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# Abstraction Conflicts in Industrial Deployment of Model-Based Interoperability Standards

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## Abstract

Model-based interoperability refers to a collaboration of independently developed systems based on heterogeneous semantic models in a common vocabulary and framework. *Abstraction conflicts* (differences in the choice and construction of abstractions of a real-world entity to fit a specified model vocabulary and framework) can significantly hamper interoperability when not taken into account during the design of interoperability standards.

This paper studies the impact of abstraction conflicts on model-based interoperability in an Intelligent Transportation Systems (ITS) domain. We presents results from a case study, discuss causes for such abstraction conflicts, and illustrate, by means of a specific model-based interoperability solution, possible approaches to address and overcome such model differences.

## Introduction

Many systems-of-systems configurations can be categorized as collaborative systems — systems which have an independent development cycle, mission, and purpose, yet do co-operate to achieve an increased intelligence (Maier, 2002). Collaborative systems typically co-operate through interoperability standards; in case of the internet the TCP/IP protocol is a prototypical example of such an interoperability standard which is supported by every computer. Other examples of collaborative systems are e.g. network-centric warfare (Carney 2005), and the semantic web (Uschod, 2003). In the ITS domain is a large, EU-sponsored research effort underway to improve road traffic safety with a co-operating systems concept (Jääskeläinen 2005).

Successful industrial deployment of interoperability comprises of both technical and organizational aspects. Technical interoperability capabilities did evolve over the years in e.g. information systems from addressing heterogeneity of systems I/O hardware, through syntax and structure of the data communicated, to semantics of information (Sheth, 1999).

Organizational interoperability (Clark 1999, Tolk 2003) comprises of the alignment of organizations, procedures, and objectives. This became a prevalent topic when information could be automatically exchanged, or in a defense setting, when e.g. joint coalition forces need to co-operate in UN peace-keeping operations.

These interoperability reference models have as implicit goal (i.e. their 'CMM level 5' equivalent) the complete alignment of all technical and/or organizational aspects (as if it where one 'extra-large' system).

In the consumer electronics industry, paradigms such as pervasive computing (Satyanarayanan, 2001) and ubiquitous computing (e.g. Edwards, 2001) have emerged. Interoperability there implies the interaction of loose, heterogeneous coalitions of embedded systems which are developed by independent, often competing vendors. Total alignment of objectives and technology never will be an option



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nor desired in such settings. The new challenge there is how to achieve a *sustainable, open,* and *autonomic* interoperability: robust for loose, heterogeneous coalitions; robust for unannounced market entrants; robust for independent system development and independent interpretation of interoperability standards; robust for use in embedded intelligence. In this paper we consider these issues and the challenges of model-based interoperability for large scale deployment, with insights from an industrial case study in the ITS domain.

This paper is organized as follows: First the size, complexity, and heterogeneity of models in the ITS domain is briefly explained. Then, we show the scale and impact of this heterogeneity and resulting abstraction conflicts on interoperability based on these models. Subsequently, we present the salient aspects of a model-based interoperability standard designed to overcome these issues. The paper ends with a discussion and options for future research.

## Models in the ITS domain: digital maps

The Intelligent Transportations Systems (ITS) domain is an area "driving" on large scale models. Models in this area are the so-called 'digital maps': detailed models of the road network describing *all* roads in a country or continent.

These digital maps have enabled car navigation: one of the most successful ITS systems today. Given an input destination, an in-car navigation system uses this model (the digital map) to determine the best route to drive, based on the user's actual location, to the desired destination. While driving, it provides detailed turn-by-turn directions.

These digital maps are meticulously collected and maintained by various mapping companies. The maps describe geographic locations and their relationships, and hence play a vital role in most location-based applications. The user value of car navigation depends on the completeness of the digital map coverage of the road network. For a country such a Germany a digital map contains approximately 2.5 – 3 million road segments. Moreover, ~10% of the roads of such digital maps changes every year somehow, as new roads are constructed, upgraded, renamed, speed limits changed etc. Mapping companies thus employ a large workforce to digitize new roads and check existing roads for changes.

**A model for road network.** The format and semantics of these digital maps are defined in an ISO-standard (ISO, 2004). This so-called GDF specification contains a very extensive model of the road network. Here a GDF-derived model (but much more simple) is used. This simplified model is taken from the AGORA-C interoperability standard (Hendriks, 2005). Figure 1 depicts this simple model for a road network.

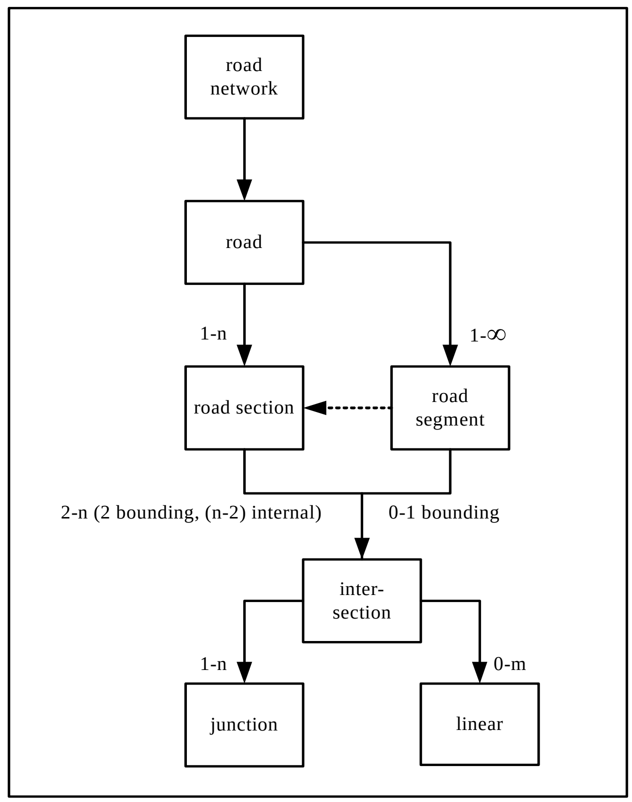


**Figure 1: Model for the physical road network**

In this model, a road network consists of roads. A road has the same name throughout and is generally considered as a whole. A road consists of road sections. Also, on a road many (in fact an indefinite number of) road segments may be defined (and referenced). A road section is a specific case of a road segment. A road section is bounded by two intersections, and may have intermediate intersections. An intersection is a connection or crossing of roads. The simplest intersection consists of just one junction (or node, in digital map terminology). Complex crossings such as motorway intersection have several junctions connected by linears: the intersection-internal roadways and link roads.

Road segments and linears have a geometric shape. Junctions have a geographic location specified as a WGS-84 co-ordinate[1].

**Table 1: Relevant attributes for the road network model**

| Attribute | Description | Value range |
|---|---|---|
| functional (road) class (FC) | Road classification based on the importance of a road or ferry connection in the connectivity of the total road network. | *Main road*<br>*First class road*<br>*Second class road*<br>*Third class road*<br>*….*<br>*Ninth class road* |
| Form-of-way (FoW) | Physical road type. | *Motorway*<br>*Multiple carriageway*<br>*Single carriageway*<br>*Roundabout circle*<br>*…..* |
| Intersection type (IT) | Type of intersection, (attribute of nodes in the road network graph) | *Freeway intersection*<br>*Roundabout*<br>*Simple crossing*<br>*….* |
| Road descriptor (RD) | Full national road number of the road, if it exists, otherwise at most five significant characters of the official name of the road. | *< zero-terminated string of characters: full road number or 3 – 5 (significant characters) for road name>* |

A subset of the attributes which are part of the road network model as shown in Figure 1 is given in Table 1, again from (Hendriks, 2005).

The functional class (FC) is a subjective indicator of the importance of the road. Typically, navigation systems use this attribute as one of the indicators whether to construct longer-distance routes over specific roads.

The form-of-way (FoW) attribute signifies the physical road layout. A road with two-way traffic on the same road surface (with a white, possibly dashed, line in between) is a single carriageway, a road with opposite traffic on separate road surfaces, separated by a median, is a multiple carriageway.

The intersection type (IT) signifies the type of intersections connecting two or more road sections. A simple crossing typically connects 2 residential roads in a 4-way junction. A freeway intersection connects e.g. two motorways.

Finally, the road descriptor (RD) already hints at interoperability issues. In the model for this interoperability standard, only a small, but significant subset of the road name is chosen. Aim of this road descriptor is to provide a locally unique substring of the road name.

# Model heterogeneity in digital road network maps

Model heterogeneity in digital maps occurs since each mapping company has its own equipment, processes, procedures, and conventions for capturing the real-world semantics of a road into the GDF model.

Goh (Goh, 1997) distinguishes the following three categories for model heterogeneity:

- **Schematic heterogeneity**, i.e. differences in model vocabularies (syntax and structure of the model)
- **Intensional heterogeneity**, i.e. differences is the universe of discourse as modeled (differences in the collection of real-world entities modeled), and
- **Semantic heterogeneity**: differences in the meaning of the information contained in the model.

In model-based interoperability (where the model vocabulary is kept constant) we are concerned with the last two categories: intensional and semantic heterogeneity.

Figure 2 shows one real-world example of model heterogeneity between maps of different vendors. The map on the left may not have a side street which is actually present in the other map (intensional heterogeneity). A road might have a different geometry or topology in the map on the right (semantic heterogeneity).

Concerning semantic heterogeneity, Goh defines three main causes — ‘conflicts’ in his terminology — affecting the information as exchanged or compared:

[1] Co-ordinate system used by the GPS satellite positioning system.

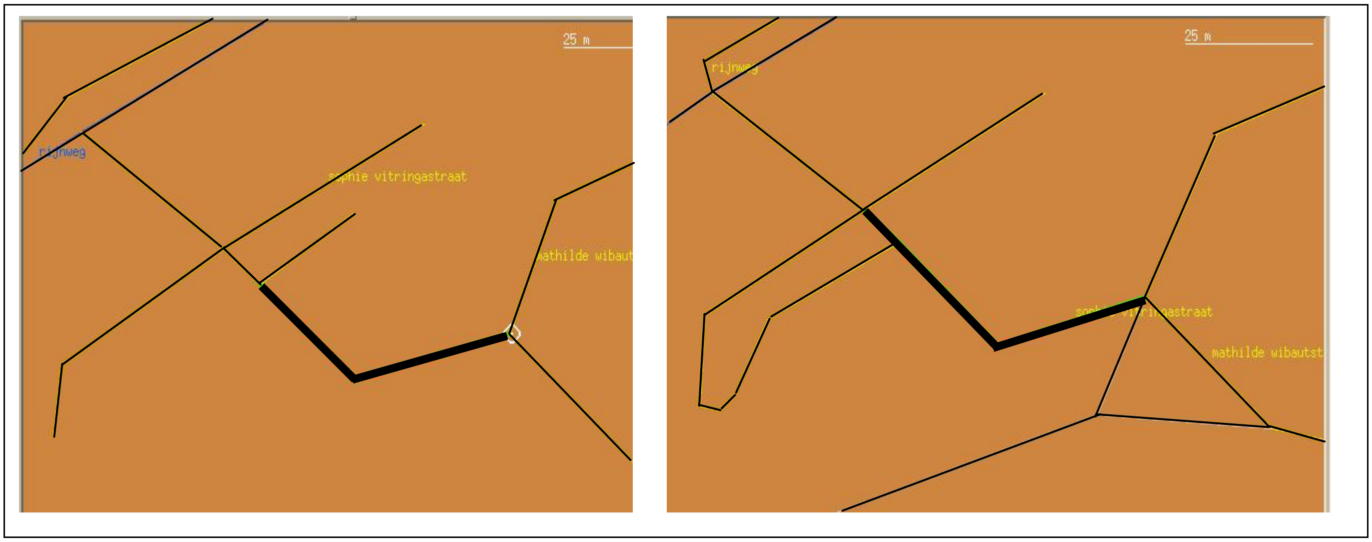


**Figure 2: An example of digital map differences (road shape, intersection topology, side-roads).**

- **Naming conflicts:** Naming schemes and conventions differ significantly (e.g. homonyms and synonyms).
- **Scaling conflicts:** different reference systems are used to measure values (e.g. metric vs. imperial units).
- **Confounding conflicts:** information items appear to have the same meaning but differ in reality due to e.g. a different temporal context (e.g. 'occurred 5 minutes ago').

Naming conflicts are widespread in digital maps: many subtle differences in road names do exist, due to choice of abbreviation (e.g. "PKY" versus "PKWY" for a parkway); due to spelling differences ("st-Goorstraat" versus "st Goorstraat"); or due to different conventions ("HWY-25" versus "RTE-25", "24$^{th}$ ST" versus "East 24$^{th}$ ST"). Scaling conflicts and confounding conflicts are absent in our case study due the definition of GDF.

**Abstraction conflicts.** Nonetheless, naming conflicts are not the only type of semantic heterogeneity observed in digital maps. Here we propose an extension of this taxonomy to capture a fourth type of semantic heterogeneity, which is defined as follows:

- **Abstraction conflicts**: Differences in the choice and construction of abstractions of a real-world entity to fit a model vocabulary and framework.

Abstraction conflicts are prevalent in digital maps. Figure 3 shows one of the commonly occurring abstraction conflicts: the modeling of a roundabout.

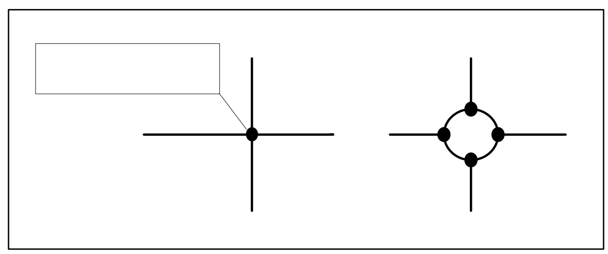

**Figure 3: Two possible representations for a roundabout.**

Roundabouts do occur with diameters ranging from zero meters (i.e. a painted circle on the junction) to extremely large ones with a diameter of hundreds of meters. The GDF model allows two forms of representation of a roundabout: as a simple intersection abstracting away the geometry (on the left in Figure 3), and as a complex intersection, representing the intersection geometry with linears with their own shape (on the right in Figure 3).

Experience shows that either model suffices for navigation through roundabouts of less than ~25 m in diameter. For map comparison and interoperability however this diversity represents a great challenge.

## Significance of abstraction conflicts in digital maps

Two of the largest mapping companies, both active in the creation of digital maps, participated in the EU AGORA project (2000-2002) (Wevers, 2003). This project had the goal to develop a model-based location referencing method, and much attention was given to the proper validation of such a method in view of actual encountered model heterogeneity in digital maps.

The AGORA project created three large test sets of locations for this validation:

- **T1: TMC location test set Germany:** sections of German Motorways between two successive Traffic Message Channel (TMC)-coded intersections: 2550 locations were compared of in total 3052 motorway locations of the TMC location table in use in 2002 (table v2.05).
- **T2: Real-world location test set Hanover:** 100 locations randomly selected from the set of road works, traffic jams and cultural events as registered by the local traffic management centre of the Hanover region between July 2000 and June 2001.
- **T3: Random location test set The Netherlands:** 1000 randomly selected locations consisting of 1 to 5 topologically connected road segments, selected in 2002 in the Netherlands. In 2004, 881 of these locations remained unchanged.

Locations in these test sets were defined on basis on 2002 versions of the maps of either vendor. These test sets were created to enable systematic validation of the proposed location referencing method as a viable model-based interoperability standard.

Here we use these test sets to analyze the type and amount of model heterogeneity and abstraction conflicts occurring between two digital maps of 'mature' areas, i.e. areas for which the compared maps were promised to be 99% complete, and otherwise 'identical in content and coverage'.

**Intensional heterogeneity.** Table 2 shows the amount of intensional heterogeneity for the three test sets. The results of the TMC location test set (Table 2, set T1) show that for these motorway locations (Functional class "Main Roads") the correspondence is very good (i.e. well over 99.5%). The few locations reported as absent were in fact mostly major reconstructions of motorway intersections, which caused displacements over several hundreds of meters.

**Table 2: Intensional heterogeneity.**

| Test set | Locations compared | Locations present in both maps | Locations (partly) absent in 2nd map |
|---|---|---|---|
| **T1** | 2550 | 2541 (99.65%) | 9 (0.35%) |
| **T2** | 100 | 95 | 5 |
| **T3** | 881 | 770 (87.4%) | 111 (12.6%) |

The results of the other two location test sets (Table 2, test sets T2 and T3) nonetheless show that significant intensional heterogeneity exists when extending the comparison of digital maps to other than motorway locations. While the size of Real-World location test set Hanover is too small to draw statistically significant conclusions, the Netherlands random location test set T3 shows that *at least 12% of the locations are not fully comparable*[2]. This disparity is not due to new road construction: these roads existed at least 2 years prior to the comparison.

In summary, this analysis shows that in mature industrial size models (i.e. digital maps where both vendors claim 99% coverage) significant intensional heterogeneity exists.

**Semantic heterogeneity.** Further to the study of comparability of digital maps, we also looked into the semantic heterogeneity of these maps. This study was limited to the locations fully present in both maps in the test sets T2 and T3 for a total of 865 locations.

For this study, we first needed to define when two locations are considered semantically heterogeneous. We based this definition on the defining geometry and attributes of a location as used in the construction of a location reference: junction

[2] Detailed analysis revealed that almost 5% of locations were fully absent, and almost 8% of locations were partly absent.

geometry, functional class, form-of-way, and road descriptors. For geometry, map vendors promise a digitizing accuracy of 95% within 10 meters. Bearing this in mind, we defined two locations to be semantically homogeneous when their defining elements in the location reference met the following four criteria:

- **Junction geometry:** Maximally 10 meter distance.
- **Functional class:** Maximally 1 class difference.
- **Road descriptor:** Exact match.
- **Form-of-way**: Exact match.

Thus, locations do not have to be identical to be semantically homogeneous. A location is considered semantically heterogeneous only when at least one significant difference exists.

**Table 3: Abstraction conflicts for comparable locations in test sets T2 and T3.**

| **Hanover Real-World and Random location test set The Netherlands**<br>Comparison of the 2004 fall versions of digital maps of two vendors | | | |
|---|---|---|---|
| **Least important Functional class** | **Locations compared** | **Semantically homogeneous** | **Semantically heterogeneous** |
| Main roads | 40 | 29 | 11 |
| First class | 23 | 13 | 10 |
| Second class | 62 | 34 | 28 |
| Third class | 81 | 58 | 23 |
| Fourth class | 659 | 497 | 162 |
| **All functional classes** | **865** | **631 (72.9%)** | **234 (27.1%)** |

Table 3 shows the result of the semantic analysis of the locations present in both maps for the test sets T2 and T3. *At least one in four locations is semantically heterogeneous*. Surprisingly this is not limited to only the least important roads: for all functional classes semantic heterogeneity does occur in significant numbers.

Breaking down this analysis even more per element compared produces Table 4. This table does not list the FC itself as this is a very subjective attribute: a weak criterion was applied with high success rate (~ 97%).

**Table 4: Detailed analysis of the origins of the semantic heterogeneity per criterion.**

| **Hanover Real-World and Random location test set The Netherlands**<br>Comparison of the 2004 fall versions of digital maps of two vendors | | | |
|---|---|---|---|
| **Least important Functional class** | **Junction geometry** | **Form-of-Way** | **Road Descriptor** |
| | **Semantically Homogenous** | **Semantically Homogenous** | **Semantically Homogenous** |
| Main roads | 85.5% | 100% | 95.2% |
| 1st class | 87.5% | 95.8% | 80.0% |
| 2nd class | 87.1% | 83.3% | 90.9% |
| 3rd class | 94.7% | 91.7% | 90.4% |
| 4th class | 93.0% | 95.4% | 94.7% |
| **All FCs** | **92.3%** | **94.4%** | **93.9%** |

Table 4 does show the average semantic homogeneity percentage per defining element. A location is considered semantically homogeneous only when all of its constituent elements are individually semantically homogeneous. A location such as a simple road section (without internal junctions) has only two bounding junctions. The average homogeneity of such a 1st class road section is thus only ~ 87.5*87.5*95.8*80.0 = 59%.

For main roads, both the form-of-way (FoW ‘motorway’) and the road descriptor (the road number) are very homogeneous. Interestingly for second class roads, a significantly lower matching rate for the form-of-way attribute is observed: e.g., a road is modeled as a single carriageway in one map and as a dual carriageway in the other map. Apparently, in this class of road importance, some medians are very small, and roads still have multiple lanes each way. Then subjective judgment prevails.

For the most important roads, motorways, the junction geometry is typically much more heterogeneous than for less important roads. For the latter, differences occur rather in road naming, form-of-way, or also road network topology. Although topology differences were not explicitly measured in this study, observation of comparable locations often revealed differences such as a single 4-way junction versus two closely spaced 3-way junctions in residential roads, to topological differences of link roads in non-standard motorway intersections.

In summary, this analysis shows that in mature industrial size databases (i.e. digital maps where both vendors claim 99% coverage) clearly *significant* abstraction conflicts do exist, *even* when a well-defined, common model vocabulary and framework (GDF) is used for years in this industry.

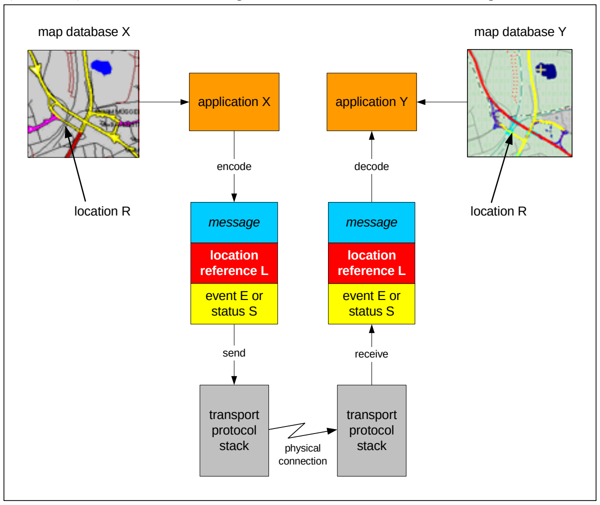


**Figure 4: The role of a location reference in an LBS application.**

## Model-Based Interoperability: Location-Based Services

In the ITS domain, Location Based Services (LBS) have spawned an important services industry providing such services as traffic telematics and tourist information (e.g. hotels, restaurants, monuments).

The typical service chain for a location based service is shown in figure 4. An application X (e.g. at a traffic telematics service provider) constructs a message about an event E or status S (e.g. a traffic problem) on a location R. The message thus contains a location reference L, derived from representation of location R in the digital map X. This message is transmitted via a protocol stack to be received by application Y, using a different digital map Y to reconstruct location R from the received location reference L.

This location reference L is thus the key customizing element. Without knowing the part of the road affected by a traffic jam, the slowdown information itself is worthless.

Location referencing demands model-based interoperability to be successful. In a market with many OEMs, service providers, mapping companies providing the models of the road network, point solutions are commercially unacceptable.

**Location referencing methods.** Two basic approaches for (interoperable) location referencing can be distinguished:

- **Pre-coding of location references**: Pre-agreed location codes are listed in a location table for inclusion in digital maps.
- **On-the-fly (or dynamic) coding:** the on-demand creation of temporary location references from a model of the location in the digital map.

Pre-coding of often used locations is done in TMC (Traffic Message Channel)[3]. This scheme has as advantage a very compact code size for transmission (CEN ISO, 2002). This method incurs large maintenance and administration costs though, and therefore is only used to code relatively few, important locations on the major parts of the road network. To date in e.g. Germany only ~ 40.000 TMC location codes are defined.

On-the-fly, model-based location coding does not have the disadvantages of the pre-coding method. Most important, the whole road network is addressable (e.g. the over 2.5 million road segments in Germany). This makes on-the-fly location referencing attractive as model-based interoperability mechanism, *but only* if it can overcome the issue of semantic heterogeneity between digital maps, *while* respecting industrial requirements (minimal bandwidth, near 100% correct location identification).

[3] This pre-coding technique is comparable to the assignment of ZIP codes to blocks of street addresses.

## Model-Based Interoperability for LBS: AGORA-C

On-the-fly location referencing looks conceptually straightforward (naively one would expect that WGS-84 co-ordinates alone would suffice). In practice, when faced with the significant model heterogeneity present in digital maps, it is not so easy to make it work.

The goal – a sufficiently high identification rate, while at the same time keeping the size of the location reference (in bytes) within acceptable limits – was set in the mid 1990's, and proved to be a difficult challenge. The EU project AGORA in 2002 was the first to achieve a 95% hit rate, but at commercially prohibitive coding sizes of on average 250 bytes. Three years of follow-on research were required to maintain this hit rate, and shrink the location reference code size to well below 50 bytes (Wevers, 2004), resulting in AGORA-C.

**The AGORA-C location referencing method.** The AGORA-C method for on-the-fly location referencing (Hendriks, 2005) explicitly acknowledges the significant presence of model heterogeneity in digital maps. From the onset on, the reconstruction of a location on a second map was considered as a 'matching' problem. Unique to AGORA-C is that this method employs not just one single matching technique, but rather three complementary options: (1) shape geometry, (2) road section typing (form-of-way, road descriptor, functional class, and driving direction) and (3) topological connectivity. The redundancy in matching options turned out to be very useful. A source of information could be used either for matching and obtaining candidate locations (to overcome semantic heterogeneity), or for confirmation or rejection of candidate locations (to overcome intensional heterogeneity). The test sets, as described before, were extensively used to verify the efficacy of the design.

In the end, the AGORA-C interoperability method consists of the following elements:

1. The AGORA-C encoding framework including the building blocks and a list of allowed attributes;
2. The AGORA-C logical data model; A flexible and efficient set of elements that succinctly model the location to be coded;
3. The AGORA-C encoding rules prescribing minimum (i.e. lower bound) requirements on a location reference constructed by an encoder (typically at a service provider);
4. A detailed description of the AGORA-C reference physical format;
5. Guidelines for an (en) coding procedure.

The encoding procedure is based on the encoding rules, and may be used as a guideline to develop an encoding algorithm. In addition to the defined highly efficient bit-oriented physical format for in-vehicle applications, other physical formats may be defined, as long as these represent the defined encoding rules.

Key objective in the AGORA-C method and specification is to permit an encoder flexibility in the choice and location of "anchoring" points, that is, the points were first contact is made with the second map. Prior methods required such points to be exactly located on a possibly complex intersection: locations where many road sections cross or run in parallel, and where much confusion can arise.

**AGORA-C: appraisal as a model-based interoperability interface.** The development of the AGORA-C method denoted a major step forward in on-the-fly location referencing. The results are sufficient for commercial use. The average hit rate is ~98 % or better. On motorways, the hit rate is near 100%. Code size is kept well below 50 bytes.

Key success factors in the AGORA-C development and method are the following:

- An explicit acknowledgement of model heterogeneity;
- An explicit semantic model of the entities to be interoperable;

- A specification containing a lower bound of requirements and a flexible, extensible, model vocabulary;
- Robustness through a three-fold redundancy in matching techniques;
- Large scale, representative testing across all types of entities to be modeled;
- A community of experienced practitioners in the field of digital maps with a multi-year collaboration history.

AGORA-C was designed to overcome abstraction conflicts. This support for multiple conceptualizations, i.e. *semantic relativism* (Saltor, 1993), has come at a price though. AGORA-C is not a clear-cut, detailed recipe, nor a programming language (API) interface specification. Rather, AGORA-C is a semantic level specification, where implementations of both a location encoding as a location decoding system have a lot of freedom *and* responsibility to ensure proper use.

In the case of location referencing, approaches to create a straightforward 'one-size-fits-all' recipe have failed (Wevers, 2006). They proved not feasible simply because the real-world semantics of road networks does not follow a 'one-size-fits-all' recipe either.

We view this as an omen: when exchanging information about 'common-sense' or 'every-day' objects for e.g. pervasive computing, clear-cut 'one-size-fits-all' recipes become brittle in face of the unavoidable semantic and intensional heterogeneity. Key question becomes what then is needed to specify, implement, and manage such information exchange to the benefit of their senders and receivers.

## Discussion & future research

In this paper, we have shown the significance of model heterogeneity and, in particular, abstraction conflicts in industrial deployment of model-based interoperable systems. Even when well-defined models are present, still the construction of real-world semantics is not guaranteed to be unique. We have demonstrated that in domains with sufficiently rich semantics, the optimization of semantic relativism is useful to achieve model-based interoperability.

We observe that very little attention is given in literature to the impact of independent model construction on model-based interoperability. However, co-operative cars, ambient intelligence, the smart home, and the digital assistant are but a few applications under consideration requiring such autonomic, model-based interoperability.

In future research, we plan to study the impact of independent construction of models with 'real world' semantics on machine interoperability. Specifically, we would like to understand the following issues:

- The influence of (sensor-based) abstractions of reality onto abstraction conflicts and model heterogeneity.
- The influence of purpose, process, and context of model construction and variations on likelihood of abstraction conflicts and model heterogeneity.
- The influence of inter-company communities of practice on the technical success of interoperating systems.

With these insights, we plan to study necessary boundary conditions on model-based interoperability interfaces and associated assessment techniques to ensure a system — once deployed — of a *sustained* effective and robust interoperation capability in a *heterogeneous* and *evolving* environment.

## Acknowledgements

Teun Hendriks was employed by Siemens VDO while performing the design of the AGORA-C location referencing method.

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## Biography

Teun Hendriks is currently a Research Fellow at the Embedded Systems Institute with a focus on interoperability and user-perceived reliability in systems engineering context. Prior to joining ESI in 2005, he was employed at Siemens VDO from 1996 onwards where he was responsible for Advanced Development Navigation and participated in EU-funded projects such as MAPS&ADAS, ACTMAP, and the AGORA project as described here.

Kees Wevers works with NAVTEQ since 1992, and is expert in digital maps, their application in navigation and ADAS systems, and in location referencing. He was chair of the ERTICO Committee on Location Referencing 1995-1997, chair of WG 5 of ISO/TC 211 from 1996-1999, member of the TMC Forum Management Group 2001-2006, and is chair of its Location Referencing Business Group since 2001. He was/is involved, on behalf of NAVTEQ, in several EU-funded projects: e.g. EVIDENCE, IN-ARTE, AGORA, SpeedAlert, MAPS&ADAS.