 2 gives an overview of these query objects. The BerlinMOD Benchmark deals also with subsets from these query object sets consisting of the first or second 10 query objects of a query object set. They are labeled by the name of the query object set followed by a 1 for the first ten or a 2 for the second ten query objects.

Name of Data Set	Tuple Content
<i>QueryPoints</i>	Object identifier and <i>point</i> value
<i>QueryRegions</i>	Object identifier and <i>region</i> value
<i>QueryInstants</i>	Object identifier and time instant
<i>QueryPeriods</i>	Object identifier and time interval
<i>QueryLicences</i>	Object identifier and a <i>string</i> representing a licence value

Table 2: Query Object Relations of BerlinMOD Benchmark

The BerlinMOD Benchmark provides two sets of queries BerlinMOD/R and BerlinMOD/NN. BerlinMOD/R addresses range queries and BerlinMOD/NN nearest neighbour queries. In this paper we will focus on the range queries, which are the main aspect of the BerlinMOD Benchmark up to now.

The query set BerlinMOD/R includes 17 queries selected of the set of possible combinations of the 5 aspects:

- known or unknown object identity,
- standard attribute, spatial, temporal, or spatio-temporal dimension,
- point, range, or unbounded query interval,
- single object or object relationships condition type,
- with or without aggregation.

We will present the 17 queries in more detail in Section 4.4 together with our NDM algorithms for these queries.



### 3 Implementation Issues

## 4 Translation of BerlinMOD into Network Data Model

In this section we describe the creation of the network object from the *streets* value of the BerlinMOD Benchmark in Section 4.1. In Section 4.2 we describe how to use this new created network value as a reference for the translation of all spatial and spatio-temporal data type objects of the BerlinMOD Benchmark into the NDM representation. In Section 4.3 we describe the indexes we build on the NDM representation to support faster query execution. We close this part with Section 4.4 where we describe the executable SECONDO queries for the NDM representation of the BerlinMOD Benchmark.

Executable SECONDO scripts for the network and index creation, object translation, and the network benchmark queries can be downloaded from our web site [19].

### 4.1 Create Network Object

The network object *net* is created by extracting the *routes* data from the *streets* object that is created by the BerlinMOD Data Generator. The extracted data *r* is used to compute the crossings of the routes of Berlin *j*. The data source lacks information about the connectivity of the street crossings, such that we use the maximum value for the connectivity code of each crossing as default value in this step. Now we can use *r* and *j* as input relations for the operator **thenetwork** to create our network object *net* representing the streets of Berlin in the NDM representation of the BerlinMOD Benchmark.

The network creation algorithm first copies all tuples of *r* to the *routes* relation of *net* and creates the B-Tree index on the route identifiers and the R-Tree index on the route curves of the *routes* relation of *net*. Then all tuples of *j* are copied to the *junctions* relation of *net* and the tuple identifiers for the both routes connected by this junction are added to the *junctions* entry. After that we build two B-Trees indexing the route identifiers of the first respectively second route in the *junctions* relation. Next for every route of the *routes* relation all junctions on this route are taken from the *junctions* relation to compute the up and down sections for each of this junctions on the route. The up and down sections are inserted into the *sections* relation of *net* and the tuple identifiers of the sections are added to the entry of the corresponding junction in the *junctions* relation. After that the B-Tree index for the route identifiers in the *sections* relation is created and the adjacency lists of *net* are filled with the adjacent section pairs defined by the *junctions* relation.

If  $|r|$  is the number of routes and  $|j|$  is the number of junctions, the algorithm needs  $O(|r| \log |r|)$  time to copy *r* to the *routes* relation of *net* and create the indexes of the *routes* relation. The creation of the *junctions* relation and the build of the B-Tree indexes takes  $O(|j| \log |j|)$  time.  $O(|r|J)^2$  time is needed to fill the *sections* relation and  $O(|j|)$  time to fill the *adjacencylists* of *net*. Altogether the complete algorithm needs:  $O(|r| \log |r| + |j| \log |j| + |r|J)$  time to create the *net* from the two input relations *r* and *j*.

### 4.2 Translate Spatial and Spatio-Temporal Data Types

In this section we describe the translation of the spatial and spatio-temporal data types of the BerlinMOD Benchmark data set into network respectively network-temporal objects. All translations are done relative to the network object *net* that we described in Section 4.1. All algorithms

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<sup>2</sup> $J = \sum_{i=1}^{|r|} j_i$ , where  $j_i$  is the number of junction on route  $i$ , with  $i \leq 1 \leq |r|$

in this section get a spatial respectively spatio-temporal BerlinMOD Benchmark data type object and the network object *net* as input. They return the corresponding NDM object respectively an undefined NDM object if the input data object is not constrained by *net*.

#### 4.2.1 Translate point into gpoint

The **point2gpoint** operation translates a point value *p* into a corresponding gpoint value *gp* if possible. This operation is also included in the other translation operations. The algorithm uses the R-Tree index of the *routes* relation of *net* to select the route curve closest to *p* and computes the position of *p* on this route curve. In case of the BerlinMOD Benchmark the *side* value of *gp* is always set to *none*, because the BerlinMOD Benchmark does not differentiate between the different sides of a street.

If *r* is the number of routes in the *routes* relation and *k* is the number of routes, which route curve bounding boxes contain *p*, the worst case complexity of the algorithm is  $O(\log r + k)$ .

This should be all to translate the point values of the *QueryPoints* relation of the BerlinMOD Benchmark into network query positions. But there is a problem with the NDM representation of junctions. In the NDM, contrary to the DMFS, each junction has more than one gpoint representation, because each junction is related to two or more routes. Hence if a junction position is given related to route *a* we won't detect the junction as passed if an mgpoint object passes the junction on route *b* in all cases, because the definition of **passes** in the network data model is slightly different from the **passes** operation in the BerlinMOD Benchmark data model. Unfortunately all query points of the BerlinMOD Benchmark are junctions. To make the results comparable, we added an operator **polygpoints**, which returns for every input gpoint value *gp* a stream of gpoint values. If *gp* represents a junction we return all gpoint values representing the same junction in *net*, otherwise we return only *gp* in the stream. So we got 221 query gpoint values in *QueryPointsNet* for the 100 query point values in *QueryPoints* and 22 gpoint values in *QueryPoints1Net* for the 10 point values of *QueryPoints1* of the BerlinMOD Benchmark. This means we always have to compute the results for the double number of query points in our NDM relativ to the DMFS.

#### 4.2.2 Translate mpoint into mgpoint

The second operation **mpoint2mgpoint** translates an mpoint value *s* into an mgpoint value *t*. The main idea of the algorithm is to use the continuous movement of *s* to reduce computation time. We initialize the algorithm by reading the first unit of *s* and use the **point2gpoint** algorithm to find a route in the network containing the *start* and the *endpoint* of this unit. We initialize the first unit of *t* with the computed network values. Then we read the next unit of *s* and try to find the *endpoint* of the new unit on the same route the last unit of *s* was found. If the *endpoint* is found on the same route we check the moving direction on the route and speed of the point in the unit. If they are equal to the actual unit we extend the actual unit of *t* to enclose the value of the actual unit of *s*. If the speed or the moving direction on the route changes we write the actual unit to *t* and initialize a new unit for *t* with the network values of the actual unit from *s*. If the *endpoint* can't be found on the same route as the last unit from *s*, we write the actual unit of *t* and start a search on the route curves of the adjacent sections to find the route curve that contains the *start* and the *endpoint* of the actual unit of *s*. We initialize a new unit for *t* with the estimated network values for the actual unit of *s* and continue with the next unit of *s*. At last we add the actual network unit to *t*.

The time complexity to find the start values for the first unit is the time complexity from **point2gpoint**  $O(\log r + k)$ . For each of the next *m* units of *s*, the time complexity is  $O(1)$  if *s* does not change the route. And it is  $O(a)$  if the end point is on another route and *a* is the maximum

number of adjacent sections. So we get a worst case time complexity of  $O(\log r + k + ma)$  for the translation of an mpoint  $s$  into an mgpoint  $t$ .

#### 4.2.3 Translate region into gline

The translation of the region values in the *QueryRegions* relation of the BerlinMOD Benchmark into gline values of our NDM is done in several steps. First of all we build a single big line object containing all network streets. Then we compute for each region of the *QueryRegions* the intersection with this big line object. At last we translate the resulting line objects of the intersection, each representing one region of the *QueryRegions* relation, into sorted gline values using the **line2gline** operation.

The algorithm of the **line2gline** operation takes each HalfSegment of a line value and computes a corresponding network RouteInterval by searching a common *routecurve* for the *start* and the *endpoint* of the HalfSegment using the **point2gpoint** operation. The computed RouteIntervals are sorted, merged and compressed before the resulting gline value is returned. If the number of HalfSegments of a line value is  $h$  and the number of resulting compressed RouteIntervals is  $r$  we get a time complexity of  $O(hO(\text{point2gpoint}) + h \log r + r)$  for the whole algorithm. Whereby the summand  $h \log r + r$  is caused by the compressing and sorting of the resulting gline but as mentioned before in 2.3 we think this time is well invested, because it is needed once and the sorted gline value is used many times.

### 4.3 Create Indexes on Network Data Model

For the use with the BerlinMOD Benchmark we created the following indexes on the network data model representation of the BerlinMOD Benchmark data sets:

- B-Tree indexes for the *licences* and *moid* attributes of the relations *dataSNcar*, *dataMcar*, and *dataMNtrip*. These indexes are similar to the indexes created in the BerlinMOD Benchmark for *dataSCcar*, *dataMCcar*, and *dataMCtrip*, because the relations *dataSNcar*, *dataMcar* and *dataMNtrip* contain the network data model representation of the *dataScar*, *dataMcar* and *dataMtrip* relation of the BerlinMOD Benchmark, respectively. We don't explain them in more detail.
- An R-Tree index of the spatio-temporal bounding boxes of the mgpoint attributes in the *dataMNtrip* and the *dataSNcar* relation. Different from the data model that uses the spatio-temporal units for the spatio-temporal indexes, we used only the big bounding boxes of the whole trips instead of the much smaller bounding boxes for each single unit as it is done in the DMFS.
- For every unit of each mgpoint we build a temporal-network bounding box and for every RouteInterval of every mgpoints trajectory a network bounding box. These network bounding boxes (*netboxes* for short) are used to create R-Trees indexing the network and temporal-network positions of the mgpoints. A temporal-network bounding box is a degenerated three dimensional rectangle. The coordinates are defined to be  $x_1 = x_2 = \text{routeidentifier}$  as a real value (The equality of  $x_1$  and  $x_2$  makes the degeneration.),  $y_1 = \min(\text{startposition}, \text{endposition})$ ,  $y_2 = \max(\text{startposition}, \text{endposition})$ , and,  $z_1 = \text{starttime}$  as a real value and  $z_2 = \text{endtime}$  as a real value. The network bounding box is defined to be a degenerated two dimensional rectangle with x,y-coordinates analogous to the temporal-network boxes.

#### 4.4 Translate Benchmark Queries

We developed executable *SECONDO* queries for each of the 17 BerlinMOD/R queries for the OBA and the TBA using our network indexes to support faster query execution. The *SECONDO* optimizer is not able to optimize SQL-queries on NDM objects yet, so we tested in our experiments many different query formulations for each query to get optimal queries delivering the correct result in a minimum of time.

The limited space does not allow us to show all our executable *SECONDO* queries for the NDM in detail, but they can be downloaded as *SECONDO* scripts from our web page. Here we give only a short overview over the BerlinMOD Benchmark queries and their NDM algorithms.

Every time we need a licence in the result or have a query licence number we need an additional step in the TBA, because we have to join the *dataMNtrip* and *dataMcar* relation using the *moid* attribute and the corresponding B-Tree indexes. We will not repeat this step at every single TBA query description.

Query 1 asks for the models of the cars with licence plate numbers from *QueryLicences*, and query 2 for the number of vehicles that are “passenger cars”. Both queries deal only with standard attributes; so we only changed the relation names and the B-Tree indexes to match the NDM representation.

Query 3 searches for the positions of the ten cars from *QueryLicence1* at the ten time instants from *QueryInstants1*. We use the licence B-Tree to select the ten cars and compute the positions of these ten cars for each of the ten time instants from *QueryInstants1* if the time instant is inside the definition time of the trip.

Query 4 asks for the licence numbers of the cars that passed the points from *QueryPointsNet*. We create a *netbox* for each *gpoint* in *QueryPointNet* and use our specialised *netbox* R-Tree of the *mgpoint RouteInterval* to select the vehicles passing the given query points.

The queries 5, 6, and 10 deal with Euclidean distance values, which are not very useful in network environments. In networks everything is constrained by the network and normally the network distances are computed instead of Euclidean distances. We decided to retranslate intermediate results into spatial respectively spatio-temporal objects and use the existing Euclidean distance operation to compute the distances between this objects to make the results comparable.

Query 5 asks for the minimum distance between places where vehicles with licences from *QueryLicence1* and *QueryLicence2* have been. We select the cars with licence plate numbers from *QueryLicence1* respectively *QueryLicences2* using the B-Tree over the *Licence* attribute of the *dataSNcar* relation. In the TBA, the resulting trajectories for each car are aggregated into one single trajectory for each car. In both approaches we create a *line* value for each resulting (aggregated) trajectory value of the *mgpoints* and compute the Euclidean distance between these *line* values for each pair of licences one from *QueryLicences1* and one from *QueryLicences2*.

Query 6 asks for the pairs of licences from “trucks” that have been as close as 10m or less to each other. We filter *dataSNcar* relation, respectively *dataMcar* relation to select the “trucks” and compute the spatio-temporal bounding box of each trip of a “truck”. We extend the spatial dimensions of the bounding boxes by 5m in each spatial direction and retranslate the *mgpoint* values into *mpoint* values in a first step. In a second step, we compute the join of the results from step one with itself using the intersection of the bounding boxes as join criteria. We filter the result to include all licence pairs of “trucks” that had sometimes a distance lower than 10m. In the TBA, we additionally remove the duplicate licence pairs from the result.

Query 7 asks for the licence plate numbers of the “passenger” cars that reached the points from *QueryPoints* first of all “passenger” cars during the observation period. The first step to solve query 7 in the NDM is equal to query 4. In a filter step we remove all “not passenger” cars from the first intermediate result. We compute for each remaining candidate trip the times the

trip reaches first the query positions. We group the resulting time instants by the identifiers of the query positions and compute the minimum time stamp of each group, which is in fact the first time the query position was reached by a car. In a last step the licences of the “passenger” cars reaching the query positions at this first time instant are computed using the specialised network-temporal index of the NDM.

Query 8 computes the overall travelled distances of the vehicles from *QueryLicence1* within the periods from *QueryPeriods1*. We select the candidate cars using the licence B-Tree, restrict the trips to the query periods and return the lengths of the trips in the OBA. In the TBA we have to sum up the length of the different trips driven by a single car within each query period.

Query 9 asks for the longest distance travelled by a single vehicle during each of the periods from *QueryPeriods1*. We restrict all trips to the periods, compute the driven distances and select the maximum length for each query periods value. Again we have to do an additional aggregation of the distances driven from the same car in the same period in the TBA.

Query 10 asks when and where vehicles with licences from *QueryLicence1* meet which other vehicles (distance less than 3m). In the OBA we first retranslate every *mgpoint* value of *dataSNcar* into a *mpoint* value and extend the spatial bounding box of each of this trips by 1.5 m in every spatial direction. After that we select the ten candidate trips given by *QueryLicences1*, retranslate them and extend their spatial bounding boxes in the same way. We join all trips from the first two steps where the extended bounding boxes intersect and filter the candidate pairs that have different licences and their distance is sometimes less than 3m to each other. We compute the position of the *mgpoint* at the times the distance between the remaining candidate pairs of *mpoint* was less than 3 m and return the licence pairs and the network positions of the first car when it has been closer than 3 m to the other one.

In the TBA we select the trips given by *QueryLicences1* from *dataMNtrip*, retranslate them into *mpoint* values, and extend their spatio-temporal bounding boxes by 3m in each spatial direction. After that we use the spatio-temporal index of *dataMNtrip* to select for each trip of the ten cars, the cars of *dataMNtrip* which spatio-temporal bounding boxes intersect the extended spatio-temporal bounding boxes built before. For every pair of candidate trips we retranslate the second trip and use the Euclidean Distance function for *mpoint* values to determine the times when the both *mgpoint* had a distance less than 3m. At last we restrict the trip of the query *mgpoint* to this times and aggregate the resulting trips into one single trip for each licence pair.

In our experiments we tried out several indexes to support a faster query execution of query 10 including the MON-Tree presented in [5]. The MON-Tree showed very good CPU times but never the less the total run time was very high. In the end the simple form described above showed the best complete run time performance of all indexes.

Query 11 asks for the vehicles that passed a point from *QueryPoints1Net* at one of the time instants from *QueryInstants1*. We build a network-temporal query box from the *QueryInstant1* and *QueryPoints1Net* relation and use the network-temporal index on *dataSNcar*, respectively *dataMNtrip*, to select the resulting trips.

Query 12 asks for the vehicles that met at a point from *QueryPoints1Net* at an time instant from *QueryInstants1*. The first step of query 12 is identical with query 11. In a second step the Cartesian Product of the result of the first step with itself is computed and filtered for vehicles which have been at the same query point at the same query time instant.

Query 13 asks for the vehicles which travelled within one of the regions from *QueryRegions1Net* during the periods from *QueryPeriods1*. We restrict the trips to the query regions and check if the restricted trips are defined within the query periods. In TBA possible duplicate licence pairs have to be removed and the resulting *moids* must be mapped to the licences of the cars to generate the result using the B-Tree *moid* index of *dataMcar*.

Query 14 asks for the vehicles that have been in one of the regions from *QueryRegions1Net*



at a time instant from *QueryInstants1*. We build temporal-netboxes from the query objects to select candidate trips using the temporal-network position index. We refine the result filtering the candidate trips really full filling the query predicates.

Query 15 asks for the vehicles passing a point from *QueryPoints1Net* during a period from *QueryPeriods1*. Analogous to query 14 we build temporal-netboxes of the of the query parameters to select the candidate trips using the temporal-network position index and refine the result filtering the candidates really fullfilling the query constraints.

Query 16 asks for the licence pairs one from *QueryLicence1* and one from *QueryLicence2* of vehicles, which were both present in a region from *QueryRegions1Net* within a period from *QueryPeriods1*, but did not meet there and then. We select the candidate trips using the licence B-Tree of *dataSNcar* relation and restrict the resulting trips to be **present** during the query periods and **inside** the query region. This is done one time for the licences from *QueryLicences1* and one time for the licences from *QueryLicences2*. The both intermediate results are joined and filtered to get the trips of different cars which where at the same period in the same region without meeting each other there and then. In the TBA we have to do a additional selection from trips with the *moids* belonging to the cars selected before by the licences and remove duplicates of licence pairs from the same period and region.

Query 17 asks for the points from *QueryPointsNet* that have been visited by a maximum number of different vehicles. In a first step we use almost the query algorithm from query 4 to select the trips passing a given query point. After that we group the cars passing query points by the ids of the query points and count the number of cars passing this query point. In a last step the point(s) with the maximum number of passing cars is(are) selected. In the TBA we have to remove duplicate vehicles from the result list before we count the number of passing cars.

## 5 Experimental Setup

For our experiments we used a standard personal computer with an AMD Phenom II X4 Quad Core 2.95 GHz CPU, 8 GB main memory, and 2 TB hard disk. We installed the Linux openSUSE 11.2 as operating system, SECONDO DBMS version 2.9.x, and the BerlinMOD Benchmark version provided in the web.

We generated three databases with different amounts of data using the data generation script of the BerlinMOD Benchmark with the *scalefactor* 0.05, 0.2, and 1.0. The following steps are done with all three databases. We first created the BerlinMOD Benchmark data and indexes using the script “BerlinMOD\_CreateObjects.SEC” for the DMFS. The NDM representation of the databases was generated by the the script “Network\_CreateObjects.SEC” that uses the algorithms and builds the indexes described in Section 4.

Table 3 shows the created amounts of data for the different *scalefactor* values in both data models. As you can see, the NDM needs less than 40% of the storage space of the BerlinMOD Benchmark data model. The main cause is that the same trip is represented by less than 50% of the units in the NDM compared to the DMFS. This is a very good result and we expect this effect to increase if the cars make long distance trips instead of moving in a single town like they do in the benchmark. In towns cars more often change the street or the velocity than cars that do long distance trips and so the compact route representation in the NDM should become more effective than in the town.



	Scalefactor 0.05		Scalefactor 0.2		Scalefactor 1.0	
Number of Cars	447		894		2000	
Number of Days	6		13		28	
Data Generation	164.761s		587.299s		3177.46s	
	DFMS	NDM	DFMS	NDM	DFMS	NDM
Data Translation and Index Build	301.72s	535.65s	1,362.72s	2,190.45s	7,419.13s	11,144.13s
Number of Units	2,646,026	1,260,888	11,296,682	5,346,971	52,140,685	24,697,709
Total Storage Space	2.26 GB	0.86 GB	9.51 GB	3.69 GB	45.76 GB	17.28 GB
Data	0.79 GB	0.44 GB	3.35 GB	1.83 GB	15.47 GB	8.40 GB
Indexes	1.48 GB	0.42 GB	6.16 GB	1.86 GB	30.30 GB	8.89 GB

Table 3: Database Statistics

The long creation time of the NDM representation is caused by the expensive mapping of spatial and spatio-temporal positions into network positions. The indexes themselves are built faster in the network representation than in the BerlinMOD Benchmark representation because they have less entries and are smaller.

We found some isolated mismatches in some query results as we compared the results of the BerlinMOD Benchmark queries and the NDM queries for the OBA and the TBA. We detected that the source data of the street map of the BerlinMOD Benchmark is not well defined in all places. Figure 1 shows two examples for the street map failures. Using a very high zoom factor you can see that single streets consist of more than one line. We corrected the source file “streets.data” of the BerlinMOD Benchmark at the places where we detected the errors and restarted the building of the databases and our experiments from scratch. With the corrected street map, all results match each other in the different data models and approaches.

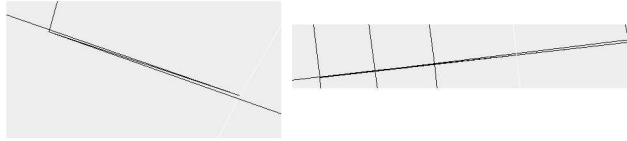


Figure 1: Example Failures in Street Map

## 6 Experimental Results

We repeated the BerlinMOD Benchmark query execution several times for both data models and approaches. The tables in Figure 2 and the graphic in 3 compare the average query run times in seconds for the different scale factors, data models, and approaches. As you can see, the total run time of all queries in the NDM is around 50% less than the total query run time of the DMFS at each scale factor.

For the queries 1 and 2, the query run times are almost the same for all data models and approaches at the different scale factors. This is what we expected because both queries deal only with standard attributes and standard indexes, which are not influenced by the different data models.

For query 3, the run times for all data models and approaches are very small. But we can see a development of the ratio of the run times between the different data amounts, data models and approaches. Although the query algorithms for both data models and approaches are almost the same, the run time ratio for the different amounts of data is different. For the small databases (scale factor 0.05 and 0.2) the NDM outperforms in the OBA the DMFS, while for scalefactor 1.0

Scalefactor 0.05				
Query	DMFS		NDM	
	OBA	TBA	OBA	TBA
1	0.125	0.109	0.128	0.088
2	0.003	0.002	0.003	0.002
3	0.245	0.205	0.227	0.268
4	6.594	7.514	0.238	0.846
5	1.072	1.585	1.098	1.031
6	14.332	6.280	3.995	3.675
7	3.458	3.191	3.893	3.192
8	0.353	0.379	0.201	0.205
9	96.724	166.434	19.840	21.783
10	104.239	31.555	62.972	76.826
11	0.150	0.096	0.224	0.443
12	0.296	0.120	0.202	0.226
13	9.959	6.551	1.094	1.113
14	0.516	0.659	1.566	1.709
15	1.144	0.857	0.579	0.488
16	6.214	14.354	0.612	1.483
17	1.126	0.719	0.228	0.262
Total	246.551	240.609	97.061	113.640

Scalefactor 1.0				
Query	DMFS		NDM	
	OBA	TBA	OBA	TBA
1	0.196	0.186	0.387	0.185
2	0.005	0.004	0.006	0.004
3	0.731	0.483	1.020	1.349
4	150.172	157.629	2.089	31.769
5	3.274	6.079	5.230	5.494
6	826.483	2002.002	270.468	235.594
7	99.086	53.099	118.840	125.206
8	0.794	0.524	0.254	0.398
9	775.458	2263.531	106.910	143.150
10	3314.518	1942.155	2150.250	1645.812
11	0.685	0.474	6.080	7.889
12	37.445	0.200	0.272	0.290
13	111.587	72.907	26.880	32.540
14	11.397	4.238	36.728	37.700
15	28.512	16.862	9.696	8.602
16	9.726	53.011	0.571	1.880
17	86.357	152.542	0.530	6.884
Total	5456.427	6725.924	2736.210	2284.747

Scalefactor 0.2				
Query	DMFS		NDM	
	OBA	TBA	OBA	TBA
1	0.123	0.096	0.157	0.099
2	0.003	0.003	0.008	0.003
3	0.501	0.327	0.424	0.349
4	32.323	39.113	0.500	6.522
5	1.657	2.985	2.394	2.198
6	57.453	45.931	15.508	13.451
7	17.184	11.150	27.084	22.814
8	0.390	0.379	0.205	0.220
9	250.626	386.452	36.323	46.187
10	447.679	126.870	286.779	287.101
11	0.247	0.165	2.119	2.958
12	4.171	0.182	0.262	0.316
13	27.028	12.106	5.865	4.669
14	1.125	1.143	8.783	9.101
15	7.800	3.874	2.543	1.876
16	6.441	25.298	0.362	0.776
17	8.722	4.042	0.289	0.641
Total	863.472	660.217	389.605	399.281

Figure 2: Compare Query Run Times in Seconds

and all TBA queries the DMFS outperforms the NDM. We think that two different effects take place. On the one hand, the number of units in the NDM is less than the number of units in the DMFS, such that the unit which contains the query time instant can be found faster. On the other hand, a *gpoint* value has more internal elements (3 *int*, 1 *real*, and 1 *bool*) than a *point* value (2 *real*, and 1 *bool*), such that result computing and copying is a little more expensive in the NDM. The advantage of the smaller number of units in a binary search is smaller if the number of units becomes bigger and the disadvantage of bigger results becomes greater; that explains the different run time ratios for query 3.

In query 4 the NDM outperforms the DMFS significantly at all scale factors (> 2 min OBA, > 6 min TBA at scale factor 1.0). The NDM index used in query 4 is much smaller (OBA 24 MB, TBA 160 MB, at scalefactor 1.0) than the spatial unit index of the BerlinMOD Benchmark (OBA 3.7 GB, TBA 3.7 GB at scalefactor 1.0) and more precise, such that we do not need an additional refinement step after the index usage in the NDM, like we do in the DMFS.

We expected the NDM to be slower than the DMFS in the queries 5,6, and 10, because we retranslate intermediate results from the NDM representation into the DMFS representation. For query 5 this holds in the OBA. We need a little more time in the NDM than in the DMFS. But in TBA the NDM outperforms the DMFS. This is due to the fact that a *gline* value has less *RouteIntervals* than a *line* value representing the same part of a curve has *HalfSegments*, such that the union of two or more *gline* values in the aggregate step of query 5 in TBA can be computed much faster than the union of two or more *line* values.

The NDM outperforms the DMFS again significantly at query 6 for all amounts of data and approaches. In the NDM we reduce the number of candidate pairs for the distance computation by pre selecting intersecting extended bounding boxes and use the operation **notEverNearerThan**

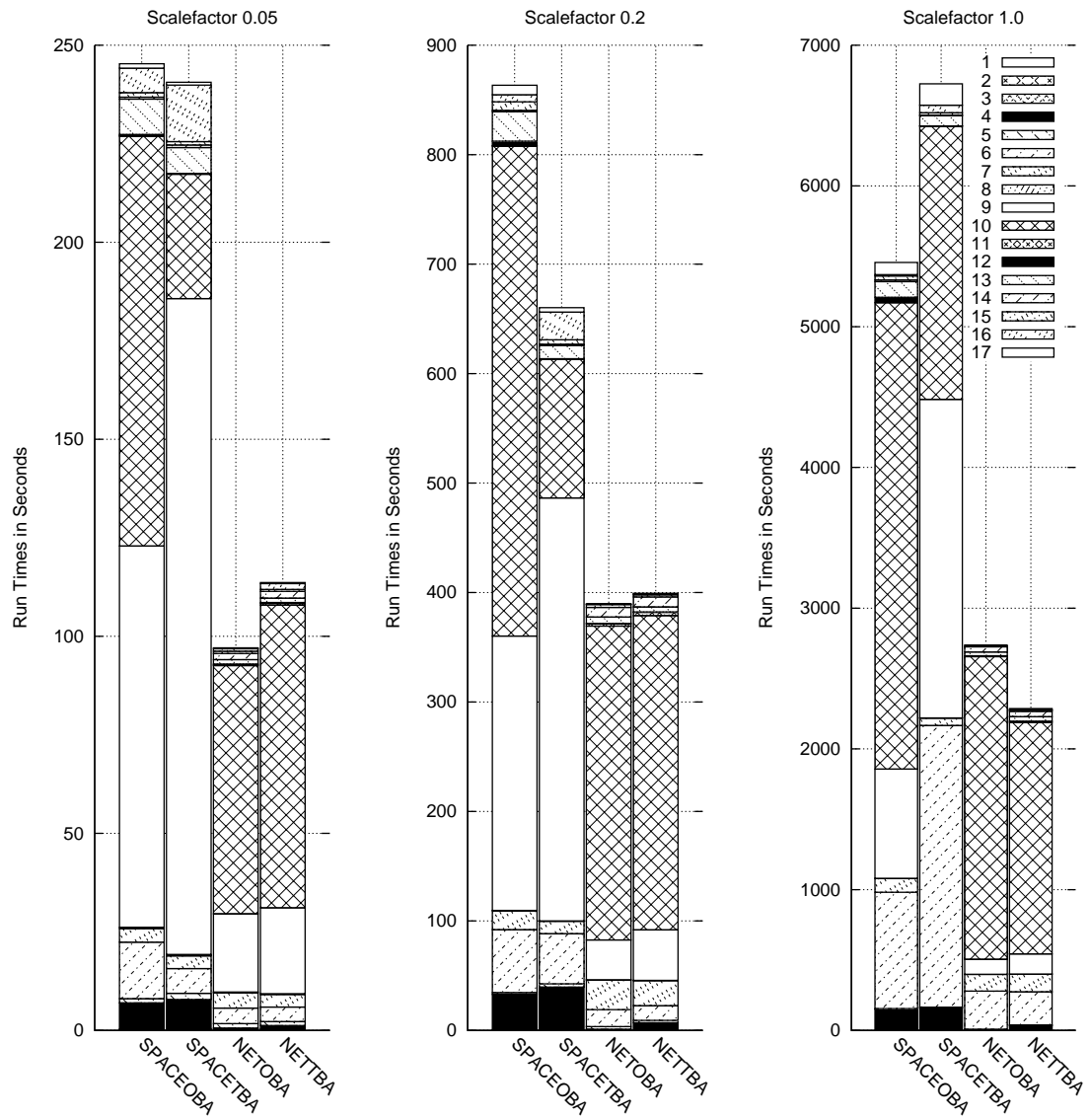


Figure 3: Compare Total Run Times

in OBA and TBA, while in the DMFS in the OBA no filtering is used and the computation is done by **minimum(distance( $mp1, mp2$ ) $\leq 10.0$ )**, and in the TBA the operation **spatialjoin** is used instead of bounding box intersection. While the operation **distance** has always a run time  $O(n)$  the operation **everNearerThan** stops computation immediately if the distance between two units is less than the query value to reduce computation time. And the operation **spatialjoin** of the SECONDO DBMS seems to have a big weakness in implementation. Otherwise the difference in the TBA query run times could not be so big ( $> 17$  min OBA,  $> 80$  min TBA, at scale factor 1.0).

After the very good results from query 4 we did not expect query 7 to have such results in the run times comparison. In fact at scalefactor 1.0 the DMFS outperforms the NDM significantly in both approaches and at all scale factors in TBA, while at the smaller scale factors in OBA the NDM outperforms the DMFS. We think there are two main causes: On the one hand we have to do the expensive operation **at** for mgpoint for the double number of query gpoint compared with the DMFS and on the other hand the test points out a weakness of the NDM implementation of the operation **at** for mgpoint. But in the end, NDM loses at scale factor 1.0 less than 45 seconds in the OBA respectively less than 120 seconds in TBA, what is not much compared with the advantages in the other benchmark queries.

Query 8 is a very fast query in both data models, although the query run time of the NDM is more than 50% less than the query run time of the DMFS. This is caused by the *length* attribute of the mgpoint and the smaller number of units of a mgpoint compared with the corresponding mpoint.

For query 9, the NDM outperforms the DMFS by orders of magnitude. The advantages named in the analysis of query 8's run time results have a much higher impact when the number of examined trips becomes bigger. At scale factor 1.0 this saves more than 10 min time in the OBA and more than 50 min time in the TBA.

The ratio of the run times of query 10 changes between the amounts of data and both data models. In the OBA and at scale factor 1.0 in the TBA the NDM outperforms the DMFS at all scale factors, while in the TBA at the two small databases the DMFS outperforms the NDM significantly. Before our experiments we expected that the DMFS would outperform the NDM in all cases, because of the expensive retranslation of intermediate results. So why is the NDM faster ( $> 20$  min in OBA and  $> 3$  min in TBA at scale factor 1.0) than the DMFS? In the OBA we use bounding boxes for a preselect of candidate trips that step is not performed in the DMFS. In the TBA the results are only better for the big amounts of data we think this is due to the fact that the number of units in mgpoint values is always smaller than in mpoint values such that the final aggregation of the different trips of the same cars can be done faster in the NDM than in the DMFS.

Query 11 is identical with the first part of query 12. So it is surprising that the run time of query 11 at scalefactor 1.0 is longer than the run time of query 12, which does additional computations. In our experiments with the different queries we have seen that there exist numerous cache effects depending on the sequence of the queries. So we think that query 12 takes profit cache effects resulting from query 11 running immediately before query 12. Another weakness of the NDM pointed out by the run times of query 11 and query 14 is that our network-temporal position index has bad run times for query *netbox* objects constructed from a single gpoint and a single time instant. This becomes worse with a higher number of indexed units. As you can see at query 15 this does not hold for query *netboxes* constructed from a single gpoint and a time interval. We have to spend some more work to figure out the problem and develop a better network-temporal position index to improve our NDM system.

In our experiments we also tested the MON-Tree [5] as network-temporal index but the elapsed run time performance was not good, although the CPU run times were small.

The bad performance of the network-temporal position index is also shown by query 13. The

NDM outperforms the DMFS significantly, but we do not use any index in the executable NDM queries, while the DMFS uses its spatio-temporal index to preselect candidate trips. The same holds for query 17.

The NDM version of query 16 takes profit from the smaller number of units in the NDM and outperforms the data model of free movement in two dimensional space.

Although we detected in our experiments some points of weakness in the network-temporal position indexing, the NDM outperforms the DMFS by orders of magnitude. The weakness of the NDM mostly occurs in queries with short run times, whereas the advantages of the NDM become apparent in the queries with long run times, such that the weakness of the network-temporal position index is covered by the advantages of the network data model.

## 7 Summary and Future Work

We presented our translation of the BerlinMOD Benchmark into the NDM and compared the capabilities of both data models, with very good results for the NDM. Our experiments show that the NDM outperforms the DMFS by orders of magnitude with respect to storage space and query run times. This is mainly caused by the much lower number of units for an *mgpoint* value compared with the number of units of the corresponding *mpoint*, which also results in smaller indexes for the NDM objects. The BerlinMOD Benchmark of the NDM pointed out that we should spend time in the improvement of the network-temporal position index and the **at** operation for *mgpoint* and *gpoint* values.

The good results of the NDM encourage us to work on an extension of the BerlinMOD Benchmark, which should enable us to compare the capabilities of different spatio-temporal NDMs with respect to the special challenges of NDM, like shortest path and fastest path computation.

Another direction of our actual work is traffic flow estimation and traffic jam representation in the NDM.

Another interesting topic for future work on the NDMs is the efficient computation of dynamic network distances between moving network objects.

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