TECHNISCHE UNIVERSITÄT MÜNCHEN
Lehrstuhl für Kartographie

Generalization of Road Network for an Embedded Car Navigation System

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Vollständiger Abdruck der von der Fakultät für Bauingenieur-und Vermessungswesen der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigten Dissertation.

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Die Dissertation wurde am 30.03.2011 bei der Technischen Universität München eingereicht und durch die Fakultät für Bauingenieur-und Vermessungswesen am 10.06.2011 angenommen.

Abstract

Automatic or semi-automatic map generalization tools generally aim to reduce the digital data amount and ensure the legibility of small-scale maps. With the enrichment of the digital mapping databases and their diversified applications, map users increasingly demand a combination of graphical attractiveness and a correct functionality, thus the development of specific automatic generalization tools. This thesis deals with the automatic selection of roads for both visualization and route planning in an embedded car navigation system.

Embedded mobile services are different from stationary desktop services. Due to their limited hardware resources such as storage capacity, computing power and time-critical applications, their underlying car navigation database must be carefully and efficiently organized. Based on an in-depth analysis of the prevailing binary KIWI format and its rationale behind a dual road network for display and route planning, the author came across the idea of establishing a multi-level dataset for map display and a multi-layer dataset for route-planning algorithms. Both datasets are integrated in the process of car navigation data authoring.

The currently available commercial geographic datasets not only reveal the continuously improved completeness of spatial information but also contain an increasing amount of aspatial information and a large number of semantic attributes incl. various classifications and complete traffic regulations. All this available information is useful in a certain way for the generalization of road network. The "selection of road" is identified as the most crucial generalization operator for the development of an embedded car navigation data system. It leads to a simplified road network which can more efficiently serve the car navigation purposes.

The navigational functions largely affect the car navigation data authoring and the subsequent simplification of road network by means of selection of necessary roads and elimination of needless roads. The selection or elimination should satisfy a number of constraints. First, in order to guarantee the correctness of vehicle positioning, road matching and route guidance, the coordinates of nodes and construction points along the individual road links and the topology of the overall road network must be preserved. Second, route-planning algorithms typically require a bi-directional connectivity for traffic flows in each layer of a hierarchical road network. Third, accelerating route-planning algorithms that are based on a vertically partitioned road network for efficient path searching require a reasonable spatial distribution of roads on the highest layer.

Keeping in mind the special constraints for navigational functions and the usual constraints for map display, the author developed five selection strategies that are respectively driven by individual attributes, road priority, "connection link", important cities and OPCV algorithm. These strategies help to build up multiple levels for visualization and multiple layers for optimal route planning in an embedded car navigation system. The two hierarchies are connected with each other through the underlying road links and nodes.

On the basis of the selection strategies, the author developed an engineering approach for the generalization of road network and implemented it with large-region test data from Germany and China for long-distance routing. The test results show a sufficient legibility of the map display and a reasonable distribution of road networks for route planning. Thus, the feasibility and usability of the approach is verified.

Zusammenfassung

Automatische sowie halbautomatische Kartengeneralisierungstools werden im Allgemeinen zur Reduzierung der digitalen Datenmenge und zur Sicherstellung der Lesbarkeit von kleinmaßstäbigen Karten verwendet. Mit der Anreicherung digitaler Mapping-Datenbanken und deren diversen Applikationen, verlangen Kartennutzer zunehmend eine Kombination aus graphischer Attraktivität und einwandfreier Funktionalität, die die Entwicklung von spezifischen automatisierten Generalisierungstools erfordert. Diese Arbeit beschäftigt sich mit der automatischen Selektion der Straßen für Visualisierung und Routenplanung in einem integrierten Fahrzeugnavigationssystem.

Integrierte mobile Dienste unterscheiden sich von stationären Desktop Services. Aufgrund ihrer begrenzten Hardwareressourcen wie Speicherkapazität, Rechenleistung und zeitkritische Anwendungen, muss die zugrunde liegende Fahrzeugnavigationsdatenbank sorgfältig und effizient organisiert werden. Basierend auf einer detaillierten Analyse des gängigen binären KIWI Formats und dessen Grundprinzip eines dualen Straßennetzes für Darstellung und Routenplanung, wird der Ansatz verfolgt, ein Multi-Level-Datensatz für die Kartendarstellung und ein Multi-Layer-Datensatz für Routenplanungsalgorithmen zu etablieren. Beide Datensätze werden integriert im Prozess der Fahrzeugnavigationsdaten-Authoring.

Derzeit verfügbare kommerzielle Geodatensätze zeigen nicht nur die ständig verbesserte Vollständigkeit der räumlichen Informationen, sondern enthalten auch eine zunehmende Menge an nichträumlichen Informationen und eine große Anzahl von semantischen Attributen inkl. verschiedener Klassifikationen und vollständige Verkehrsvorschriften. All diese verfügbaren Informationen sind, in bestimmter Weise, nützlich für die Generalisierung des Straßennetzes. Hierbei wird die Selektion als entscheidender Generalisierungsoperator für die Entwicklung eines integrierten Fahrzeugnavigationssystems identifiziert. Es führt zu einem vereinfachten Straßennetz, dass Fahrzeugnavigations-Anwendungen effizienter gestaltet.

Die Navigationsoperationen beeinflussen im hohen Maße das Fahrzeugnavigationsdaten-Authoring und die anschließende Vereinfachung des Straßennetzes durch Auswahl der wichtigen Straßen und Eliminierung unnötiger Straßen. Die Selektion sowie die Eliminierung sollten eine Reihe von Bedingungen erfüllen. Erstens, die Koordinaten der Knoten und Konstruktionspunkte entlang individueller Kanten und die Topologie des gesamten Straßennetzes müssen erhalten bleiben, um die Richtigkeit der Lage, des Map-Matching, und der Wegführung zu gewährleisten. Zweitens, Routenplanungsalgorithmen erfordern typischerweise eine bidirektionale Konnektivität für Verkehrsströme in jeder Ordnung eines hierarchischen Straßennetzes. Drittens, die beschleunigenden Routenplanungsalgorithmen, die mit einem hierarchisch geordneten Straßennetz eine effiziente Wegfindung generieren, erfordern eine angemessene räumliche Verteilung der Straßen hoher Ordnung.

Unter Berücksichtigung der besonderen Randbedingungen für Navigationsoperationen und den üblichen Bedingungen der Kartendarstellung, wurden in dieser Arbeit fünf Selektionsstrategien entwickelt, die jeweils durch Straßenattributen, Straßenpriorität, „Connection Link“, wichtige Städte und OPCV-Algorithmen gesteuert werden. Diese Strategien helfen multiple Levels für die Visualisierung und multiple Layer für die optimale Routenplanung in einem integrierten Fahrzeugnavigationssystem zu erzeugen. Die beiden Hierarchien sind über die zugrunde liegenden Knoten und Kanten des Straßennetzes miteinander verbunden.

Auf Grundlage der Selektionsstrategien, wurde in dieser Arbeit ein technischer Ansatz für die Generalisierung von Straßennetzen entwickelt und mit Testdaten großer Regionen aus Deutschland und China für Langstreckenrouting implementiert. Die Testergebnisse zeigen eine angemessene räumliche Verteilung der Straßen hoher Ordnung und eine angemessene Lesbarkeit der Kartendarstellung. Demzufolge wird die Machbarkeit und Bedienbarkeit des Ansatzes bestätigt.

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Chapter 1

Introduction

1.1 Motivation

Automatic map generalization has made great progresses for more than four decades. It serves to reduce the amount of data, speed up the mapping process or ensure the legibility of small scale maps. With the enrichment of the digital mapping databases and their diversified applications, map users increasingly demand a combination of graphical attractiveness and a correct functionality, thus the development of specific automatic generalization tools.

This thesis deals with the automatic generalization of road network for both visualization and navigation functions, such as vehicle positioning, road matching on map, route planning and guiding, in an embedded car navigation system. The navigational functionality in the real world is coupled with a number of special generalization constraints which require new strategies.

In order to guarantee the correctness of vehicle positioning, road matching and route guidance, the coordinates of nodes and construction points along the individual road links and the topology of the overall road network must be preserved. This requirement, however, is not sufficiently considered in existing map generalization methods driven by spatial constraints. For example, Figure 1.1 demonstrates the results of two generalization operators - selection and collapse. Two maneuver links in Figure 1.1a are omitted due to their short length, and a typical roundabout pattern in Figure 1.1c is collapsed into a point intersected by two single carriageways. Apparently the roads in Figure 1.1b,d do not allow the car navigation systems to provide adequate route guidance based on the changed traffic flows and road patterns.

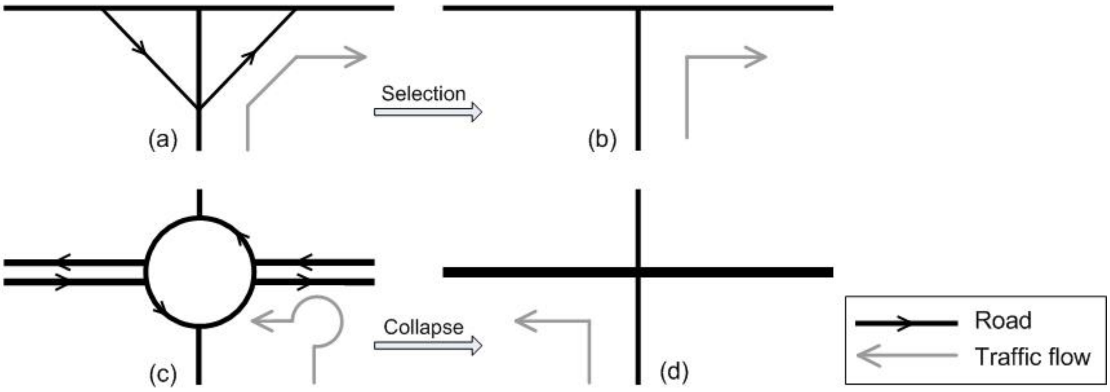


Figure 1.1 Problems with conventional generalization operators

(a)(b) Selections of roads; (c)(d) Collapse of roads.

The connectivity for traffic flows in each layer of a hierarchical road network is required to support the correct performance of route-planning algorithms. Figure 1.2 indicates another typical problem caused by the existing selection operator that two crisscross roads in grade separation can no longer reach each other because the traffic flows from single carriageway to dual carriageway become invalid after all ramps and a U-turn are eliminated. In this case, traffic regulations should be used to confirm bi-directional connectivity for route planning. However, it is no trivial task to recognize various connection links, such as ramps and maneuver links, and decide which of them should be selected.

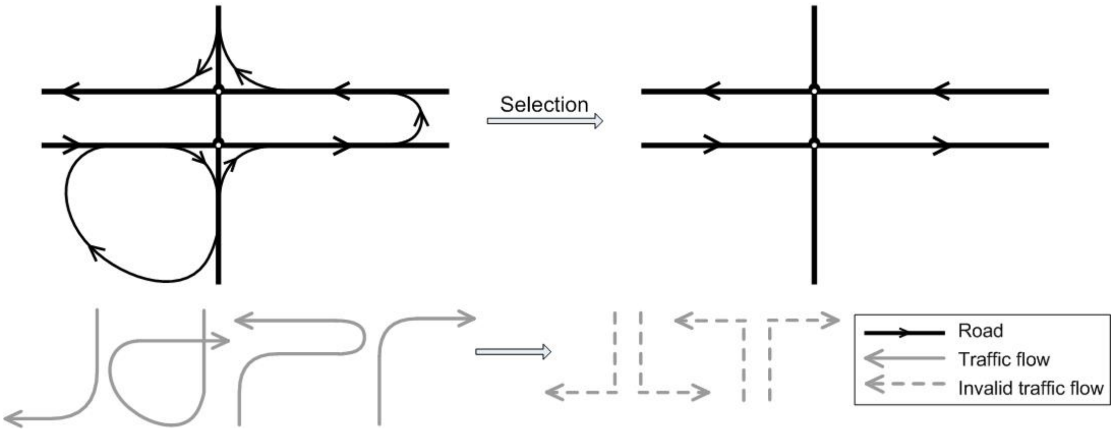


Figure 1.2 Connection problems

Even if a road network has a good connectivity, it may still miss significant links along some optimal routes. Figure 1.3a demonstrates such a well-connected road network which is exclusively composed of superior roads above certain importance degree. The route in red will be identified as the optimal route with shortest time by an accelerating route-planning algorithm. In the reality, however, there exists a true optimal route marked in green in Figure 1.3b. The difference between the red one and the green one is characterized by a decisive shortcut which may be an inferior road in blue. If this decisive path is included in Figure 1.3a, the optimal route can be automatically detected. The task to detect decisive paths among a large number of inferior roads and add them to the layer of superior roads is computationally challenging and necessitates an efficient algorithm.

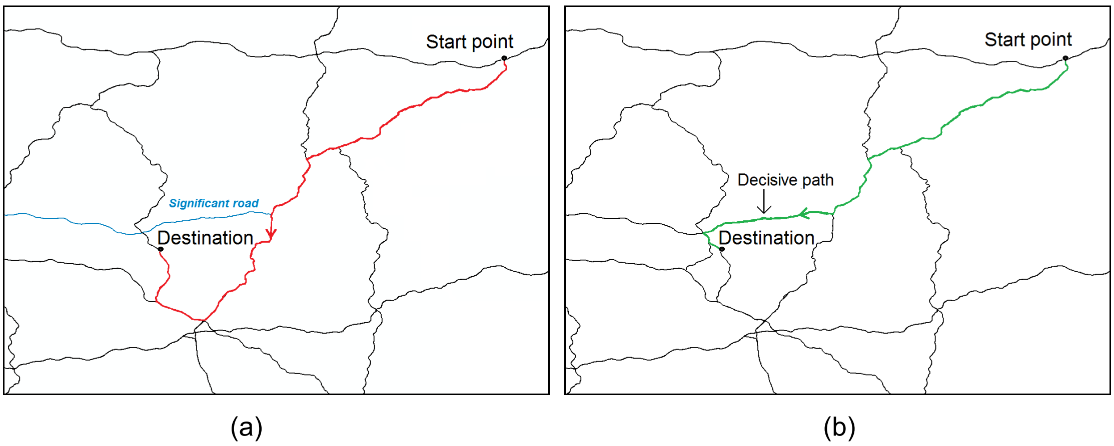


Figure 1.3 Routes found on two differently road networks

(a) A suboptimal route in red when a decisive path in blue is missing;

(b) An optimal route in green in the reality.

Besides the deficiencies related to navigation functions, there are also a number of bottlenecks related to map display at smaller scales for which only the important roads should be visualized because the display space cannot accommodate too many details. However, if the selection of roads is merely dependent on their relative importance in terms of functional classes, administrative levels, widths etc., the results may contain some unacceptable artifacts. As shown in Figure 1.4a, the road network in southern Germany and western Austria after selection operation becomes disconnected in many places including the border region, while Figure 1.4b reveals an unbalanced distribution of the selected roads in Northeast China and the reader might get the impression as if the north part of the region were uncultivated, although in the reality there is a well-developed traffic infrastructure.

This thesis is focused on the refinement as well as extension of existing selection methods and development of new strategies to close the aforementioned research gaps. An engineering approach of generalization is anticipated which should allow the construction of a reasonable hierarchical road network for both map display and car navigation services.

(a) (b)

Figure 1.4 Unacceptable results of selection based on insufficient governing information
(a) Disconnected road network in southern Germany and western Austria;
(b) Shrewd density distribution of selected roads in Northeast China.

1.2 Goal

This thesis strives for the effective semantic generalization of road network for both a good display and optimal route planning for an embedded car navigation system. It involves the following four research tasks:

1) Comprehend the characteristics of navigational road-network generalization by analyzing the road-network organization in car navigation data. Car navigation data in currently available embedded systems is composed of two sets of road networks: multi-level road network for display and multi-layer road network for route planning. The same road network is visualized at a suitable map scale and the corresponding abstraction layer that supports the optimal route planning. The authoring process of navigation data involves essentially the model generalization which has to satisfy a number of semantic generalization constraints related to navigational functions.

2) Interpret the available information embedded in road networks with particular attention to navigational requirements. All information describing a road network including implicit clue will be analyzed and classified. Moreover, the relative usage and importance of various semantic attributes will be reflected in the individual generalization methods.

3) Propose combinational generalization strategies to solve the existing problems with focus on selection as the essential operator. Based on the rich information in currently available navigation datasets, we improve two methods of road selection by individual attributes and road priority. Connection links are classified and recognized to support the method of road selection by connection link, which can ensure the connectivity of road network. Furthermore, important cities related to a test area are used as anchors to efficiently identify the arterial roads, thus construct a high-layer road network with guaranteed connectivity. Finally, we propose a specific method of road selection with the help of "optimal path comparison and validation algorithm" (OPCV algorithm), which can lead to the refinement of the high-layer road network for the searching of optimal long-distance routes in it.

4) Implement an engineering approach on the basis of the combinational selection strategies

to construct hierarchical road networks in car navigation data authoring and verify their reasonability with large-region test data.

1.3 Outline

Figure 1.5 shows the related technology, main contents and structure of the thesis.

Three dashed boxes represent three disciplines - cartography, navigation and transportation network that are touched by the research topic on generalization of road network in car navigation data authoring. The solid boxes with chapter numbers and locations indicate the scope and relationships between the individual chapters.

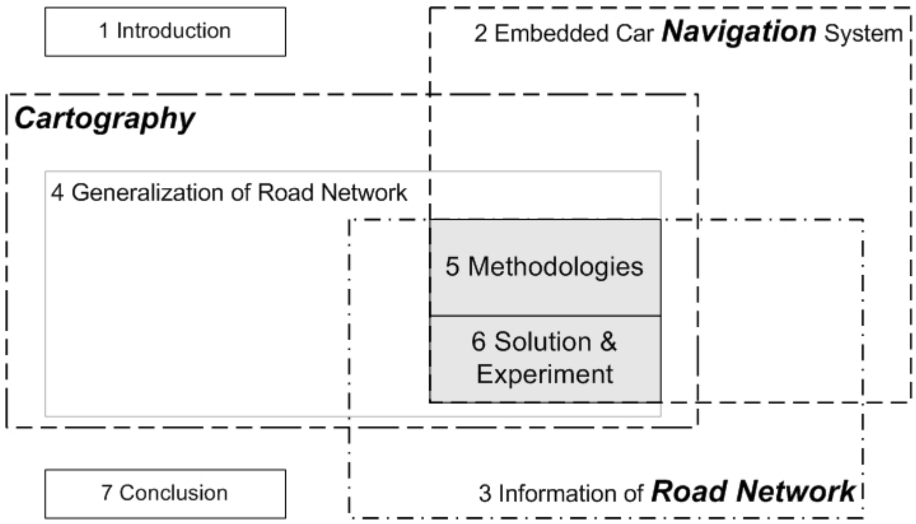


Figure 1.5 Structure of the thesis and relationships between individual chapters across different disciplines

Chapter 2

Embedded Car Navigation System

An embedded system is a computer system designed to perform one or a few dedicated functions usually with real-time computing constraints (Heath 2003; Michael 2007). It is embedded as part of a complete device including hardware and mechanical parts (Michael & Anthony 2006). By contrast, a flexible personal computer is designed to meet a wide range of end-user needs and to be independently used. Embedded systems share the following 5 common characteristics: (1) specific tasks, (2) embeddable parts, (3) real-time functions, (4) reliability, and (5) low cost and focused performance.

A car navigation system is a typical embedded system as a subsystem of the overall vehicle to provide the optimal path and guide drivers to an expected destination from the current location. Virtually all the automatic transport vehicles by air, land and water must satisfy the high demand on safety, reliability and usability. The corresponding equipments and subsystems must adhere to the same principles. A car navigation system is no exception and it requires a real-time operation system (OS), robust hardware, and software support tailored for special customers. Furthermore as it is a commercial product, its market acceptance strongly relies how far its cost can be kept low for the required quality. Therefore, the minimum indispensable hardware resource is usually adopted as a solution for mass production.

An embedded car navigation system specifically refers to an on-board (also called in-dash) system which is neither a portable navigation device nor desktop navigation software. Instead, it is a mature product with high quality, stability and safety assured by the embedded navigation hardware, software and data. The configuration of navigation hardware is introduced in section 2.1, while Section 2.2 is dedicated to general functions of navigation software. The route-planning algorithm is overviewed here because it is not only the core algorithm in navigation software, but also a component of generalization methods handled in this thesis. Section 2.3 elicits the standard format, content, characteristics of organization, and authoring of embedded car navigation data in detail.

As a whole, the limited hardware resource of an embedded system requires the special organization of navigation data, where the multi-level road network in map display data and multi-layer road network in route-planning data should be converted from a source dataset by means of generalization. In order to satisfy constraints for navigation purposes, generalization of road network in car navigation data authoring system reveals some new characteristics that do not exist in traditional digital maps.

2.1 Hardware

As Ganssle et al. (2007) mentioned, “In embedded devices, all the electronics hardware resides on a board. The electrical path of circuit is printed in copper, which carries the electrical signals between the various components connected on the board.” All electronic components are connected to this board and thus making up the circuit. All hardware components on an embedded board are located in the hardware layer of the typical embedded system model as shown in Figure 2.1.

The major hardware components can be classified into five major categories: CPU; memory where the system software is stored; input devices; output devices; data pathways or buses. The system software layer includes an embedded OS and/or hardware drivers which enable the applications from the application software layer to run and operate the components.

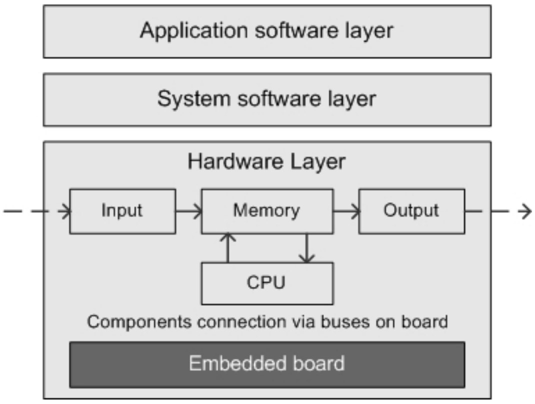


Figure 2.1 A typical embedded system model

A car navigation system is an extension of the general embedded system model with some more complex components. It contains four functional blocks as shown in Figure 2.2. The mainframe consists of navigation data, navigation software, embedded OS and/or drivers, as well as necessary hardware components such as embedded board, CPU and memory. Signal receivers are input devices that gather all useful information including coordinates from GPS receivers, angular velocity and angular acceleration from gyroscope for inertial navigation, real-time speed from speedometer and traffic information from traffic message channel[1] (TMC). Human-machine interfaces (HMI) are terminals with which drivers interact in order to control the navigation unit. In HMI devices, hard button and remote control are also input devices that send operating instructions. Audio or speaker outputs voice information; meanwhile the LCD renders maps and navigation information. Furthermore the LCD touchpad can input operating instructions as an input device. Communication devices keep the connection with networks outside of the navigation system. Both input and output take place within the vehicle. Vehicle buses allow the above three parts to communicate with each other. Sometimes GPS receivers, gyroscope, hard button, remote control, LCD touchpad, audio or speaker are integrated in the mainframe and interconnect with the embedded main board so that their data can be transferred via pathways or buses in the main hardware.

All hardware components and embedded OS are more or less mature and comply with vehicle standards regulations, therefore not much difference can be found between the various solutions of hardware structure and OS configuration.

The quality of navigation software and data plays a decisive role in the performance of a navigation product. In addition, navigation software and data within the limited hardware resource are getting more and more complex for users.

[1] http://www.tisa.org/technologies/tmc/

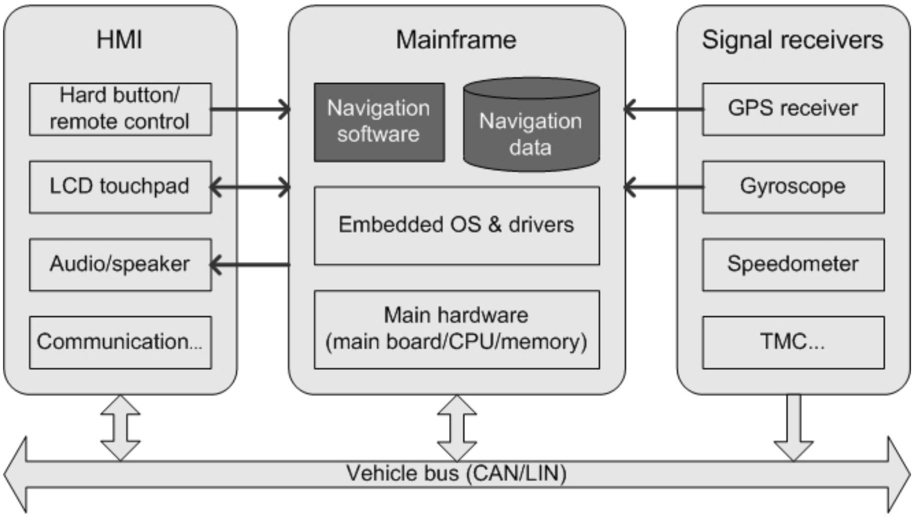


Figure 2.2 Car navigation system structure

2.2 Software

The software of an embedded car navigation system is a type of application software running on an embedded hardware platform and responsible for the realization of all general navigation functions. Firstly it receives and processes positioning signal such as GPS coordinates, angular information from gyroscope, vehicle signal such as speed, light, turn, turning directions and real-time traffic information. Then it reads the relevant navigation data. After setting a destination by a point of interest (POI) or on the map, it searches an optimal route or several routes that satisfy special conditions. Finally it guides drivers correctly, safely, quickly and comfortably to the destination by means of enlarged view, indicating arrows, detailed annotations in combination with voice prompts.

With the growing user demand, navigation systems tend to integrate more and more extended services. Vehicle information display, media player (DVD/MP3/Radio/TV), Bluetooth telephone, security alert etc. can be added in the in-dash navigation unit which is also termed as before-market navigation unit. In the meantime, portable navigation devices such as personal digital assistants (PDAs), mobile phones and iPhone are typically extended with games, internet applications and media player (MP3/Radio/TV).

Some general functions of the navigation software are listed in Table 2.1 in which map display algorithms, combined algorithms for vehicle positioning and road matching, and route-planning algorithms count as the core functions. Map display algorithms are responsible for map texturing and rendering, text placement without overlapping, anti-aliasing, transformation of map perspective (2D/3D/birdview) and certain dynamic cartographic generalization. The operators of cartographic generalization implemented here include enlargement, displacement, exaggeration, smoothing, collapse, and so on. The anti-aliasing algorithm as a smoothing method is coupled with another generalization operator - simplification which leads to reduced number of intermediate points along a line. The conventional line drawing algorithms typically create serrated edge or stairway effect on diagonal line segments, thus influence the graphic quality on the LCD. Using an anti-aliasing algorithm, such as the Wu algorithm and sub-pixel algorithm, the problem can be efficiently resolved.

Table 2.1 General functions of navigation software

Module	Item	Content or comment
Map display	Basic elements	Road network / background
	Notes	Street name / house number / background
	Landmark icon	2D / 3D
	Color schemes	Day / night / auto to illumination
	Map scale	Range / change step / free scale
	View mode	2D / 2.5D / 3D / bird view
	Dual view mode	Display for guidance and menu
	Map direction	North / head up
	Time display	Local time
	Map scrolling	Use hard button / touch panel
	Language	Multi-language in menu and map
	Track	Record for return routes
Set destination	Map	Set on the map directly
	POI	Search by name or keyword
		Search by category
		Search by telephone number
	Address	Search by street name, house number or zip code
	Nearby	Search by nearby locations
	Favorites user defined	Home / company / university / stadiums …
	History destination	Recently used location
Route calculation	Strategy	Shortest distance
		Shortest time
		Most economical
		Highway priority
	Route edit	Set and change waypoints and strategy
	Reroute automatically	After deviated from existing route
Route guidance	Whole route display	From start point to destination
	Turn information	Turn list and turn by turn
		Turn arrow guidance
		Signpost
	Detailed information	Lane guidance
		SA/PA by highway
		Enlarged junction and schematic intersection
	Distance and time	Distance to turn and time of arrival
	Voice guidance	Turn / distance / time /… Language setting
Others	General set	Resolution
	Input control	Hard button / touchpad / remote control
	Positioning	GPS / dead reckoning by gyroscope
	Vehicle signal process	Illume / speed / break / reverse

For vehicle positioning, coordinates on ground can be directly obtained from GPS receivers. On certain occasions, however, no GPS signals can penetrate through a tunnel or under an overhead. Moreover, the precision of GPS coordinates is usually at a low civil level (10 meters) and strong signal interference may occur near high buildings or in valleys. In an in-dash car navigation system, therefore, dead reckoning is additionally deployed to estimate the current position and real-time speed based on a previously determined position and movement speed over elapsed time intervals calculated with an integral operation based on the angular velocity and angular acceleration of gyroscope. By applying a filtering algorithm such as Kalman filter (Kalman 1960), all position and speed information from GPS receivers, gyroscope and the speedometer is processed so as to remove random and systematic errors and return more precise locations. Since roads are digitized as vector lines (not areas), it could happen that a returned position does not locate on a vector line. In this case, curve-fitting, curvature-matching and pattern-recognition algorithms are used to snatch the position and fit it on a vector line. The positioning algorithm and road-matching algorithm operate in coordination within a road network. For instance, the roads and the movement traces of a vehicle can be matched up by comparing the prevailing directions of roads with the moving directions at the estimated positions. The positions are then timely corrected at intersections or junctions.

The route-planning algorithm has the task to find the optimal path from current location to an expected destination according to a route-planning strategy. The algorithm is derived from the shortest path problem in graph theory, which has been investigated since half a century. The classic shortest-path-finding algorithms were discussed by Ford (1956), Bellman (1958) and Dijkstra (1959). The Bellman-Ford algorithm and Dijkstra algorithm have laid the foundation for the subsequent theoretical work. In the practice, a lot of effort has been directed to speed-up techniques which are classified into three types: goal-directed search (e.g. A* algorithm (Hart et al. 1968) and an in-depth investigation (Dechter & Pearl 1985)), bidirectional search (Lenie & Dennis De 1977; Dennis De 1983; Luby & Ragde 1989; Hermann & Gerhard 1997) and network partitioning (Huang et al. 1996; Jing et al. 1998; Berry & Goldberg 1999; Jagadeesh et al. 2002; Holzer 2003; Möhring et al. 2006; Geisberger et al. 2008). The route-planning algorithms in a navigation system can be integrated with one other to obtain additional computational efficiency. Extensive studies with this regard were conducted by Vitter et al. (1999), Jagadeesh et al. (2002), Reinhard et al. (2010), Pijls & Post (2006) and Nannicini et al. (2008). On the other hand, as a commercial product, a car navigation system should always assure the support for an optimal route. This can be reached by improving data structures used for a large mobility area such as a whole continent where it is particularly challenging to build up a hierarchical navigational road network that allows vertical network partitioning of route-planning algorithms.

2.3 Data

Car navigation data is the most important element that influences the quality of navigation services provided by embedded systems that have nearly the same configuration of hardware and software. Therefore, market sector is striving for the constant improvement of quality and coverage of up-to-date navigation data.

Car navigation data for motor or embedded mobile services is quite different from the navigation database for desktop applications and must be specially organized because of the limited resource available in the navigation hardware. Section 2.3.1 introduces the two standard formats of car navigation data: the Physical Storage Formats (PSF) of KIWI[2] and Shared Data

[2] http://www.kiwi-w.org/index_eng.html

Access Library (SDAL[3]). Here Geographic Data Files[4] (GDF) is also discussed, which it is an exchange format rather than a standard format. Using the PSF of KIWI as an example, Section 2.3.2 describes the contents of navigation data, and Section 2.3.3 explains the characteristics in comparison with the data formats of ArcGIS[5], MapInfo[6] and GDF. The nature of road-network generalization for navigation purposes is analyzed in line with the need to build up a reasonable hierarchy of road data for the optimal path-finding algorithm. Furthermore, it is a key step of navigation data authoring as described in Section 2.3.4.

2.3.1 Standard format

Currently, two standard formats of car navigation data are prevailing: the Physical Storage Formats (PSF) of KIWI (the latest version 1.22) and SDAL (the latest version 1.7). Nearly all navigation engine suppliers or navigation system integrators adopt these two formats, or extended formats similar to them in terms of the structure and contents. KNF (KOTEI[7] navigation format), for instance, is derived from KIWI. CARiN Database Format[8] (CDF) is a proprietary navigation map format created by Philips Automotive Systems which was sold to Siemens VDO and used in the VDO navigation system itself. It is not a standard format.

KIWI was sponsored by WG3, a working group of SC 34, which itself is a subcommittee of Joint Technical Committee 1 of the ISO and IEC, for a standardization of navigation disk format in 1995, and then 17 companies related to car navigation systems in Japan participated in the KIWI committee and started to research it. KIWI Ver1.0 was completed based on X-format (copyright of former XANAVI Company) in 1997 and the most recent edition of it is KIWI Ver1.22 which has incorporated the requirement from EU and USA. The standardization of Physical Storage Format (PSF) for car navigation systems has been argued in ISO TC204/WG3 and is an open specification. Kiwi-W consortium was taken up by the navigation related companies in Japan and started in 2001 as an organization for promoting standardization of map disc for car navigation systems. Most navigation systems from Eastern Asia use KIWI format or the same structure of KIWI format.

SDAL was publicly released in 1999 by NA, a dominating data supplier who focuses on the support and solutions of detailed street-level navigation data. SDAL Format is also an open commercial standard and provides a shared, common PSF in which data is arranged on map media which is clean and code-free, allowing compatibility without the logistical hazards of carrying and maintaining unique data access libraries (DAL) to work with each manufacturer's ever-changing proprietary platform. Moreover Navteq provides an SDAL compiler that translates map data and value-added data into an SDAL-compliant media format. Most navigation systems from North America and Europe use SDAL format and the solution.

Claussen et al. (1989) and Liu et al. (2005) considered GDF to be a standard navigation format because it was used in many navigation systems on desktop or large servers. In fact, the GDF is quite different in terms of the PSF. Being a flat plain text ASCII file and multi-layered organization in accordance with the coordinates, features, objects, attributes and relationships; GDF is not intended to be directly used for any large-scale geographic application. Instead, it is a general data format without any touch with navigation hardware and software. For this reason, GDF is better regarded as an interchange format and requires authoring into a more

[3] http://www.navteq.com/sdalformat/index.html

[4] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=30763

[5] http://www.esri.com/products/index.html

[6] http://www.pbinsight.com/welcome/mapinfo/

[7] http://www.kotei-navi.com.cn/

[8] http://www.yourautonetwork.com/gps_systems.html

efficient format. Section 2.3.3 will discuss the differences between GDF and navigation data format in detail.

The PSF of both KIWI and SDAL reveals the similar structure, contents, functions and characteristics. The difference lies in index sequence and syntactic relation of data blocks. So the organization and characteristics of navigation data is discussed taking the PSF of KIWI as an example.

2.3.2 Content

As shown in Figure 2.3, Car navigation data is composed of three main building blocks - map display data, route-planning data and positional reference data - and many extended contents.

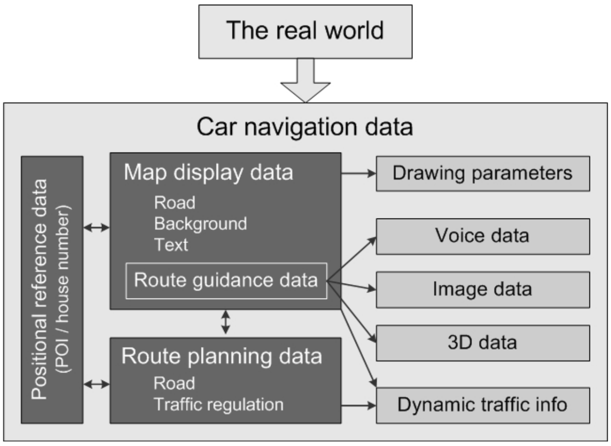


Figure 2.3 Content organization of navigation data

(1) Map display data

It is called main map data in KIWI. It is about the visible information on the LCD screen. Three display layers are defined in the graphic engine of the navigation software: background, road and text annotations. Road network is core of navigation data. All other features, for instance, railways, rivers, lakes, gardens, woods, buildings etc., are classified as background objects which serve the users as necessary orientation and references. The text layer floats above the road layer to explain and clarify the individual features. Figure 2.4 demonstrates the relation of the three layers for part of city Munich.

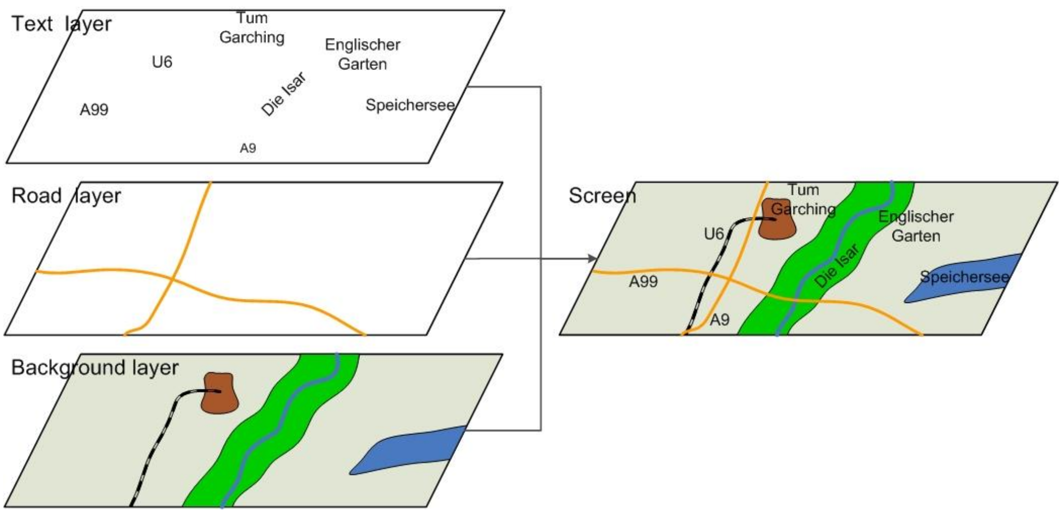


Figure 2.4 Three map display layers

Route guidance data contains instructions to lead drivers to the destination along the right route safely. Some instructions are:

1) Turn guidance arrow
2) Turn list and turn by turn
3) Signpost
4) Lane guidance
5) Highway service area and parking area (SA/PA)
6) Enlarged junction
7) Schematic intersection
8) Distance to turn and time of arrival

A normal example is shown in Figure 2.5. The left-turn arrow indicates the orientation at the top left; 'Frauenstrasse' at the bottom is the current street, 'Isartorplatz' at the top is the next street on the planned route; '414m' means the distance from current street to next street; '1.1km' means the distance to destination.

Figure 2.5 An example of guidance information on the screen of a navigation unit

(2) Route-planning data

It contains road data and traffic regulations for route planning. Its characteristics and the reason for its special definition for route-planning purposes are explained and compared with display road data in Section 2.3.3. The traffic regulation data is also specially organized in the navigation data format that is derived from traffic regulations in real world. An analysis is conducted in Section 3.5.

(3) Positional reference data

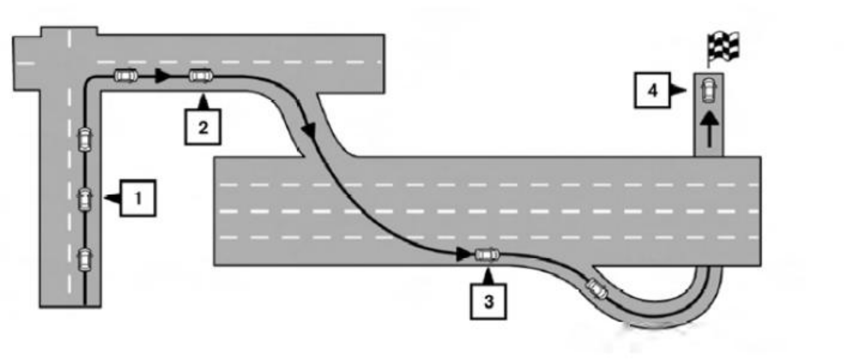
It mainly contains POI and street address (stored in road data) for setting a destination. POI can be searched by name, category, telephone number, street address, and intersection. In source data or database, POI records are stored in tables and their indices are automatically set up by the database server. In navigation data, however, a type of specific index for searching POI records is set up and offsets pointing to the corresponding road features are calculated by coordinates and street address. Both of them are stored in physical files, which can speed up the searching in car navigation systems.

These three main building blocks of the car navigation data are closely related. Every displayed road feature on the map and its corresponding road object in the route-planning data are linked with each other. Every record in positional reference is again connected with a road object, therefore, it is easy to match a POI record to a road link or find all POI records near a road link by the offsets pointing to each other.

In addition to the main building blocks, the right part in Figure 2.3 shows the extended parts including drawing parameters, voice data, image data, 3D data and TMC data. Drawing parameters are exclusively defined for the visualization and support several color schemes. Image data and 3D data are stored here for the naturalistic display effects close to the reality, while voice data and dynamic traffic information are special contents in navigation data.

(1) Voice data

It is essential part of guidance information and sometimes more important than route guidance data for display because it is dangerous to frequently look at screen. Drivers therefore may choose the audio channel of the guidance. Figure 2.6 shows an example of voice guidance matched to the graphic.



LNV0943

VOICE GUIDANCE DURING ROUTE GUIDANCE

When approaching a guide point (intersection or corner), destination, etc., during route guidance, voice guidance announces the remaining distance and/or turning direction.

Touch "Voice" on the upper left of the screen to repeat the voice guidance.

Example of voice guidance:

[1] "In about one quarter mile (400 meters), right (or left) turn." "Right (or left) turn ahead."

[2] "In about one quarter mile (400 meters) freeway entrance on your right onto (road number and direction)." "Freeway entrance on your right onto (road number and direction)."

[3] "In about one mile (1.6 kilometers), exit on your right." "Take the second exit on your right."

[4] "You have reached your destination. Ending route guidance."

Figure 2.6 Voice guidance in 2011 Nissan Navigation System Owner's Manual targeted for Canadian customers[9]

(2) Dynamic traffic information

Such as RDS-TMC (Radio Data System & Traffic Message Channel) service are usually intended for real-time usage. It is typically received from navigation units and integrated in route-planning algorithms to avoid jam or other traffic incidents. It can also be derived from traffic information analysis with historical database, road information under different weather conditions, light intensity dependent on weather and time etc. Furthermore, Telematics10 and emergency warning system for vehicles can be integrated in navigation systems, so as to enrich navigation data.

2.3.3 Organization characteristics

As a market-oriented product, car navigation systems should ensure not only correctness but also a non-stop service for nobody is willing to pay for a unit that reacts slowly or provides discontinuous services. The special organization of car navigation data has the purpose to speedup the realization of all functions within the source limits of an embedded environment.

In terms of content, two sets of road networks are maintained in car navigation data to support

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9 http://www.nissanusa.com/pdf/techpubs/2011/2011-Nissan-LC-Navi.pdf

10 Integrated use of telecommunications and informatics: http://www.telematicstandard.org

display on the one hand and route planning on the other hand. They are managed in two different management units: parcel and region. Based on the management units, an inter-dependent hierarchical road network can be built up for multiple map scales. This is the key point of this study to find a hierarchical road-network for route-planning algorithm by using the idea of generalization of road network. As far as the organization of every road link or node is concerned, it is a special method of integrated expression/organization which differs from the layered expression that separates spatial information from aspatial information.

The PSF of car navigation data is expressed as binary data that has two advantages: (1) much space of car navigation data is saved because the data structure can be defined at any length. For instance, the flag information in Table 2.2 is stored using one bit and other fields are stored using four or ten bits; and (2) plenty of pointers are used that can speed up the process of searching and computing by bitwise operation. Both advantages are desirable concerning the limited resource of embedded navigation hardware.

Table 2.2 An example of flag information (expansion header information in KIWI)

No.	**Bit**	Description	Value	Meaning
1	**15**	Manufacturer identification area type (flag)	0	Manufacturer identification code
			1	Additional table for manufacturer identification codes exists
2	**14**	Expanded data size area type (flag)	0	Expanded data size
			1	Additional table for expanded data sizes exists
3	**13-10**	Manufacturer identification area	0-15	The index number in the additional table for manufacturer identification codes
4	**9-0**	Expanded data size area	2-128	Data size = ("expanded data size"+1) * 2

(1) Two sets of road networks for display and route planning

Figure 2.8 illustrates the map display data managed as a collection of uniform parcels that consist of arbitrary rectangles called regular parcels. Normally, the LCD screen of a navigation system takes a rectangular shape. The parcel size at each map scale is designed to be consistent with the size of LCD screen. Generally it is efficient to read the data of only one parcel and display its content on the screen at the corresponding map scale. But the map should not be rendered parcel by parcel. Instead, it should be smoothly scrollable. Figure 2.7 manifests with an example the required parcels for a smooth scrolling of map display. During the initialization process, not only the central parcel that largely overlaps with the area of the current mobile activity, but also its eight adjoining parcels are loaded into the memory. Furthermore, considering the zooming operation that changes the map scale, the data from nine parcels at smaller scale (Figure 2.7a) and nine parcels at larger level (Figure 2.7e) are additionally loaded for display in the initialization process. When scrolling the map, the central parcel will be piecewise shifted in eight different directions. If it is shifted in vertical or horizontal direction, three new neighboring parcels will be loaded (e.g. Figure 2.7a à b). A diagonal shift requires five new neighboring parcels to be loaded (e.g. Figure 2.7c à d). Generally when scrolling the map in a specific current level by loading 3-5 parcels, the higher level would load 0-3 parcels and the lower level would load 9 parcels. This means, a total of 27 parcels should be loaded for the rendering process at three different scale levels, and 12 to17 parcels (up to five parcels respectively at a smaller scale and the current scale, and nine parcels at a larger scale) should be additionally loaded for scrolling. To assure a nearly real-time map display speed of 0.01 second for maximally 27 + 17 parcels, the parcel size in KIWI is designed to be 128 KB. The maximum resource consumption is 3.456 MB (128*27/1000) for initialization and 2.176 MB (128*17/1000) for scrolling.

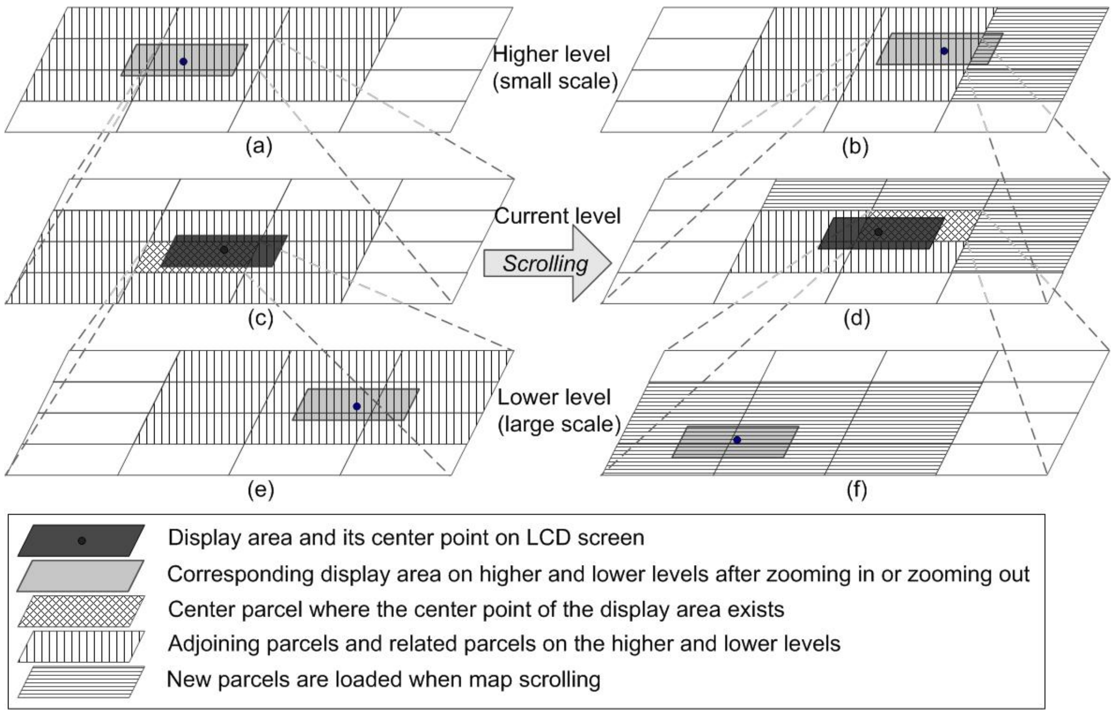


Figure 2.7 Required parcels for map display initialization and map scrolling
(a)(c)(e) Required parcels for map display initialization
(b)(d)(f) Required parcels for map scrolling

Unlike map display, the route planning is based on region rather than parcel. The ground surface on which land traffic takes place can be partitioned into polygon-shaped regions either in alignment with administrative divisions or bounded by significant geographic features such as rivers or ridge lines of mountain ranges. Within each region the traffic planning and design reveals a high degree of integrity. There are also more traffic activities within a region than between regions. It is therefore reasonable and efficient to take region as the basic management unit and develop region-wise route-planning algorithms.

While the parcel for map display data is a uniform rectangle bounded by the coordinates of the lower left corner and the upper right corner, a region for route-planning data is irregularly shaped. The coverage area of a region is defined as the bounding box indicated by the latitude and the longitude of the lower left corner and the upper right corner. Regions use the geographic coordinates' latitude and longitude. For display purposes, the geographic coordinates will be converted to coordinate offsets. Each parcel contains therefore coordinate offsets based on its parcel ID carrying the corresponding information of latitude and longitude. Its lower left corner is set to (0, 0) as the origin, the upper right corner is set to (255, 255).

The management units, parcel and region are the major distinction between two road networks and they affect the speed of organizing, searching, reading and displaying. Their different attributes and relationships are listed in Table 2.3. Obviously, the road network for display has much more attributes than the road network for route planning that is in essence a directed weighted graph. Without such a separation, a route-planning algorithm will slow down a great deal because it has to read many attributes that are irrelevant for the route finding. Likewise, the speed of map display will become less predictable if irregular polygons are taken as management unit.

Table 2.3 Detailed information in two sets of road network

Network	Type	Item	Detailed Contents
Route-planning data	Attributes of link	Link cost	Distance
			Time
			Fee
		Passage limit	Vehicle type
			Time
		Area types	Urban, suburban, semi-urban, rural area;
	Attributes of node	Coordinate	Latitude and longitude (no height)
		Node cost	Time
		Boundary flag	Network connection between regions
		Intersection info	Aggregated for high layer organization
	Connectivity	Link to link	According to node id
	Regulation	Permit	Transfer forbidden to permit regulation
		Priorities	Amend weigh
Road display data	Attributes of link	Geometry	Node, construction points
		Road name	Official name, alternate name, prefix, suffix, base name …
		Route number	Number, direction, name type …
		Street address	Left side reference address, non-reference address, address scheme, format, type…
		Road class	Administrative class, functional class, display class, network class
		Form flag	Roundabout, frontage road, intersection internal, undefined traffic area, ferry, indescribable, maneuver link …
		Construction info	In process data, paved or not, bridge, tunnel, ramp
		Lane info	Orientation, number, width …
		Median strip	Divider Info: width, place, materials …
		Administrative info	Administrative name, postal code
		Lane info	Orientation, number, width…
	Attributes of node	Coordinate	Relative X, Y, (Z)
		Intersection name	In several countries, e.g. Japan
		Traffic signal	Traffic lights at intersections
		Boundary flag	Network connection between parcels
	Topology relationship	Link to node	Attributes of link
		Node to link	Degree and sequence
	Guidance	Signpost	Name, type, orientation, shield, distance

(2) Multi-level map display data and multi-layer route-planning data

With the introduction of Internet and the growing demand on display performance, a large number of web map services have been developed. They adopt a physical multi-level storage database with each level corresponding to a certain map scale range. For example, Google maps[11] make use of a quad tree for storing and access to their pyramid tiles[12] (Burt 1981; Ogden et al. 1985) containing large uniform areas mingled with small detailed areas. This technology is similar to the hierarchical organization of display parcels of car navigation data. As shown in Figure 2.8, the road network for display is organized as a 16-ary tree. Parcels are aggregated at higher levels corresponding to smaller map scales. The whole patch at the lowest level (level-1) corresponds to the light gray patch at level-2 which is the smallest parcel for this level. The whole patch at level-2 consists of sixteen parcels. Up one level, a parcel at level-3 consists of sixteen parcels at level-2, and so forth. There is no limit to the number of levels in PSF of KIWI, but six to seven levels are prevailing in current car navigation systems.

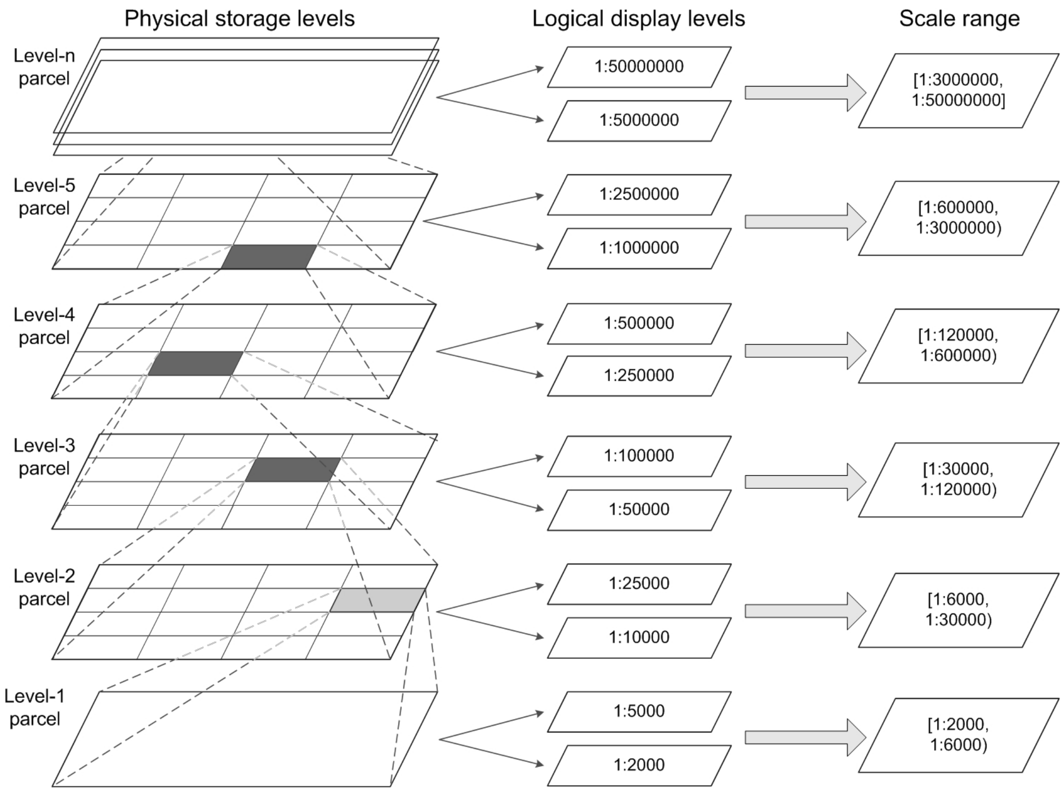


Figure 2.8 Hierarchical organization of parcel for map display at multiple scales

With regard to logical level or display level, more than ten levels can be shown on a navigation device, which is comparative to nineteen display levels of Google maps. In a similar way to digital map for which one physical level corresponds to several display levels and the features shown on different display levels are selected by some display attributes, a *1: n* relationship can be established between the route-planning data using region as management unit and map display data using parcel as management unit. In addition, a preview called smooth zooming or free zooming is used in car navigation systems, thus allows the map to be viewed across the scales or display levels.

Figure 2.9 demonstrates the hierarchical division of regions. A region on a higher layer is

[11] http://maps.google.com/

[12] http://www.maptiler.org/

composed of a number of smaller regions on a lower layer as Figure 2.9a shows. Figure 2.9b shows the tree structure of the hierarchical division. How many hierarchical layers are necessary depends on the region area and the speed requirement for route-planning algorithms. Empirically, three or four layers are adopted in car navigation systems.

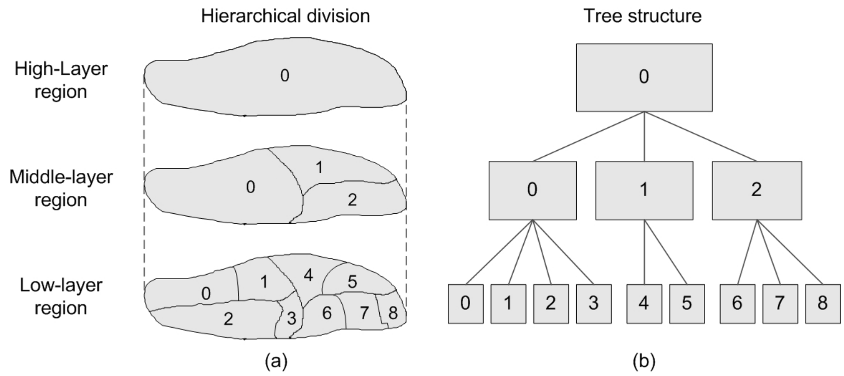


Figure 2.9 Hierarchical organization of region for route planning at three layers
(a) Hierarchical division; (b) Tree structure.

To summarize, multi-level parcel management for road map display is used to improve the performance of the graphic engine under resource constraints, whereby the hierarchical multi-layer region management can satisfy the requirements for accelerating route-planning algorithms. The multi-level organization is the prerequisite for car navigation data. Since the source map data for the car navigation data authoring is usually stored in a single level, generalization is considered to build up multi-level display data. Generalization is a process in which maps at a smaller scale are derived from a source map at a larger scale.

(3) Integrated expression

Integrated expression is a type of physical organization for complex objects. It sets all object information incl. location, attributes, topology and relationships together. As demonstrated in Table 2.3, a road link for route planning has two nodes with coordinates, attributes such as link cost, connectivity and regulations with other links or nodes as relationship; a road link for display has two nodes and several construction points with coordinates, topological relationships, attributes such as road name, road class, form flag, signpost information to different orientation from the road link as relationships.

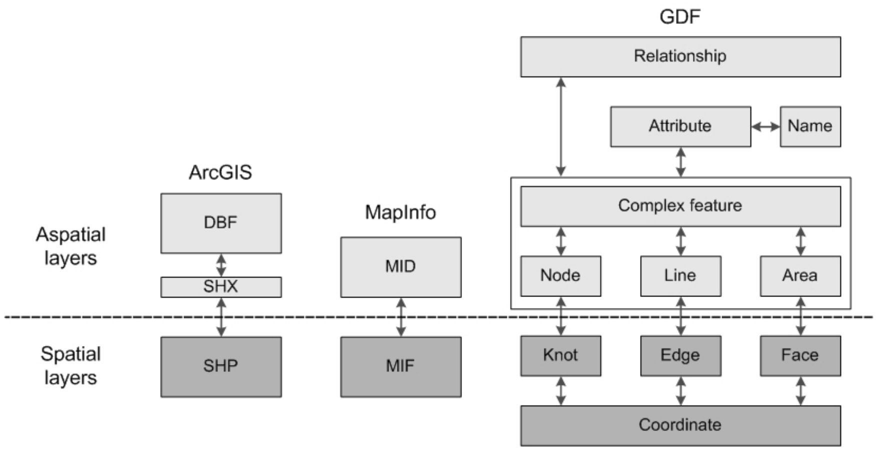


Figure 2.10 Layered expression in ArcGIS, MapInfo and GDF

Unlike the integrated expression, a layered expression is adopted in ArcGIS, MapInfo and GDF. In ArcGIS and MapInfo, the spatial data and aspatial data are separated in two layers. Figure 2.10 shows that spatial data reference to geometrical information is stored in SHP file or MIF file, and aspatial data including feature category, attribute and relationship is stored in DBF or MID. SHX file is an index file that maintains the relation between SHP file and DBF.

GDF works with even more layers and is straightforward to understand and update as a plain-text ASCII file. Referring to Figure 2.10, its spatial data has two layers: coordinates and cartographic primitives including knot, edge and face. The aspatial data have three layers: feature (including node, line, area, and complex feature combined by at least two types of single features), attribute & name, and relationship. However, it is hard and slowly to find all the contents describing the same object in a large GDF file that usually contains more than 100 000 lines. For this reason, GDF is a not suitable format for real-time navigation services.

Compared with the layered expression, the integrated expression in KIWI avoids frequent searching and reading actions, therefore, allows a faster load of complete object information.

(4) Flexible offsets and suboptimal updating principle

With the KIWI format map features can be quickly identified by means of offsets in the binary file. Two types of offsets are used to maintain two kinds of relationships. Firstly, the homolog road links and nodes in parcels and regions have offsets pointing to each other (green arrow in Figure 2.11). Secondly, the homolog road links or nodes between different scale ranges of parcels or between different aggregation layers of regions have offsets pointing to each other (blue arrow in Figure 2.11). In addition, each road network on higher level parcel or higher layer region is a subset of the road network on lower level parcel or lower layer region. In other words, all nodes and road links on higher level parcel or higher layer region can find the corresponding ones on lower level parcel or lower layer region to maintain the association by offsets.

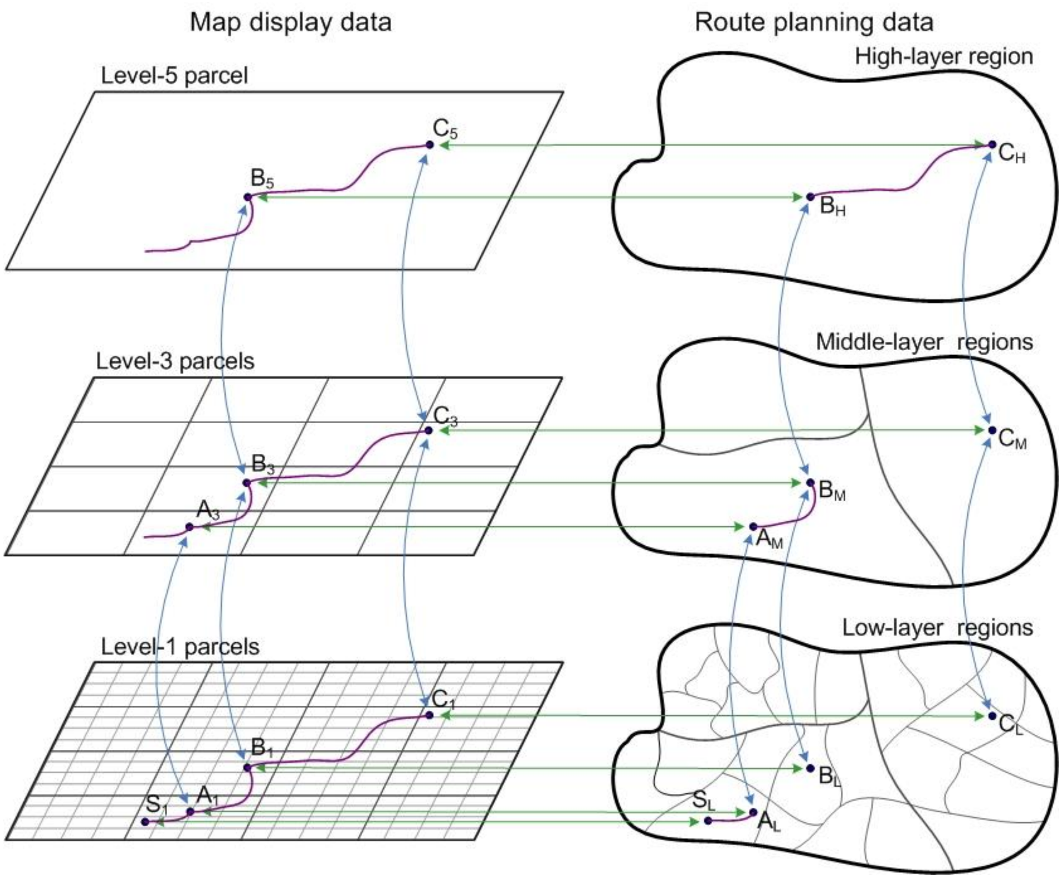


Figure 2.11 Offsets (in green) between parcels and regions & offsets (in blue) between neighboring levels and layers

The example in Figure 2.11 assumes that node B and C exist in a parcel at level-5 which corresponds to a high-layer region, node A exists in a parcel at level-3 corresponding to a middle-layer region, and node S exists in a parcel at level-1 corresponding to a low-layer region. Each node is annotated with a suffix indicating the level of its parcel and the layer of its region. The process of finding a route from a start point S_1 to a restaurant represented by POI which near the node C_1 involves the following steps:

1) Find node C_1 in a parcel at level-1 based on the offset to the restaurant in POI.
2) Find node S_L and C_L in the low-layer region based on the offsets of node S_1 and C_1 pointing to node S_L and C_L.
3) Get geographic coordinates (latitude and longitude coordinates) of S_L and C_L, thus the coverage area, to decide the aggregation layer of the regions involved in the route-planning process. In this case, the region at the highest layer should be involved selected where the destination C_H is located in the same region as the starting point because the destination C_M is located in different regions from the location of starting point S_L at middle layer.
4) Read out all road data in the coverage regions and calculate the route with an automatic accelerating route-planning algorithm. The route represented in purple in Figure 2.11 includes three segments crossing three layers: S_L to A_L in the low-layer region, A_M to B_M in the middle-layer region, and B_H to C_H in the high-layer region.
5) Find all correspondent nodes A_1, B_1, C_1, A_3, B_3, C_3, B_5, and C_5, and by the offsets of their homolog nodes at the corresponding parcel levels.
6) Get the screen coordinates for A_1, B_1, C_1, A_3, B_3, C_3, B_5, and C_5, and display the route going through them in all levels.

While the route-planning process proves very flexible and efficient with the offsets, the updating process of car navigation data in KIWI follows the principle of reproduction rather than differential update. The offsets usually point to absolute and relative physical positions in files. Once a change is made somewhere, the offsets should be changed accordingly. For example, if a road link is inserted or deleted, the topology of the road network at every related scale level of map display data and the corresponding aggregation layer of route-planning data must be reorganized, and the offsets reset.

If the car navigation system adopts an embedded database technology to support differential update, the current binary file can be abandoned. And the index technology of database would also replace the usage of offsets.

2.3.4 Data authoring

Car navigation data authoring is a process that transforms various source databases such as the data of ArcGIS, MapInfo and GDF to PSF of navigation data including self-defined data format derived from standard navigation data. The data authoring performs two main tasks: context conversion and reorganization.

Firstly, context conversion aims not only to pick up the necessary navigation information, but to mine and combine useful information that specially supports navigation functions. The necessary navigation information may include:

1) An integrated road-network topology with appropriate precision. This is the prerequisite for vehicle positioning and road matching, and also ensures the connection of the road network. Incidentally, the length of each road link can be calculated as a link weight to support the shortest path calculation.
2) Basic attributes of road, such as name, class, form (e.g. bridge and tunnel). They can support the display of roads.
3) Basic navigation attributes of road, such as the speed limit or average speed, freeway and tolls. Like the road length, speed information supports the shortest time calculation.

4) Correct and integral traffic regulations including traffic direction of road links. This is self-evidently the essential part that makes navigation systems useful.
5) POIs that describe landmark positions and other detailed information.

The source data suppliers can usually provide many attributes of roads and other topographic data types such as rivers and woods as well as multi-layered geometric and semantic information. In the source data, however, there is often a lack of the integrated road-network topology and traffic regulations. For example, 72 regulations are documented in the downtown area of Munich in the Open-street-map[13]. In spite of the large number, they are not fit for navigation data authoring. Many of them can be derived from the topology and relations between links and directions. Similarly, many road attributes in car navigation data cannot be directly taken over from source data as shown in an example in Table 2.4 and often the traffic regulations in source data are expressed in different forms as illustrated in Figure 2.12. Therefore, data authoring may involve complex conversions.

Table 2.4 Attribute conversion of a 3:2 relation

ArcGIS	PSF of KIWI	
Intersection internal = 1	Plural junction flag = 1	Plural junction type = C
Indescribable link = 1		Plural junction type = M
Maneuver link = 1		Plural junction type = I

Figure 2.12 Conversion of a regulation form

Secondly, a lot of work should be processed for reorganization, such as binary file organization, data partition by parcel and region, multi-level organization, offset setting, POI organization and so on.

Figure 2.13 shows the general workflow of car navigation data authoring. Along the supply chain of car navigation services, the navigation data suppliers implement the data conversion from source data to PSF of car navigation data customized by navigation engine/software suppliers. It involves two intermediate databases - Geographical Database (GeoDB), Navigation Database (NaviDB) hereafter managed by commercial database management systems such as Oracle, MS SQL Server.

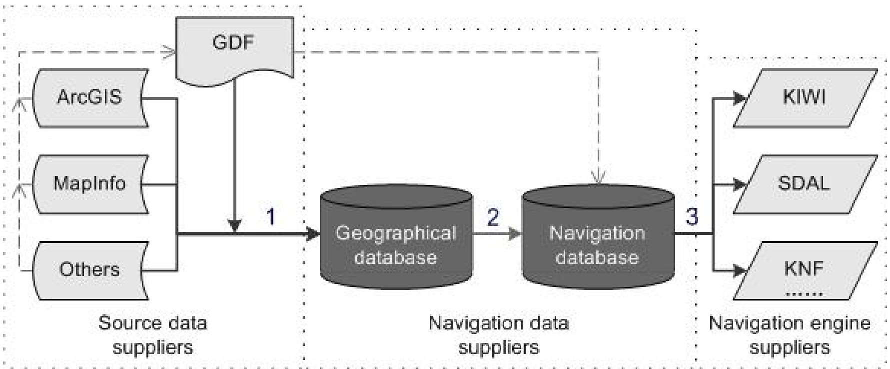


Figure 2.13 The workflow of car navigation data authoring

13 http://www.openstreetmap.org/

In the workflow in Figure 2.13, GDF is used as the predecessor of GeoDB. Since GDF is a flat file and not suitable for mass data management especially data query, it is replaced by GeoDB. The following reasons explain why the NaviDB and GeoDB are used as intermediary containers:

1) The data volume is too huge to be directly converted from source database to target database. For instance, the size of source data of North America is over 50GB and that of China is over 10 GB. This requires a stepwise data authoring with partitioning and parallel processes.
2) It is easy to manage the mass data for storage, query, statistic analysis and data mining, validation, updating und further value-added data services in a database system.
3) The most important is that a general platform is helpful to realize the automated standard engineering process and deal with multi-source data and navigation data. The GeoDB provides a standard structure for geographic information, while the NaviDB provides a similar structure with the standard PSF of car navigation data. Thus a seamless authoring process is possible between GeoDB and NaviDB.

Consequently, divided by GeoDB and NaviDB, the workflow is composed of three essential conversions:

1) Conversion from source data to GeoDB;
   - Inspection of the applicability of source data for navigation;
   - Standardization of source data incl. categorization of geographical objects, map projection transformation, harmonization of attributes;
   - Generation of network topology.
2) Conversion from GeoDB to NaviDB;
   These two databases have different management units, coordinate systems, definitions of objects, attributes and relationships. Therefore, the following measures are needed:
   - Data partition and management to build up multi-level parcels and multi-layer regions;
   - Generation of navigation features by separating the data for display from data for route planning, and authoring of background features;
   - Integrated expression of navigation features;
     - Coordinate transformation in parcels;
     - Attribute matching and transformation;
     - Standardization of traffic regulation related to route planning;
     - Standardization of guidance information related to display.
   - Generalization and integrated expression of background features at higher abstraction levels;
   - Generalization and integrated expression of road network for parcel display at smaller scales and route planning at higher aggregation layers of regions. The way how to deal with the generalization of road network is the point of our research.
3) Conversion from NaviDB to PSF of car navigation data.
   This involves the conversion to a binary file, calculation of offset and index generation.

Chapter 3

Information of Road Network

This Chapter interprets all useful information of road network in commercial datasets for generalization in car navigation data authoring. While the spatial information lays down a foundation for the subsequent spatial analysis of road network, aspatial information that gives meanings to the individual roads plays a significant role for a thorough understanding of interactions between the natural environment and human activities. A combination of spatial and aspatial information is necessary to reach a reasonable generalization of road network.

The first four sections are dedicated to the spatial information and primitive aspatial information, which are recorded as road attributes including road identity, spatial information, road classification and other individual attributes. The last three sections describe the relevant combined information particularly for navigation purposes, such as traffic regulation, guidance and point of interest, which are usually expressed as complex relations by a set of column in a table or a mount of tables.

3.1 Road identity

The identity of a road can be described using a unique identifier and various names such as official name, alternative name, postal name, names that bear further information about the shape, history, nearby landmark, relative direction etc. A road, especially a route, can also be numbered using a numeric value or an alphanumerical combination showing route type, level and direction etc. Exit number can be seen as a type of road name on the ramp link, which can help to pick up all exit links of autobahns or roundabouts.

The identity of a road can serve various purposes such as:

1) Check the quality of source data by comparison with road class and access limit information.
2) Sort the road priority by the route type level and name type.
3) Indicate the function and importance of a road, and
4) Indicate the distinction between an urban street and a rural road.

Street addresses are composed house numbers and street names. They are structured following certain rules and used as terminating points of a route in navigation system.

3.2 Spatial information

All spatial characteristics can be acquired using spatial methods or derived from location information and recorded as road attributes, so that they can be easily retrieved and updated.

The commercial datasets usually use the decimal latitude and longitude coordinates. For example, WGS-84 (World Geodetic system 1984) is used in Europe and Beijing-54 in China. Length, orientation can be calculated from coordinates of nodes, width and lanes by means of image understanding, and forms such as single-carriageway, dual-carriageway, parallel link, bifurcation, intersection, roundabout, ramp, stubble link and traffic area by pattern recognition methods based on shape and topology relationship. This type of information can help to confirm the priority order of roads.

Topology relationship in road network indicates the connectivity and relative position between road links. Connectivity is expressed by that the identifications (IDs) of start node and end node of a road link are recorded as two attributes of the road link. For example, in Figure 3.1a, link-1 connects with link-2 at node-B, and similarly in Figure 3.1b, link-3 connects with link-4 at node-D and link-5 connects with link-6 at node-E. However, because node-D is different from node-E, link-3,4 disconnect with link-5,6, or called overpass. Relative position can be confirmed by the location of construction points, which finds out the mistake in a dual-carriageway simplification in Figure 3.2 as an instance. By the way, the degree of node is a useful attribute referring to the importance.

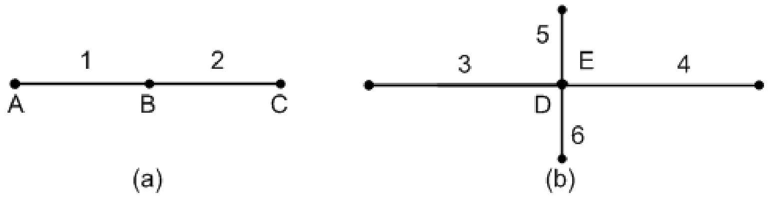


Figure 3.1 Connectivity recognized by topology relationship
(a) Connected; (b) Disconnected in the cross directions

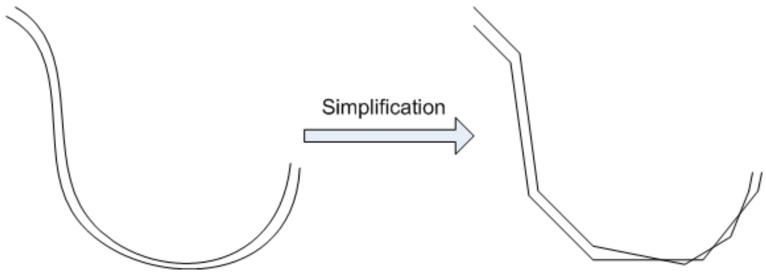


Figure 3.2 Relative location recognized by topology relationship

It is also important to differentiate urban area from rural area because the road systems of urban area and rural area are different and many generalization methods of road network are concentrated on urban area or rural area only. This distinction can be automatically recognized in terms of relative contribution density of road network, or directly indicated by administrative information (name, class, type and city center information) and postal information (code, district). In addition, the roads and nodes along administrative boundary should be especially marked, as they are used in the road network at both sides of the boundary.

3.3 Road classification

Roads can be classified for the purposes such as administration, construction engineering, transportation, network analysis and display. All of road classifications are very useful to order the road priority for selection.

(1) Administrative classification

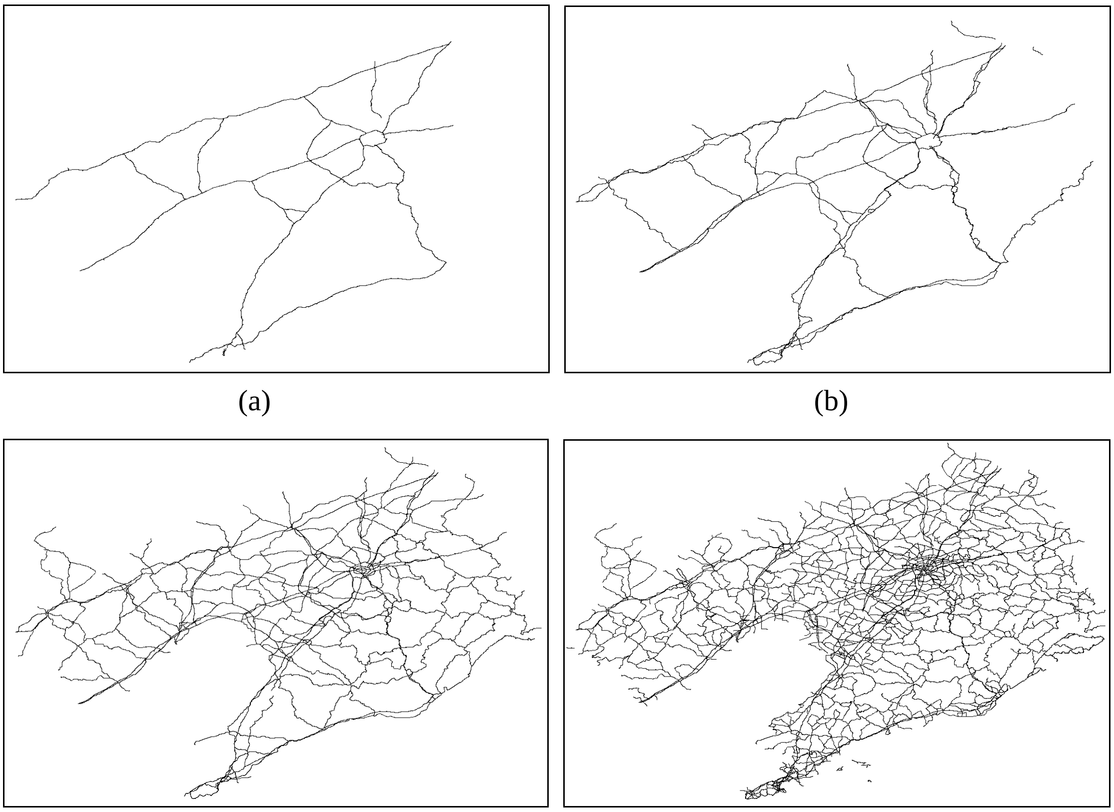
Road classes denominated by administrative levels are used in nearly all countries for urban development and road management. Some examples are listed in Table 3.1 where the classes indicate the corresponding administrative level, the regional extent, and the relative importance. The major routes in Europe have a European number co-existing with the national number of the specified country. Figure 3.3 shows the road network of Liaoning Province, China according to a more detailed administrative classification in Table 3.2. Apparently the distribution of roads at different levels is not balanced. Roads at higher administrative levels are not seamlessly connected.

Table 3.1 Administrative classification

Class	China	Germany	USA	Japan
0	Freeway	Autobahn	Interstate route	Motorway
1	National highway	Bundesstraßen	US highway	National highway
2	Provincial highway	Landesstraßen	State route	County highway
3	County highway	Kreisstraßen	Minor road	Local road
4	Village road	Gemeindestraßen		Minor road

Table 3.2 Detailed administrative road class of China

Road class	Description	Road class	Description
0	Freeway in rural area	6	Village road
1	Freeway in urban area	8	Other road
2	National highway	9	Minor road
3	Provincial highway	10	Ferry line
4	County highway	11	Pedestrian road



(a) (b)

(c) (d)

Figure 3.3 An example of administrative class in Liaoning Province

(a) Road class=0,1; (b) Road class=0,1,2;

(c) Road class=0,1,2,3; (d) Road class==0,1,2,3,4.

(2) Functional classification

(U.S. Department of Transportation, Federal Highway Administration (DTFHA) 1989) “Functional classification is the process by which streets and highways are grouped into classes, or systems, according to the character of service they are intended to provide. Basic to this process is the recognition that individual roads and streets do not serve travel independently in any major way. Rather, most travel involves movement through a network of roads. It becomes necessary to determine how travel movement can be channelized within a limited road network in a logical and efficient manner. Functional classification defines the nature of this channelization process by defining the role that any particular road or street should play in serving the flow of trips through a road network. ”

“The basic idea in functional classification is schematically illustrated in Figure 3.4. In the left diagram, lines of travel desire are shown as straight lines connecting trip origins and destinations. Relative widths of lines indicate relative amounts of travel generating or attracting power of the places shown. Since it is impractical to provide direct-line connections for every desire line, trips must be channelized of a limited road network in the right diagram of Figure 3.4. Note that the heavy travel movements are directly served or nearly so; and that the lesser ones are channeled into somewhat indirect paths. The facilities are shown in which are descriptive of their functional relationships. Note particularly that this hierarchy of functional types relates directly to the hierarchy of travel distances which they serve. Since the cities and larger towns generate and attract a large proportion of the relatively longer trips, the arterial highways generally provide direct service for such travel. The intermediate functional category, the collectors, serves small towns directly, connects them with the arterial network, and collects traffic from the bottom-level system of local roads, which serves individual farms and other rural land uses.”

"Allied to the idea of traffic channelization is the dual role the highway network plays in providing (1) access to property, and (2) travel mobility. Access is a fixed requirement, necessary at both ends of any trip. Mobility, a long the path of such trips, can be provided at varying levels, usually referred to as "level of service." It can incorporate a wide range of elements (e.g., riding comfort and freedom from speed changes) but the most basic is operating speed or trip travel time. It was pointed out in the discussion of Figure 3.4 that the concept of traffic channelization leads logically not only to a functional hierarchy of systems, but also to a parallel hierarchy of relative travel distances served by those systems. This hierarchy of travel distances can be related logically to a desirable functional specialization in meeting the access and mobility requirements. Local facilities emphasize the land access function. Arterials emphasize a high level of mobility for through movement. Collectors offer a compromise between both functions. " This is illustrated conceptually in Figure 3.5.

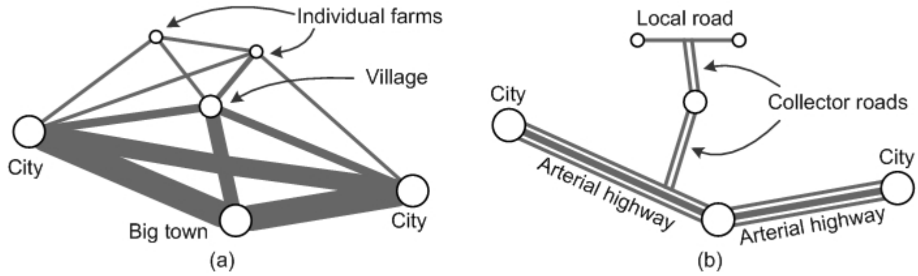


Figure 3.4 Channelization of trips (U.S. DTFHA 1989)

(a) Desired travel lines; (b) Trip channelization in the reality.

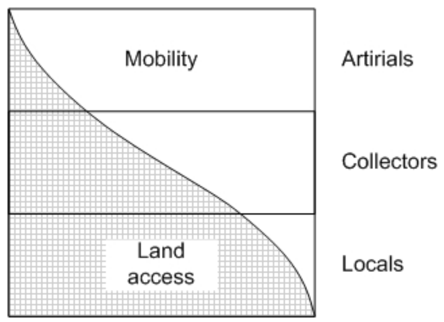


Figure 3.5 Proportion of service (U.S. DTFHA 1989)

Functional road class is usually provided in databases of North America and European countries, although these databases have their own classification criteria and class names. In Table 3.3, the functional meanings of European highway classes are explained, and Figure 3.6 shows the road network in the northeast of Munich. Similar to the administrative classification, roads at higher functional priority level are not seamlessly connected.

Table 3.3 General functional classification

Class	Description	Category
0	Motorways (highest class)	Arterial road
1	Roads not belonging to motorways of major importance	
2	Other major roads	
3	Secondary roads	Connecter road
4	Local connecting roads	
5	Local roads of high Importance	
6	Local roads	Local road
7	Local roads of minor importance	
8	Others (lowest class)	

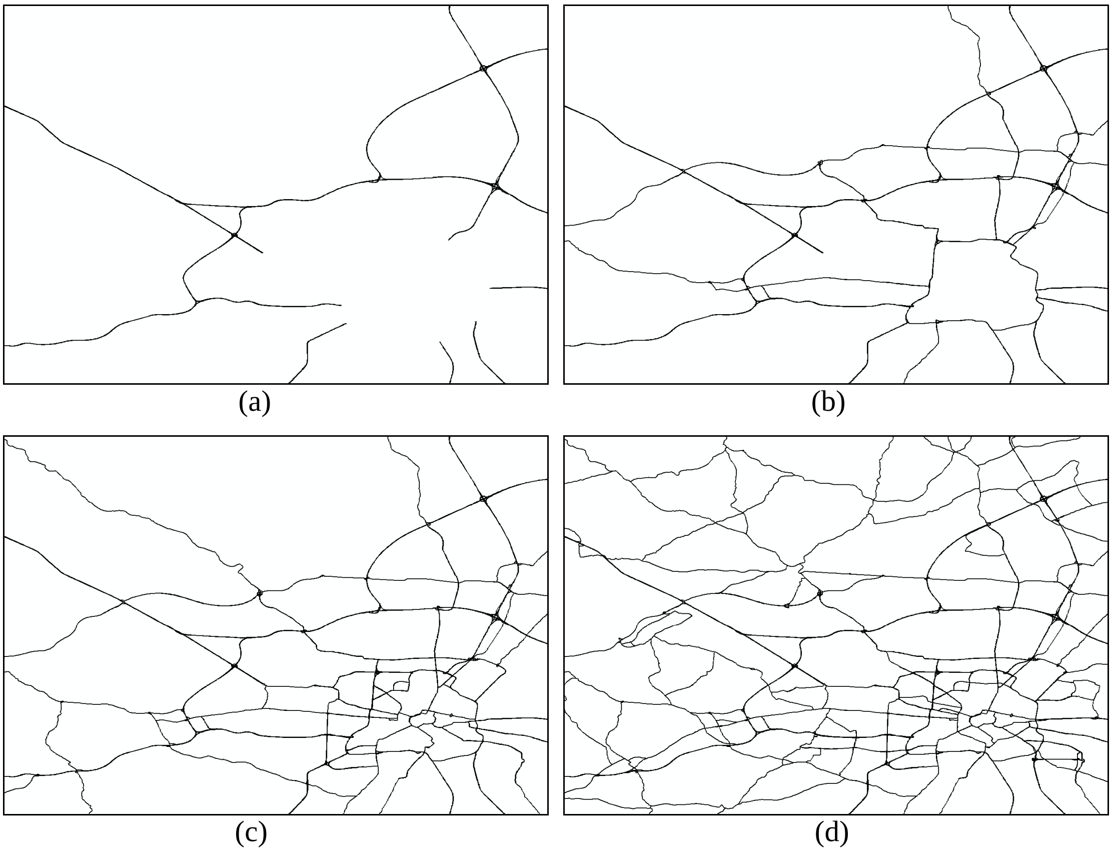


Figure 3.6 An example of functional road class in the northwest of Munich
(a) FRC=0; (b) FRC=0,1; (c) FRC=0,1,2; (d) FRC=0,1,2,3.

(3) Network classification

In TeleAtlas data (version of 2010/09), networks were classified following criteria defined in Net 2 Class (N2C) and Net B Class (NBC).

Table 3.4 N2C of Europe

N2C	Description
0	Roads of international importance: Most important roads and ferries for through traffic that connect the most important municipalities of the country and of the neighboring countries.
1	Roads of national importance: Important roads and ferries for through traffic used to travel within the country.
2	Roads of regional importance: Most important roads for through traffic used to travel between different regions of the country.
3	Local roads of high importance: Roads making minor settlements accessible.
4	Local roads: All road elements that are used only to reach a certain address or destination. They also include stubbles that are connected to roads of N2C 0, 1, 2, 3 or 4.
5	Local roads of minor importance: Unpaved or poorly maintained roads that have no connectivity function but only a destination function. They also include stubbles that are connected to roads of N2C 5.
6	All restricted roads: Roads inaccessible for normal traffic. They also include all stubbles that are connected to roads of N2C 6.

N2C classifies roads and ferries based on their relative importance in the overall road network. Seven classes of N2C are listed in Table 3.4, and Figure 3.7 shows road networks in the northwest of Munich according to N2C. It is very complete and integrated in each road-network level here; furthermore the road density in each level corresponds well to different map scales. For this reason, N2C is considered to be the best reference to order road density.

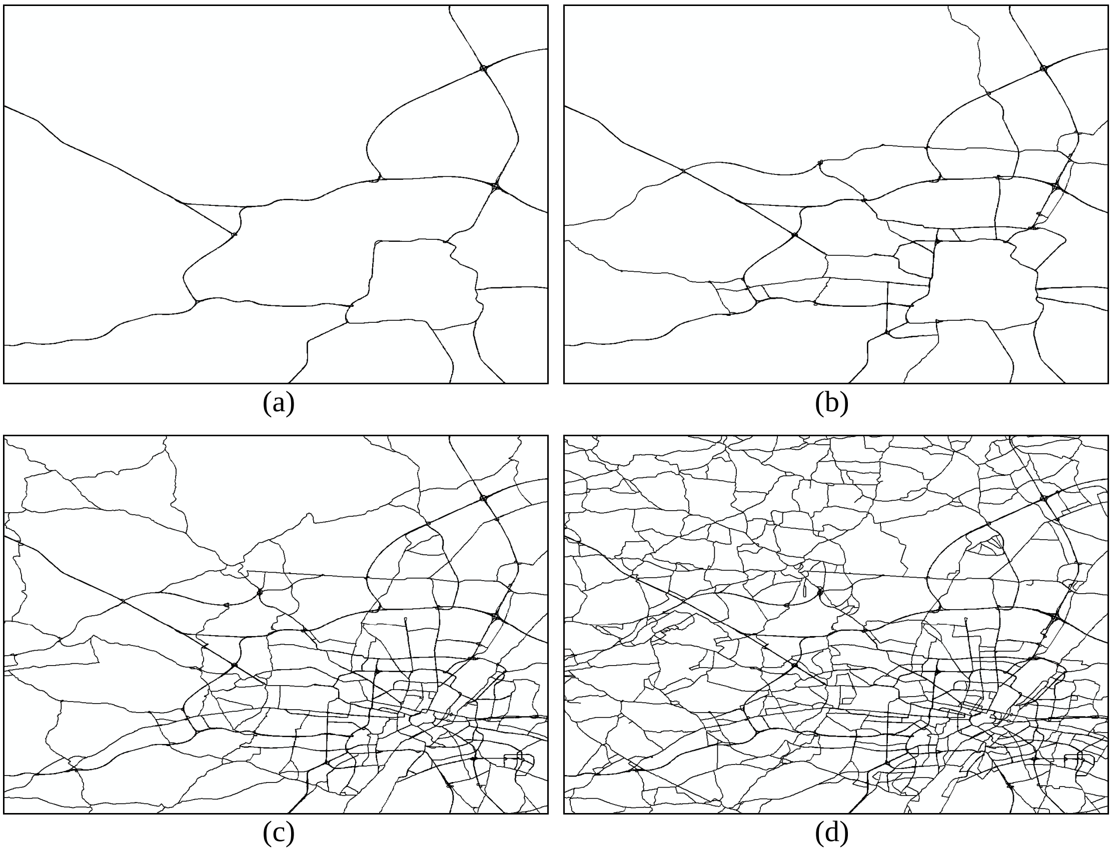


Figure 3.7 An example of network class in the northwest of Munich

(a) N2C=0; (b) N2C =0,1; (c) N2C=0,1,2; (d) N2C=0,1,2,3.

NBC is a classification of roads and ferries based on the importance of the network they belong to. There are six closed-network classifications of NBC listed in Table 3.5, they are as complete and integrated as N2C, but with a focus on small scale map. It can be considered as a good supplementary of N2C to order road density.

Table 3.5 NBC of Europe

NBC	Description
0	Not applicable. (default)
1	Connections between the most important cities on a continent; Most important cities on a continent with populations >= 300,000.
2	Most important connections between most important cities within a country; Most important cities in a country with populations >= 100,000.
3	Alternate connections between most important cities within a country.
4	Connections of less important cities within a country and between neighboring countries.
5	All remaining road elements and ferry connections used to travel between regions of the same country, and to neighboring countries.
6	All road elements and ferry connections used to travel in the same region of a country.

(4) Display classification

In addition to the classifications, display class exists in the Chinese road database and is defined for multi-scale spatial representation according to the requirements of digital maps and web map service providers, which means generalization of road network is a task for source data suppliers. Five display levels are defined as listed in Table 3.6 and demonstrated in Figure 3.8 with the road networks of Liaoning Province. Comparing with the administrative classification, the networks have good connectivity, but the road density is less balanced than with N2C of Europe. As a whole, it is a good reference to order road priority in China.

Table 3.6 Display class of China

Display class	Description
1	Freeways between important cities and within cities; Under control of access, supporting highest speed and maximum traffic volume; Disconnection permitted.
2	Other connections between important cities, and connections between them and display class 1 roads; Supporting higher speed and mobility; With good connectivity. (Most national highways, several provincial highways, and connection roads between themselves or between them and freeways.)
3	Connections between secondary cities, and between them and display class 1-2 roads; Supporting high speed and mobility; With good connectivity. (Some of national highways, most provincial highways, several county roads and connection roads between themselves or between them and higher level roads.)
4	Main roads in cities and connections between them and display class 1-3 roads; Supporting high speed and mobility; With good connectivity.
5	Other roads.

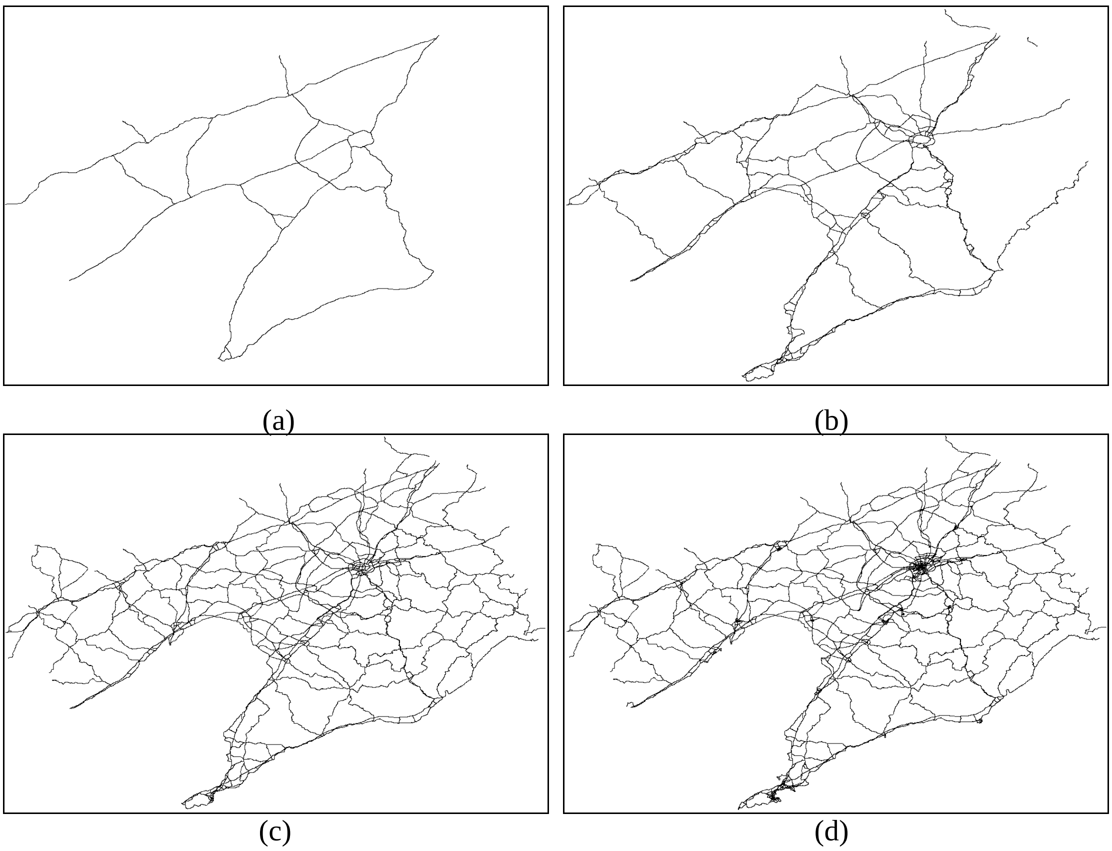


Figure 3.8 An example of display class in Liaoning Province

(a) Display class=1; (b) Display class =1,2;

(c) Display class =1,2,3; (d) Display class =1,2,3,4.

3.4 Other road attributes

Besides the above-mentioned classified attributes, many other attributes are collected in commercial datasets.

Construction information contains many attributes including IPD (in process data) state, pavement state (may be not paved) & paved materials, and construction form such as bridge, tunnel, ramp, ferry, and so on. For road selection, the road in process or not paved can be omitted in higher-layer road network, while big bridges, long tunnels and complex ramps are important enough to remain.

Private roads, frontage roads, back roads, accommodation roads and toll roads are indicated as road attributes without systematic classification. Usually private roads, frontage roads, back roads are omitted in middle and small scale maps. The toll attribute plays a fundamental role for finding the most economical route although the unit cost of a road consists of not only the toll but also the energy consumption. As a reference of function, almost all toll roads having higher quality and access conditions are selected in middle-layer or high-layer road network, and they are even classified by the toll dues.

Besides that, the access limited motorway is indicated as freeway.

3.5 Traffic regulations

Access limits apply to vehicle type, speed and direction of traffic flow. Some examples of traffic regulations for vehicles are demonstrated in Figure 3.9.

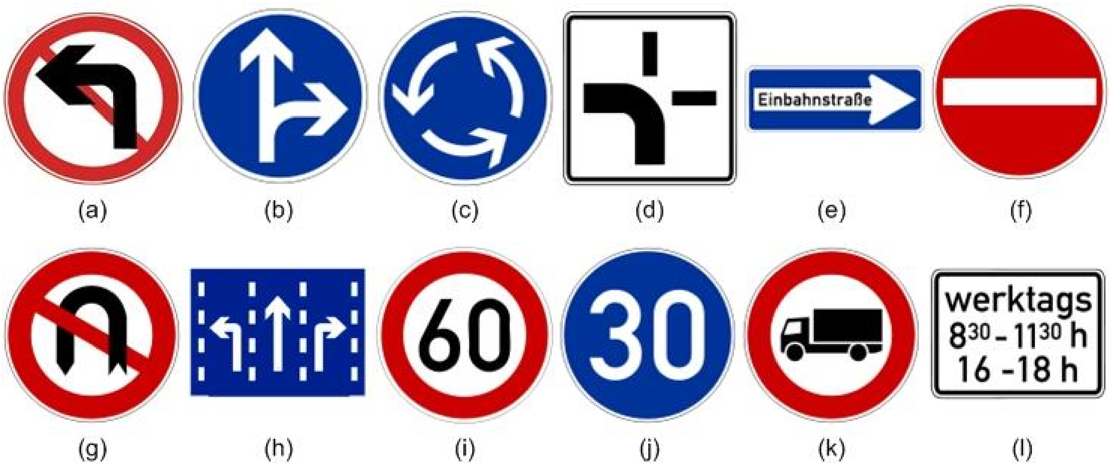


Figure 3.9 Traffic signs

(a) Prohibit access; (b)-(c) Mandatory access; (d) Priority access between links;
(e) Forward pass; (f) No entry; (g) Prohibit of U-turn at the middle of two-way road;
(h) Traffic direction of lane at the end of road link; (i) Maximum speed limit;
(j) Minimum speed limit; (k) Vehicle type limit; (l) Parking time limit.

Vehicle types include automobile, bus, taxis, carpool, truck, through traffic, delivery, emergency vehicle, private, pedestrian, and so on. Their limit indicates what kinds of vehicles are allowed on the link. For car navigation system, if automobiles are not allowed, or only pedestrian is allowed, the road link should be omitted even in the low-layer road network.

With regard to speed limit, maximum and minimum speed limit should be acquired and maintained in the source data. For navigation purposes, the average speed or recommended speed is useful but difficult to confirm. Therefore, the recommended speed should be inferred from the road priority and other attributes such as direction of traffic flow.

Direction of traffic flow may have access restrictions either along one road link or between two or more road links, i.e. turn forbidden. The direction restriction along one road link is treated as an attribute value as illustrated in Figure 3.10. The turn forbidden is expressed as regulation. Sometimes, the turn forbidden can be derived from direction restrictions as shown in Figure 3.11.

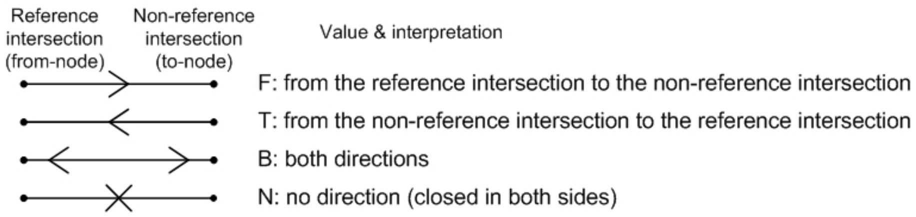


Figure 3.10 Value and interpretation of road link direction

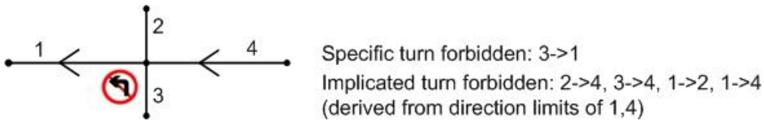


Figure 3.11 Implicated turn forbidden derived from direction limits

When the traffic flow of a road has only one direction (From or To), three cases can be recognized:

1) One-way road. It is usually a minor urban road can be omitted in middle layer.
2) Dual carriageway. It can occur in urban or rural areas. Here a condition to judge the road priority is hidden. The priority of a dual carriageway is usually higher than that of single carriageway of the same class.
3) Connection link. It can be a ramp, an entrance/exit of motorway, or a maneuver link.

In addition, division information indicates if and where a divider exists. It helps to judge the road priority and implicates whether a U-turn is allowed or forbidden. Two attributes are possible: Divided legal with the values - ‘Y’ or ‘N’ - that indicates whether the divider of road segments is a legal barrier, not a physical one; and divided location that in turn has five values - L: Road link only, A: All including road link and the intersections at both end; F: Road link and the reference intersection (from node); T: Road link and the non-reference intersection (to node); and N: No Divider.

3.6 Guidance

Guidance information is not richly recorded in source data. Normally, it is well reflected in signposts as shown in Figure 3.12 where the detailed information, such as cities, directions, route numbers and distances, important junctions or intersections can support the generalization of road network.

Figure 3.12 Guidance information on signposts

3.7 Point of Interest

POI can have many attributes such as name, coordinates, street address, functional category (e.g. school, restaurant, hotel), nearby intersection, telephone number, entrance/exit and so on. More than seven million POIs with detailed information have been identified in China by Navinfo (the latest version 2011), and Tele atlas offers 26 million POIs globally[14]. Figure 3.13 shows the example of Antiga Pinacoteca[15] with opening hours, web site, email address, traffic information, photos and even English language service. It is rather convenient to find the attractive points between which the optimal paths can be calculated in the selection process of generalization of road network.

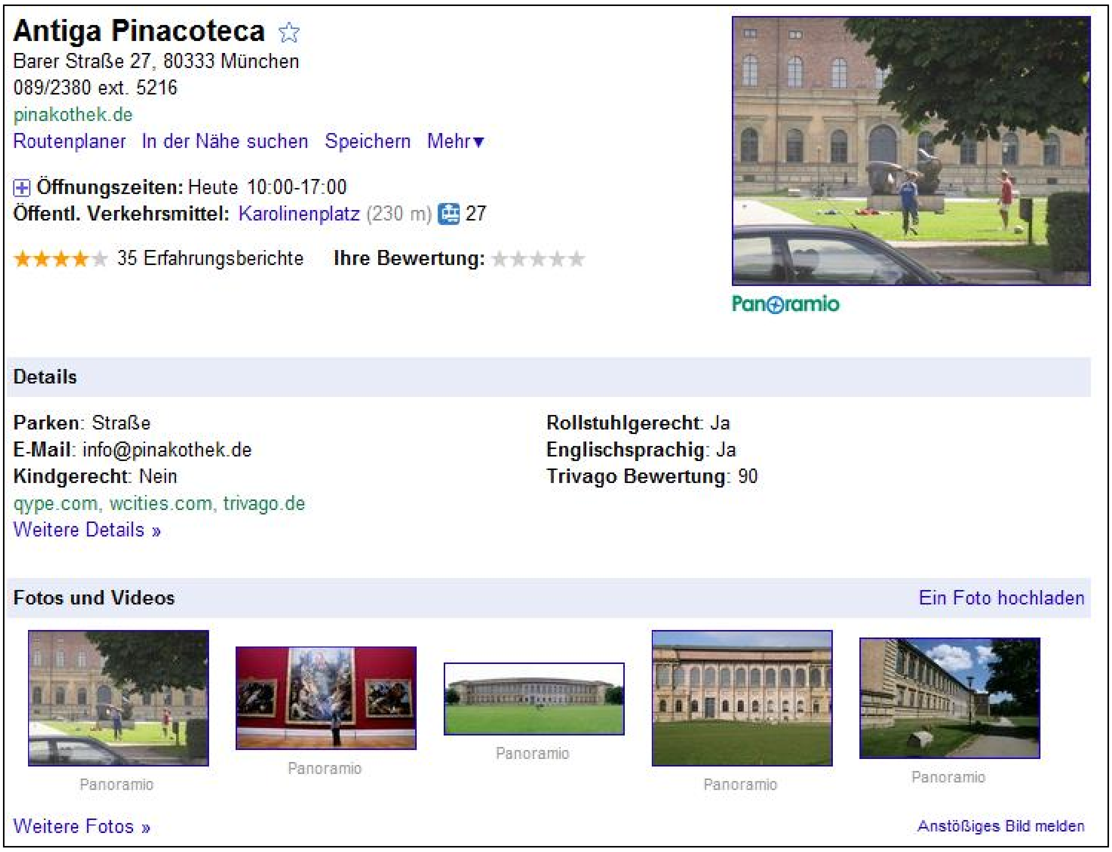


Figure 3.13 An example of detailed POI information

[14] http://licensing.tomtom.com/OurProducts/PointsofInterest/index.htm

[15] http://maps.google.ie/maps/place?cid=9320239353061032119&q=Antiga+Pinacoteca&hl=en&dtab=0&sll=48.143488,11.57432&sspn=0.011516,0.019015&ie=UTF8&ll=48.150483,11.564441&spn=0,0&z=17

Chapter 4

Generalization of Road Network

Road maps are among the most widely used maps ever since the ancient times. Road-network generalization has been therefore intensively studied. Section 4.1 reviews the related contents of generalization, such as cartographic and model generalization, semantic generalization by using aspatial information, and automated generalization. Section 4.2 classified the types of generalization operators of road network, and reviewed the methods for realization of those operators. Based on the state of the art of map generalization as theoretical basis, Section 4.3 analyzes the generalization characteristics of road network in car navigation data authoring, which is the guideline of methodologies and the total solutions.

4.1 Overview of generalization

In cartography, map generalization is the process of deriving a new map (or map database) from a source map (or map database) at a larger scale. During the process, the contents and complexity of the source map are reduced, while the major semantic and structural characteristics for a required purpose are appropriately retained. Map generalization is more than simplification and scale reduction. It represents a process of information extraction and emphasis of the essential while suppressing the unimportant details. It maintains spatial and logical relations between map objects and legibility of the map, and also preserves accuracy as far as possible.

4.1.1 Cartographic and model generalization

Weibel & Jones (1998) classified generalization into two main approaches, known as the cartographer driven (cartographic generalization) approach and the feature reactive (database or model generalization) approach. Cartographical generalization can be defined as a geometrical simplification in a scale reduction process while model generalization is mainly oriented to a structural filtering (Richardson & Mackaness 1999; Weibel & Dutton 1999; Jiang & Claramunt 2004; Neuffer et al. 2004). Model generalization filters the data through a scale reduction process, whereas cartographic generalization deals with representation or visualization of the data at a required scale (Weibel & Jones 1998). However these two generalization approaches are closely related (Jiang & Claramunt 2004), and model generalization is often a pre-process of cartographic generalization (Weibel 1995).

Cartographic generalization represents the process of deriving a graphic product or visualization from a source database (Weibel & Jones 1998). It involves displaying the geographical features required for a map’s purpose or scale, while removing irrelevant detail that would clutter and confuse (1Spatial 2007). Hence, it has to deal with the specific problems of graphical zymology. When the scale of a map is decreased, there is less physical space to represent the geographical features of a region. At the same time, the features need to be exaggerated in the size of the symbols to be distinguishable at a smaller scale. As the features fight for representation in the reduced map space, some features need to be discarded, and those remaining may be further simplified, smoothed, displaced, aggregated or enhanced (Joao 1998). In cartographic generalization clarity and logical consistency of graphic expression is given priority over positional accuracy and completeness (Weibel & Jones 1998). The primary aim is for the resulting map to convey a clearly readable image which is aesthetically pleasing. It is constraint-based process used by cartographers (Jiang & Claramunt 2004), which involves intensive human knowledge obtained through professional cartographic expertise and practice. Thus the result depends on cartographer’s skills, including his/her visual/aesthetic sense, but it is not stable, some is good and some is bad. The way forward is the incorporation of a data modeling process, as it provides a detailed description of the database structure. In other words, model generalization is used as prerequisite to advance cartographic generalization.

Model generalization is the process of deriving a digital landscape model (DLM) of coarser resolution from a DLM of higher resolution (Müller 1991) and concentrates on the derivation of reduced databases from a source database (Weibel & Jones 1998). Model generalization is part of the so-called “object generalization” and aims at a simplification of the geometry, topology, and semantics of objects, but not of their graphical representation (Jiang & Claramunt 2002). Thus it consists of statistical and filtering processes (Brassel & Weibel 1988), and is mainly oriented to structure-based filtering (Weibel 1995; Jiang & Claramunt 2004) in order to decrease the number of features which are no longer relevant in the generalized map, without changing the shapes of the remaining features. As the geometry is not modified in the process, model generalization is often used in situations where aesthetics are less important than accuracy (1Spatial 2007).

As database generalization never generates graphics as output, it prioritizes spatial accuracy and completeness (within the accuracy specifications of the target database) and does not encompass displacement due to symbolization problems (Weibel & Jones 1998). Furthermore, reducing the number of features in database generalization is a key task that can be accomplished by six major operations based on the geometric, semantic relationships, and database constraints that are well documented in the literature (McMaster & Shea 1989, 1992). These include simplification (line generalization), aggregation (combination geometrically and thematically), symbolization (for line, polyline and point), feature selection (elimination and deletion), exaggeration (enlargement) and displacement or moving objects (Oosterom 1995). Among these operators, the selection which may also be referred to the elimination is the most important operator in model generalization process. It may be carried out for various purposes: for controlled data reduction (to save storage and increase computational efficiency); to derive data sets of reduced accuracy and/or resolution; or as a pre-processing step to cartographic generalization (Jiang & Claramunt 2002).

4.1.2 Semantic generalization

In cartography, semantic information is usually treated as an aspect of descriptive information being abreast of geometry information and topology information. Semantic information is also called aspatial information and refers to all non-spatial attributes and relationships describing the identity and meanings of the underlying spatial objects. The spatial data and aspatial data are separately organized as two layers in ArcGIS and MapInfo as Figure 2.10 shows.

Weibel (1997) discussed whether the model generalization is sufficiently explained by semantic and geometric data modeling methods which define the relevant object classes and their attributes. This is the first time of referring to semantic information in map generalization. Jones et al. (2005) defined semantic generalization as activities concerned with the choice of the appropriate categories of information that should be represented.

Together with geometric and topological information, semantic information is used to derive constraints or measures guiding the automated generalization process (Section 4.1.3). Kilpelainen (1997) proposed a measure of semantic accuracy according to which two objects far from each other should still lay proportionally far from each other after generalization transformations. Jansen & Kreveld (1998) defined the clutter function to evaluate the consistency of cartographic generalization by means of semantic constraints. Stell & Worboys (1998) discussed the imprecision which arises through limitations of semantic and geometric resolution of data representations. Weibel & Jones (1998) retains the notion of abstraction similar to the semantic modeling process as part of a hierarchical classification scheme where related entity types, or classes are conceptually grouped into more abstract types at higher levels. Lu et al. (1993) represented the general schema of abstraction by automatically constructing attribute hierarchies demonstrated in Figure 4.1. The schema can be adopted to deal with content generalization.

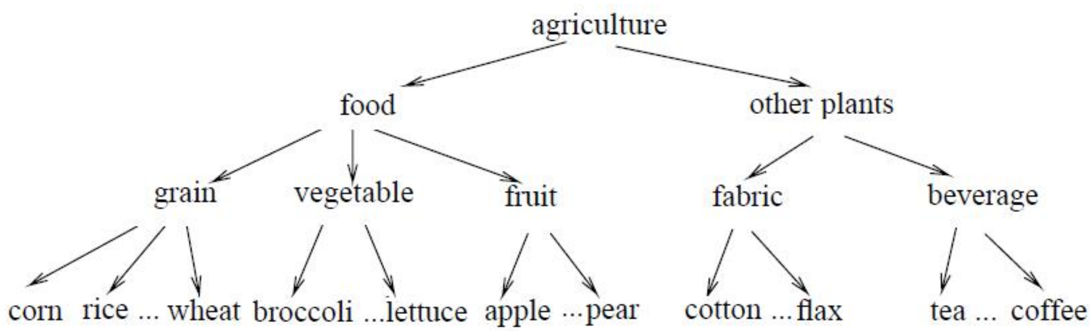


Figure 4.1 An agriculture hierarchy (Lu et al. 1993)

For road network, Richardson & Thompson (1996) and Reynes (1997) proposed similar techniques to select significant nodes within a network, such as train stations or post offices, and then determine the shortest paths between the selected nodes. The frequency of use of a road in various shortest paths is then used as a criterion for classifying its relative importance. Li & Choi (2002) discussed the association of road elimination with six types of thematic attributes: type, length, width, number of lanes, number of traffic ways and connectivity. Sinha & Flewelling (2002) explained a method of multi-criteria line generalization to incorporate road category and road class into the generalization process. Kulik et al. (2005) realized an ontology-driven map generalization algorithm, called DMin, to simplify a road network in which the road classes and tasks are parameterized as semantic weights as shown in Figure 4.2.

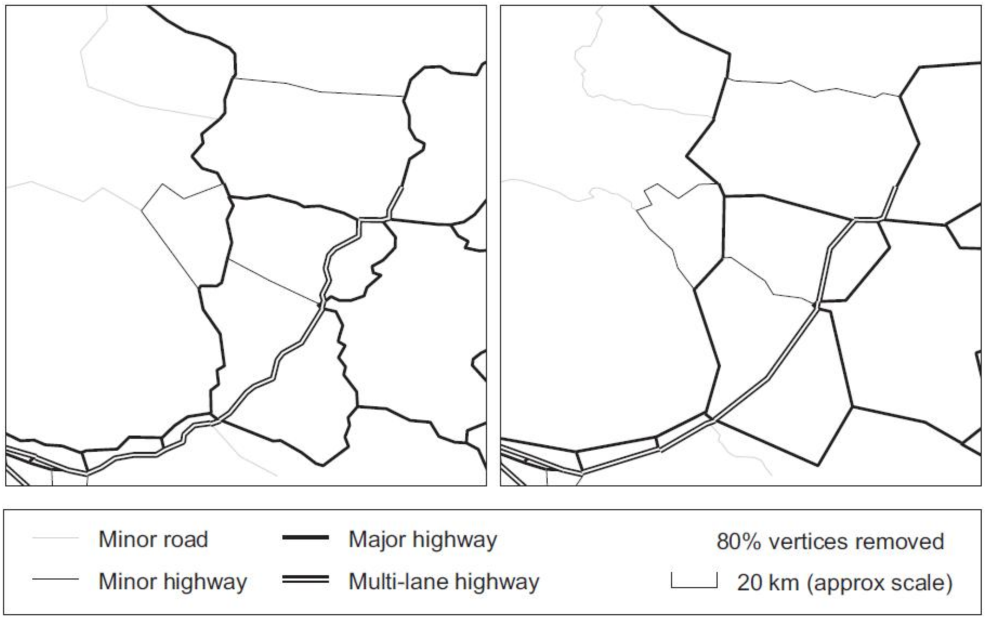


Figure 4.2 Road-network simplifications by DMin (Kulik et al. 2005)

4.1.3 *Automated generalization*

Ever since the paradigm changes from manual cartography to digital cartography, automatic generalization has been subjected to research efforts by both scientific researchers and cartographic practitioners. Heretofore cartographic generalization renders the features for display/visualization as a means of communication. It is a subjective process involving extensive cartographic expertise and skills obtained through practice since maps should satisfy the basic requirements for graphic clarity and legibility, and contain only the relevant map features including their geometric and semantic attributes (Meng 1997). The manual map generalization lacks the consistency of using generalization operations or parameters. Different specialists may create different results of generalization. The largely automated model generalization brings a reduction in the cost and workload of the manual process. Since the database is highly structured and attributed, the model generalization does not require much human intervention. This has stimulated a rapid growth of research on how to automate the overall cartographic generalization.

Automatic cartographic generalization process is interpreted as a function from a source set to a (generalized) target set of geo-spatial features. The source set holds certain properties such as geometric, topological and non-spatial properties as well as their combinations. These properties must be preserved after the generalization. Three books were devoted to automatic generalization (Buttenfield & McMaster 1991; McMaster & Shea 1992; Muller et al. 1995), and several frameworks have been proposed (Brassel & Weibel 1988; Shea & McMaster 1989; Steiniger & Weibel 2005). In these frameworks, three elements such as constraint, data model, and method are defined and integrated. To derive a visually correct map, a number of constraints should be satisfied during the generalization process. Rules are established regarding when these constraints should be set up. For this reason, the solutions of generalization are focused on those conform to a set of conditions. For a map, these conditions are determined by the map specifications, cartographic knowledge of map symbols and geographic knowledge of represented phenomenon. Constraints are violated when geographic information undergoes a change of scale, theme or representation medium, resulting in a decrease of necessary space to accommodate all the map features. Weibel (1997) listed four types of constraints that generalization methods must respect namely metric, topological, semantic, and Gestalt. He studied these four types of constraints in particular for line simplification; moreover they can be used for other generalization operators as well. Duchêne et al. (2001) designed four constraints on the road network agent: topology constraint, junction clearance constraint, road overlap constraint, and micro-road satisfaction constraint, which are worth considering in this thesis.

Over the last three decades tremendous efforts have been made to derive numerical methods applicable to automatic generalization, in order to generate maps at different scales by utilizing advanced GIS-based technologies (McMaster & Shea 1992; Bälia et al. 1995; Joao 1998). Scientists have benefited from object-oriented paradigm (Ruas 1998) and agent-based systems (Lamy et al. 1999; Barrault et al. 2001; Duchêne et al. 2001; Duchêne 2003). Release of commercial GIS generalization tools has been well received by national mapping agencies (Kilpelainen 1997; Lee & Hardy 2005). Powerful generalization tools for deriving multiple scale data from a master database (e.g. Peschier 1997; McKeown et al. 1999; Thomson and Richardson 1999; Jiang & Claramunt 2002) and full embedment of the generalization capability in map compilation have become prevailing (Lee 2003). An essential step in digital map production is to load data into a generalization software module which in turn requires the user to adapt and give priority to constraints.

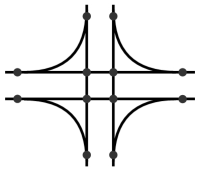
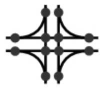
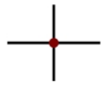
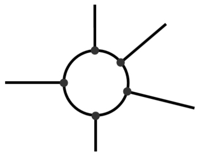
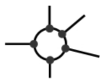
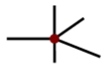
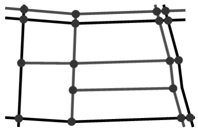
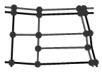
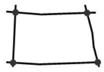
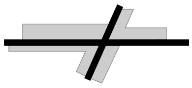
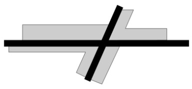
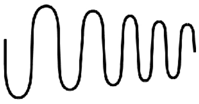
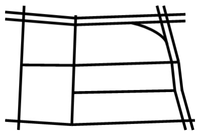
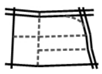
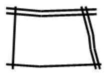
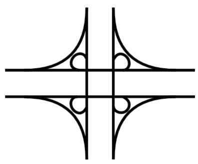
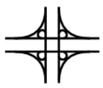
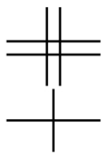
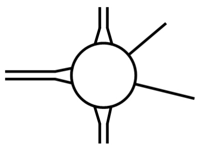
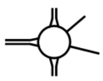
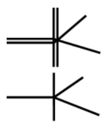
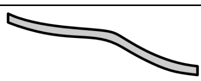
4.2 Operators and algorithms

Generalization operators can be classified with regard to different characteristics. Most operator classifications are project-driven (Beard & Mackaness 1991; McMaster & Shea 1992; Hake et al. 1994; Liu et al. 2001; Alessandro 2003), so that they do not serve any generalization application. For instance, Beard & Mackaness (1991) proposed eight operator and four categories that are embedded within a larger scheme for a map design system which could be attached to a GIS. Except that, Förster (2007) proposed a comprehensive framework to classify operators and describe the impact of individual operators. In his framework, not only the characteristics of road network but also the purposes of road-network generalization are considered for the classification of the operators. Moreover, Li (2007) summarized the algorithmic foundation for implementations of all generalization operators classified by feature type and two levels of individual features and a set of features.

Referring to the operator classification from Li and Förster, we approach a specified classification of road-network generalization in embedded car navigation systems. Generally, spatial features for a two-dimensional representation are categorized into point, line and area. A road network consists of a set of points (nodes and construction points) and a set of lines (road links). Points can be eliminated or represented by point symbols, and road links are represented by line symbols or ribbon-like area symbols which emphasize, for instance, the width of main roads in large-scale traffic maps. Areas covered by the roads are represented by area symbols or point symbols. This latter case, for instance, is useful to emphasize the gravity center of a road network in small-scale maps. Thus generalization operators of road network can be divided into three classes that handle point, line and area features respectively.

Table 4.1 shows the taxonomy of road-network generalization operators that have been extensively studied and implemented. In particular, selection and simplification of line are introduced in detail, as they are adopted for the model generalization in car navigation data authoring.

Table 4.1 Generalization operators of road network

Type	Operators	Large-scale	Photo-reduced	Small-scale	Memo
Point	Aggregation				Aggregate complex intersection with nodes into a node
					Aggregate round-about with nodes into a node
	Selection				Lead to omission of road link by reduc-ing nodes
	Simplification				By reducing shape-points
Line	Enlargement				Enlargement in all directions
	Exaggeration				Enlargement in spe-cific direction
	Displacement				Avoid overlapping
	Schematization				For winding moun-tain roads and hair-pin turns
	Selection				Pick up important road links or omit minor road links
	Collapse				Double-to-single
					Complex-to-simple for complex intersections
					Complex-to-simple for complex roundabouts
Area	Collapse				Area-to-line

(1) Aggregation of Point

Aggregation of point features means the categorization of a set of points into a cluster and then replaces it with a single point. By using this operator, all nodes of a complicated intersection can be aggregated into a composite node. The basic idea of K-means clustering (MacQueen 1967) is to partition a set of N points into K clusters that are mutually exclusive. Iterative self-organizing data analysis technique algorithm (ISODATA) is an interactive algorithm which stars with a single cluster and applies a split-and-merge technique to progressively partition the points into more clusters through constantly assessing the similarity within a cluster (Tou & Gonzalez 1974). Based on ISODATA, Jiang & Harrie (2004) evaluated a street network. Mackaness & Machechnie (1999) developed an algorithm for the aggregation of road junctions following some principles in graph theory.

(2) Selection of Point

When the map scale is reduced, many point symbols will clutter in the display. Therefore, selection operator is necessary and less important point features should be omitted, this is also called selective omission. Unlike point aggregation where the aggregated nodes represent a cluster in which every original node plays a role, the nodes to be omitted in the selection operator are simply less important. Their omission leads to the elimination of links connecting them. Wang et al. (1985) developed an automated method based on an adjacency matrix of a road network and calculated the intensity of all vertices according to the connectivity principle of graph theory. Jiang & Claramunt (2004) built up a structural representation of a street network using graph principles where vertices represent named streets and links represent street intersections. They generalized an urban street network by selecting points instead of selecting characteristic streets. Qian (2007) put forward a polarization transformation algorithm which is able to convert the vertex set of a road network to a one-dimensional spectrum line. The characteristic points along the line are then selected, the road network can thus be simplified.

(3) Enlargement, Exaggeration and Displacement of Line

Small but important objects need to be enlarged to satisfy the visibility requirement (Haunert 2008). For instance, roads are remarkably expressed in traffic maps and their widths are usually not proportionally reduced to the map scale. Enlargement of an area means causes a uniform expansion in all directions. Unlike enlargement, exaggeration tends to enlarge certain object classes or object parts. For instance, international highways are exaggerated more than main roads in urban area even if the latter may have a broader width in the reality. Exaggeration operation is also called caricature if certain characteristic parts of a line are highlighted. A set of caricature algorithms (Fritsch & Lagrange 1995) was used to detect important structures in the frequency domain. The IGN (1977-1978) developed a series of caricature algorithms to deal with very specific problems. The specification of control parameters, however, is not yet solved.

Both enlargement and exaggeration may distort the shape, thus result in graphical conflicts between neighboring objects, in which case objects should be moved or the shape of the objects should be modified to avoid overlaps. This is termed displacement or modification. Modification can be regarded as displacement of object parts.

(4) Simplification of Line

Simplification is the process of making something easier to do or understand by reducing the amount of details. Selecting a subset of vertices or construction points along a line, typically leads to simplification of road features. The point-reduction algorithms aim at making the best approximation of the original line with a minimum number of points. According to the psychological discovery of Attneave (1954), some points on an object are richer in information than others, and that these few points (with richer information) are sufficient to characterize the shape of the object. In other words, a large number of points with less information can be removed without causing large deformation to the line.

This also applies to spatial features.

In most applied methods, geometric parameters were taken as criteria. Simple sequential algorithms were based on the number of points (Dutton 1998), length (Walking algorithm) (Müller 1987), angle (McMaster 1987; Li 1995), and perpendicular distance (Lang 1969; Dougenik 1980), while iterative algorithms managed not to miss any important features. The Jenks algorithm (Jenks 1989; Reumann & Witkam 1974) and Li algorithm (Li 1998) used the minima and maxima in both the X and Y directions. The Ramer algorithm (Ramer 1972) argued progressive splitting based on perpendicular distance first, the same principle was published by Douglas & Peucker (1973) a year later and became better known than the others. Duda & Hart (1973) described the Forsen algorithm as being the same as the Douglas-Peucker algorithm. A Split-and-merge algorithm based on perpendicular distance was attributed to Duda & Hart (1991). Another iterative method is Visvalingham-Whyatt algorithm (Visvalingham & Whyatt 1993) which progressively eliminated points with small effective areas so as to ensure the least area displacement. The functions of the basic geometric parameters were used in alternatives to represent curvature values, and this type of algorithms belong to the category of corner detection, such as the Rosenfeld-Johnston algorithm (Rosenfeld & Johnston 1973) based on cosine value, Teh-Chin algorithm (Teh & Chin 1989) based on distance and chord ratio, Nakos-Mitropoulos algorithm (Nako & Mitropoulos 2003) based on local length ratio.

In order to avoid topological conflicts, for example, in the dual carriageway, Müller (1990) developed a geometric procedure for the removal of spatial conflicts. de Berg et al. (1995, 1998) developed an algorithm to avoid spatial conflicts by considering the chain as a graph. Saalfeld (1999) made use of the dynamically updated convex hull data structure to efficiently detect and remove potential topological conflicts. Zhang & Tian (1997) modified the Douglas-Peucker algorithm to ensure that the new line segments are moved to one side of original line.

By the way, a smoothing operator is a filtering process to remove small crenulations, and it is not necessarily directly related to scale change (Li 2003). It is often understood as a cosmetic operation to improve the aesthetic quality, and sometimes the result of a smoothing operator expresses better the tendency or the most significant characteristics of a line. In a road network, each road link is generally composed of two nodes and a series of construction points. A curved road, e.g. a ramp between a highway and a slip road which connects main roads, is displayed as a set of smooth curves instead of polylines, thus a greater similarity to the original road shape is preserved. Among many smoothing methods, the Snake algorithm (Kass et al. 1987; Burghardt & Meier 1997; Borkowski et al. 1999; Steiniger & Meier 2004; Burghardt 2005) and Cubic Spline algorithm (Press et al. 1992; Burden et al. 1997; Bartels 1998) are fit for road smoothing. Gold & Thibault (2001) proposed a method for generalizing cartographic lines based on medial axis transformation, or skeleton retraction, which can preserve the topological structure of the object and avoid any overlaps with neighboring objects. It can be regarded as a simplification or smoothing method.

(5) Schematization of Line

The schematization operator is used for the transformation of an initial set of features into a subset, while maintaining the distribution characteristics and pattern of the original set. "The result should be a connected and less congested network that represents a similar pattern at the smaller scale." (Kazemi & Lim 2007). The reduction of bends in line generalization is referred to as schematization. It is useful to deal with winding mountain roads and hairpin turns in mountains or hilly region. The structuring process is more complex and usually uses a combination of several basic algorithms including selection, aggregation, simplification, etc. "Individuals seem to judge the shape of the line on two criteria: the directionality of the line and the basic sinuosity of the line" (McMaster, 93), so the sinuosity should be firstly recognized and then be schematized. Planzanet et al. (1995), Planzanet (1995, 1997) and Lecordix et al. (1997) developed balloon algorithms to find one bend or several bends, and used accordion algorithms to reduce the number of bends, either at the vertex or at the base.

(6) Selection of Line

In the generalization process, different atomic operators act to transform the information representation in different ways, principally either by the omission of data or by the reorganization of data. Selection of roads from a network belongs to the former category. As a central operator for generalization of navigational road network, line selection is approached using various theories and measures.

- **Graph theory**

  Road selection can be based on graph theory, such as directed network (weighted graph), minimum spanning tree, dynamic decision tree, shortest path algorithm, and so on. Mackaness & Beard (1993) and Mackaness (1995) utilized directed network (weighted graph) to support road-network selection, and derived several preliminary rules for the generalization process from graph theory. In particular, Thomson and Richardson (1995) as well as Thomson & Brooks (2000) used the concept of minimum spanning trees for road-network selection. Peng & Müller (1996) introduced a dynamic decision tree structure in an attempt to partly circumvent the problem of urban road-network generalization through the use of object classification and aggregation hierarchies, topological data structure, decision rules, and artificial intelligence technology.

  Touya G. (2007) used shortest paths algorithm (Dijkstra 1959) in rural road network between important points to guide the road selection and check the continuity as in urban/rural interface zones. The shortest path algorithm in this context indicates the relative importance of road links and nodes.

- **Stroke**

  Thomson & Richardson (1999) defined a structural element “stroke” which can be derived following the "good continuation" principle in Gestalt psychology (Wertheimer 1938) and Thomson (2006) approached the functional-graphical nature of strokes via a broader consideration of perceptual grouping. A stroke is a group of roads gathered by not only continuous curvature but also homogeneous semantic attributes and is stopped at hanging node, roundabout, branching crossroad or turning. Characteristics of a road network can be preserved if salient strokes are kept during data reduction or selection process. Thom (2005) used it to detect dual carriageways; Heinzle et al. (2005) treated stroke as a pattern of road network. Edwards and Mackaness (2000), Touya (2007), Chaudhry & Mackaness (2005), and Liu (2009) applied the methods of stroke to reach the good results road-network generalization.

- **Road density**

  Road density is another useful constraint or measure for the selection as it provides metric and statistical information about overall road distribution at the macro and micro levels. Zhang et al. (2004) presented a method to select salient roads based on connection analysis which is a favored criterion for maintaining the density variations in road network. Zhang (2008) developed an object-oriented measurement to measure the distribution of density across a map in generalization. Liu (2009) proposed an algorithm for road density (grid method) analysis based on skeleton partitioning for road generalization. Mesh density is another measure indicating the local distribution density of road network. Mesh was defined as the smallest sub-region which could not be divided by roads. Hu et al. (2007) put forward this idea and presented a method for selective omission of street network for digital map generalization. Then Chen et al. (2009) presented an approach to automatic map generalization by using mesh density. Tian (2008) presented a generalization algorithm based on the ordered generalization tree structure to support the progressive representation models. In these research works, the road- network generalization is constrained by the topological and distributional information such as minimum separation rule, connection analysis, progressive representation, skeleton partition and mesh integration.

- **Pattern**

  Patterns were defined as property within objects, or between objects that is repeated with sufficient regularity by Mackaness & Edwards (2002) who argued that it is useful to consider any given map as a view of the subset of all possible patterns inherent among objects in the database, and viewed the process of generalization as being about manipulation and portrayal of pattern for any given scale and theme such as road network. Early in 1995, Sester identified in her dissertation nine node types in the low level of details and several road types according to their node degrees and the arrangement of the intersecting lines. Urban pattern was studied by many researches. Heinzle, Anders & Sester (2005) conducted the automatic localization of a city centre on the basis of pattern analysis and detection in road networks. They defined four kinds of patterns: strokes-pattern, star-like pattern, ring-like pattern and grid-like pattern. In their follow-up works, methods were developed to automatically recognize these patterns (Heinzle et al. 2006; Anders 2006; Heinzle & Anders 2007; Heinzle et al. 2007). Touya (2007) presented a generic process for road-network selection by enriching the data with structures and patterns recognition. Zhang (2004) described the components and properties of grid-like patterns, star-like patterns for road-network modeling and generalization using geometrical parameters and objects.

- **Area ratio of road symbols**

  Gulgen & Gokgoz (2008) developed a road-selection method which can preserve the area ratio of road symbols in a map. The areas in the map space covered by road symbols were used as a measure to decide the maximum reduction limit. Exaggerated road symbols in target scales claim more area, thus requires the elimination of some unimportant roads. The method aims to show cartographic relationship between retained roads and scale change during the generalization.

Selection of roads can also be guided by semantic information as indicated in 4.1.2.

(7) Collapse of Line and Area

Aggregation of a road network is used in two cases: one is to merge dual carriageways, e.g. divided highway converging to a single line; the other is to merge all road links of a complex intersection to a point adjacent to main roads, which is similar to the aggregation of point features. Aggregation of points mainly considers the distribution of points or point clusters, but road network aggregation pays more attention to the pattern of the road links. In addition, aggregation is different from road selection, because all roads involved in aggregation are too important to omit. The location and the shape after aggregation may be displaced or changed to form a new pattern, but the topological relationship and connectivity with the adjacent road links should be kept.

Thom (2006) proposed an aggregation operator to solve several types of conflicts. To deal with the aggregation of dual carriageway, the straight skeleton algorithm (Haunert & Sester 2004), triangulation method (Annita 1998) and Delaunay triangulation method in (Thom 2005) can be used.

A road is often represented as a narrow area when the map scale is large enough. When the large-scale map is converted into a small-scale map, the area representation should collapse into line representation, which is one type of area collapse operator. The principle guiding collapse of road area representation is analog to that of dual carriageway aggregation. Wang & Doihara (2003) developed a method to generalize road areas after detecting intersections and creating polygons covered by road features.

4.3 Generalization characteristics of road network in car navigation data authoring

In car navigation systems, generalization of road network is conducted during the car navigation data conversion to map display data and route-planning data and in the navigation engine. Both model and cartographic generalization operators are necessary as listed in Table 4.2.

Typical cartographic generalizations, such as enlargement, displacement, exaggeration and smoothing of road based on car navigation data, are automatically accomplished in the navigation software or navigation engine for a readable and aesthetic display/visualization.

Referring to section 2.3.4, the generalization of road networks in car navigation data authoring is addressed for navigation database, this type of generalization apparently belongs to model generalization, but it is applicable for both map display and route planning.

In addition, the generalization operators of map display data concentrate on efficient display under certain constraints of the navigation display engine. Therefore model generalization for map display data can be seen as a pre-processing of cartographic generalization of the navigation software.

Table 4.2 Generalization applications of navigational road network

No.	Operators	Car navigation data conversion		Navigation software (navigation engine)
		Map display data	Route-planning data	
1	Simplification & Smoothing of line	Omit redundant construction points in navigation engine; Avoid intersecting of two sides of simplified dual carriageway	-	Remove small crenulations of road; Avoid serrated edge on low-resolution LCD by anti-aliasing algorithm
2	Selection of line and point	Key process to satisfy rural road density and urban pattern	Key process to build up hierarchical road network for accelerating route-planning algorithm	Display in step with map display data; No dynamic generalization is done.
3	Aggregation of point	Keep the original shape of intersection and build up the corresponding pointers to composite node	Aggregate a complex intersection into a composite node to simplify traffic regulation and complexity of route-planning road network for speedup	Display in step with map display data; No dynamic generalization is done.
4	Enlargement Displacement Exaggeration of line	-	-	Dynamic map display by navigation engine, Including notes
5	Collapse of line	-	-	Collapse dual carriageway to single carriageway
6	Schematization of line	-	-	Hard to realize automation

Since the navigational functions largely affect the generalization process of road network, a number of special constraints for car navigation data authoring besides the normal constraints must be considered.

First, in order to guarantee the correctness of vehicle positioning, road matching and route guidance, the coordinates of nodes and construction points, and topology of road network should not be changed. In Table 4.2, displacement, enlargement, exaggeration, collapse and schematization are not permitted in data authoring, but they can be automated (with the exception of schematization) accomplished by navigation software for dynamic display. Simplification omits the redundant construction points along a road without changing the morphological and topological characteristics. After a dual carriageway is simplified, for example, the two sides of the carriageway should not intersect each other. A complex intersection can be aggregated to a composite node in route-planning data to simplify the complex traffic regulation involved in this intersection. However the shape of road is kept unchanged in the map display data, which should build up the corresponding pointers to a composite node in route-planning data. Furthermore, the intersection enlargement (e.g. left side of Figure 4.3) or 3D analog scene (e.g. right side of Figure 4.3) will help to show the complex intersection clearly.

Figure 4.3 Intersection enlargement diagram and 3D analog scene

Second, bidirectional connectivity for traffic flows is required in the higher-layer (middle layer and high layer) road network, which is fundamental for route-planning algorithm. So traffic regulations must be additionally considered in the generalization process.

Third, accelerating route-planning algorithms that work on vertically partitioned road network for efficient long-distance path searching require a reasonable distribution of roads on the higher layer. In other words, since the selected roads for map display should be consistent to the corresponding route-planning data, the multi-level road network for map display cannot be separately treated from the route-planning algorithm, especially when network partitioning is considered.

The above constraints for car navigation data authoring which is in essence a process of model generalization obviously indicate that (1) the selection of road is most important and (2) connectivity and consistency have the larger priority than some conventional selection criteria. For example, small connection links that are too short to be selected in conventional generalization process will be kept in car navigation data authoring because they preserve the connectivity of routes.

With the advent of the information age, the precision of spatial information has been improved, as well as the aspatial and combined semantic information has been greatly enriched. Thus plentiful information as interpreted in chapter 3 can be used to extend formal selection methods, for example selection by individual attributes and road priority. Especially, implicit relationships are mined for new selection methods, such as connection relationship between main links and connection links, service relationship between arterial roads and important cities, and symbiotic relationship between hierarchical road network and accelerating route-planning algorithms with vertical partitioning.

Car navigation data authoring is an automated process for efficient conversion and update, while the automated generalization framework shown in Figure 4.4 is a sub process of the navigation data authoring. This is derived from the framework for the generation of (thematic) maps from GIS Data (Steiniger & Weibel 2005). Compared to the framework of Steiniger and Weibel, this new framework has also three stages but with modified contents. Structure analysis is the first stage and consists of data model definition and pre-processing. The data model is designed for the input and output of all methods including pre-processing, generalization algorithm, and even evaluation processes according to the requirements of model generalization. The resulted spatial constraints (called A) include topological relationship, road pattern, and dependency. Generalization for route planning is conducted in the second stage with constraints from navigation functions and other spatial constraints (called B) including road density, urban pattern, and so on. The generalization methods for map display and for route planning interact with each other and have to consider all constraints in a consistent way.

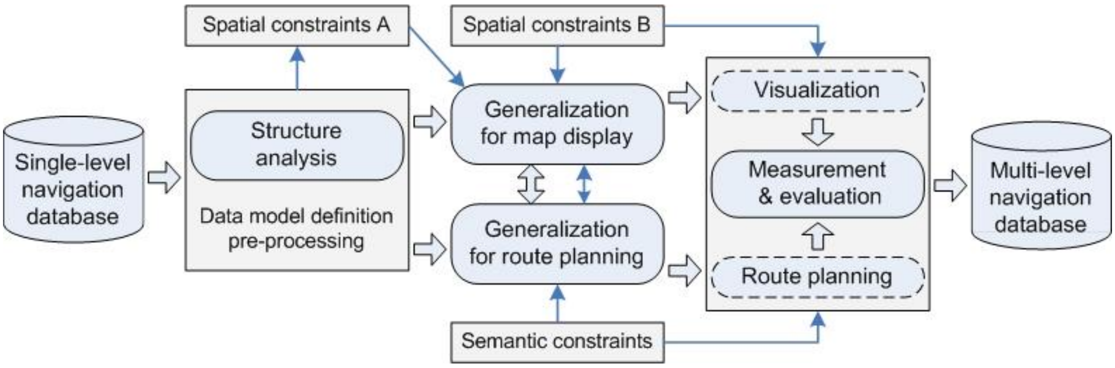


Figure 4.4 Automated generalization framework for car navigation data

Evaluation is activated in the third stage. Here spatial constraints of visualization are used to measure the results of the generalization for map display. Meanwhile, a system test on a test platform or on roads is triggered to inspect the correctness of the route-planning algorithm. The necessary and sufficient condition of road selection is the correctness of all related optimal paths. The performance of map display is a secondary condition in car navigation systems because basic display performance is enough for small LCD-screen. For example, it is possible to pick up (or upgrade) a road, such as a mountain pass and a coastal road, from a low class to the high-layer when it proves a critical path in a region under a poor traffic infrastructure. Actually, speed and functional class should be given more attention.

Overall, the generalization characteristics of road network in car navigation data authoring are overviewed briefly comparing traditional digital maps as follows, in which the three special function constraints is the most important characteristics.

1) Model generalization;
2) Three special functional constraints (spatial accuracy, connectivity and reasonability);
3) Specified operator: selection;
4) Using combined information especially relationships;
5) Automated process;
6) Evaluation according to correctness of all related optimal paths.

Chapter 5

Methodologies

In order to build up an adequate hierarchical road network in car navigation data authoring process, five strategies of road selection are proposed in this chapter. Table 5-1 shows the information involved in the recognition and selection process of each method, and the constraints satisfied by each method.

Table 5.1 Individual selection strategies with required information and constraints

Method	Recognition	Selection	Constraint
Selection by individual attributes	All possible related attributes	Functions of attributes	Spatial accuracy
Selection by road priority	Road class, speed, traffic flow	Road density	Spatial accuracy
Selection by connection link	Spatial pattern, attributes, traffic regulation	**Connection relationship**	Spatial accuracy Connectivity
Selection by important cities	**Service relationship**, selection of cities, traffic regulation, speed		Spatial accuracy Connectivity
Selection by OPCV algorithm	**Symbiotic relationship**, traffic regulation, speed, test case	Critical route	Spatial accuracy Connectivity Reasonability

Before the road features are selected or omitted, they should be recognized. For example, different types of connection links are first separated by their characteristics and are then selected. The selection method by important cities is an exception that has only selection process by transferring the object from roads to cities. The important cities should also be recognized.

All related attributes and traffic regulations explained in chapter 3 are available in source datasets, but the relationships (in bold in Table 5.1) are always implicit in the real world. They are connection relationships between connection link and main link, service relationships between arterial roads and important cities, and symbiotic relationship between accelerating route-planning algorithm with network partitioning and its necessary data base of the corresponding hierarchical road network. What is more, the relationships act as key point of selection in the last three methods, while attributes and spatial information are used for configuration or preprocessing.

As to the three functional constraints, not all methods can ensure connectivity and reasonability for route planning, but the selection operator preserves the spatial accuracy. The two selection methods by important cities and connection link can ensure the connectivity of road network and only the selection method by OPCV algorithm can satisfy the reasonability for route planning by a self-proving process. Actually, the five methods are used in combination for mutual complementation in order to maximally satisfy all functional requirements of car navigation system.

In addition, the two selection methods by connection link and OPCV algorithm is specified for navigational functions, but the others are applied as general selection methods for generalization of road network in cartography.

5.1 Selection by individual attributes

Usually roads assigned to the same value of an individual attribute would appear together or disappear together at the same target map scale after generalization. For example, freeways (e.g. freeway=1) appear at nearly all scales, but parking places (e.g. fow=5) tend to be omitted in most cases.

This method deals with all values of useful individual attributes one by one. The decision for selection or omission of road features is made according to the meanings of each value. The strategies for selection by individual attributes are prevailing: select all roads of a necessary; omit all roads of no use on each scale. For navigation purposes, the selection is considered as a preprocessing to ensure that unnecessary roads are omitted and necessary roads are picked up, though it is not enough to gain a complete and reasonable network.

Figure 5.1 shows the omitted minor roads that are not fit for automobile traffic, Figure 5.2 shows the omitted low-class roads that are unimportant for long-distance route planning, while Figure 5.3 shows the high-class roads that should be kept because they are probably necessary for regional route planning. The test region of these figures is located in the north-east of Munich.

Besides the attributes involved in these diagrams, many related ones can be used in this method, including frontage road, service road, exclusive road, road with traffic limit in terms of speed, vehicle type, and direction of traffic flow, construction information state, pave state and materials, the number of lanes and width and so on.

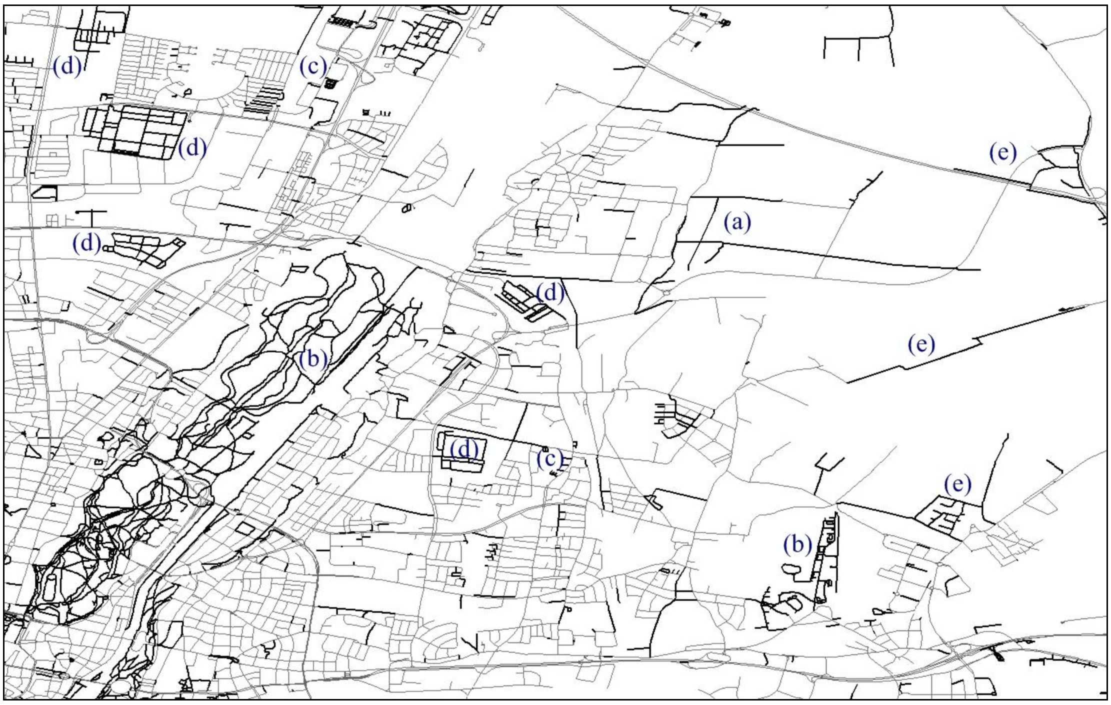


Figure 5.1 Omitted minor roads (in bold) in the northeast of Munich

(a) Back road (primary sector service road); (b) Walkway and pedestrian street; (c) Parking place; (d) Private road; (e) Road closed in both sides.

Figure 5.2 Omitted low-class roads (in bold) in the northeast of Munich (FRC=7,8 or N2C=5,6)

Figure 5.3 Selected high-class roads (in bold) in the northeast of Munich (FRC=0,1,2,3 or N2C=0,1,2,3 or NBC=1,2,4,5,6)

5.2 Selection by road priority

Selection by road priority follows a similar principle to the selection by road class, but it goes beyond the road class as the road priority results from a combinational consideration of kinds of road classes and other attributes. Once the priority order of the individual roads is determined, the related statistics such as the proportion of road length, road density of each priority level can be easily calculated. In this way, a priority level that matches the given standard or level of best detail becomes the threshold below which all roads will be eliminated.

The method to determine the road priority level involves two steps:

1) Analyze the relevant attributes in a database, and rank the road attributes based on their usages firstly. For navigation purposes, network-related attributes are more important than those related to function and administration. Directions of traffic flow and speed category are then used to refine the order when necessary. The attributes used to determine and refine the priority are listed in Table 5.2. For example, the order of relevant attributes in Germany is (N2C > NBC > FRC), and in China is (display class > direction of traffic flow > road class).
2) Get a road priority matrix as the union of attribute values. It is easy to obtain from a database by SQL after relevant attributes are ranked. For example, "select net2class, netbclass, frc, count(*) from road order by net2class, netbclass, frc" can get the counts of each priority level for Bavaria State as Table 6.13 shows.

Table 5.2 Road priority matrix

Priority	Functional class / administrative class	Net class / display class	Direction of traffic flow	Speed category	…
…	…	…	…	…	…

Table 5.3 shows the total and proportion values of some attributes at three limits of priority level in comparison to the reference values for a commercial navigational dataset in the bottom row. The network composed of roads from priority levels (1-61) reveals the largest similarity to the reference value in terms of proportion of count and length. If the limit is set at the priority level-60, the similarity decreases, while the priority level-62 as the limit reveals the least similarity. Figure 5.4 demonstrates the selected roads based on three limits. Taking the reasonability for route planning in the middle-layer road network into account, generally as many roads as possible should be selected within the allowable bounds of selection proportion of road length and road density. For this reason, the limit at 61 is the best solution, or there will be too many roads if the roads from level-62 are included.

Table 5.3 Alternative solutions and reference statistics of Bavaria State

Priority selection	Area (k skm)	Low-layer road links		Middle-layer road links				
		Count	Length (km)	Count	Count (%)	Length (km)	Length (%)	Density (km/skm)
…	…	…	…	…	…	…	…	…
1-60	70.55	1996716	300618.9	215977	10,8%	33826,5	11,3%	479,5
1-61	70.55	1996716	300618.9	242065	12,1%	37855,2	12,6%	536,6
1-62	70.55	1996716	300618.9	510842	25,6%	76673,3	25,5%	1086,8
…	…	…	…	…	…	…	…	…
Reference	***70.55***	***1551693***	***224838.1***	***197569***	***12.7%***	***29942.6***	***13.3%***	***424.4***

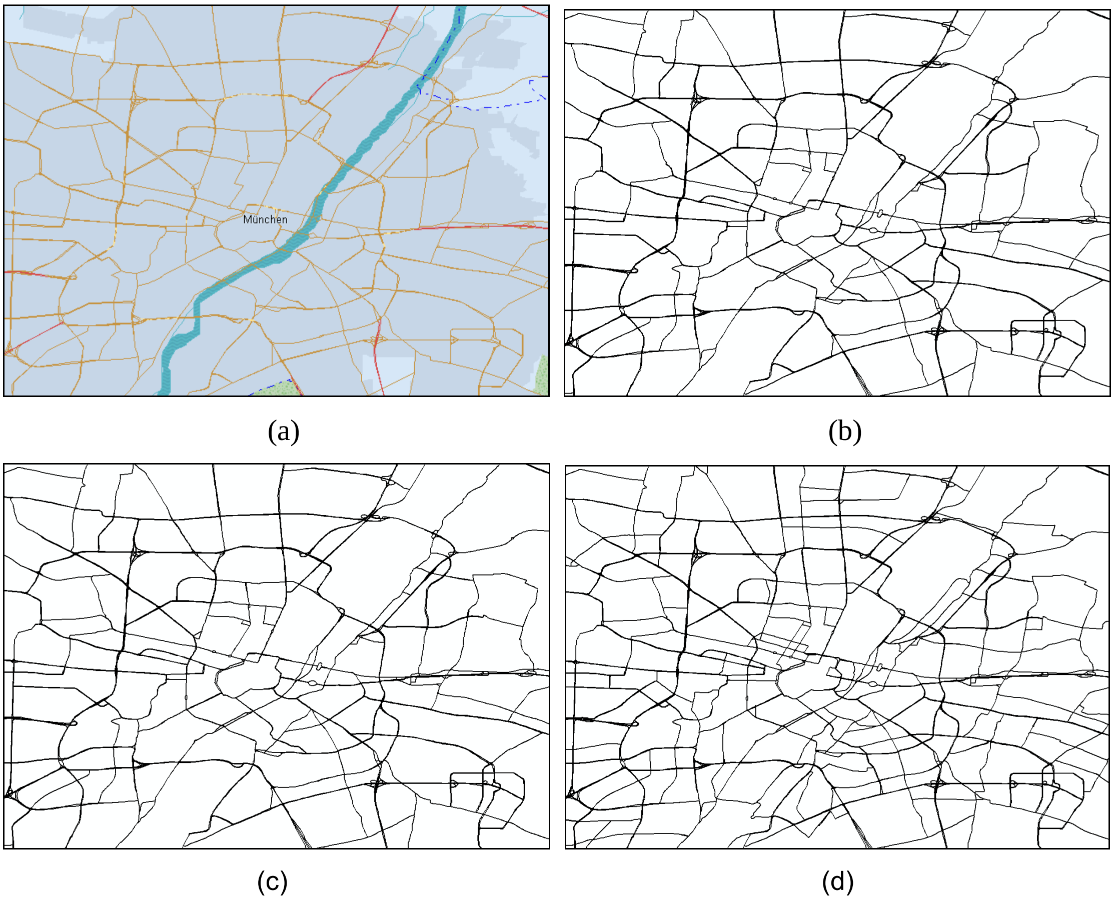


Figure 5.4 Comparison of middle-layer road networks in Munich

(a) Reference data; (b) Roads of priority levels 1-60;

(c) Roads of priority levels 1-61; (d) Roads of priority levels 1-62.

The selection by individual attributes and by road priority for the middle-layer road network can provide a reasonable visual impression. In the selection result, however, some road links are disconnected, which is undesirable for navigation purposes. Therefore, further selection criteria are necessary.

5.3 Selection by connection link

In traditional cartographical generalization, connection links are usually collapsed or aggregated because they would overlap main links. But for navigation purposes, connection links play a significant role for the preservation of the connectivity in a real-world road network. Therefore, they deserve a careful treatment.

5.3.1 Connection classification

Table 5.4 lists three primary categories and 15 secondary categories of connection classification. The primary categories are defined according to their connected objects and functions; furthermore it is related to the difficulties of road selection and collapse. A main link represents a main part of a road and extends in a continuous direction with a view to pass from one place (city/town/intersection) to another, which usually has a formal official name. A main link is easy to select by road priority according to regular road classification. A service link is usually connected to a side of a main link for traffic relief, parking or other services, which would not be used in long-distance route planning, so it tends to be omitted after generalization. Connection links bridge the gaps between main links, thus keep accessibility between main links. For navigation purposes which require the connectivity, however, the connection links must be carefully treated in generalization of road network in car navigation data authoring, which is the motivation to propose the connection classification.

Table 5.4 Connection classification

Primary category	Secondary category
Main link	Motorway
	Dual carriageway except motorway
	Single carriageway
	Inner link of intersection
Service link	Relief link of auxiliary road
	Service link of auxiliary road
	Service area (including the road links of entrance and exit)
	Parking area (including the road links of entrance and exit)
Connection link	Inner connection link
	Directional ramp
	Entrance/exit of motorway
	Non-directional ramp
	Maneuver link
	Roundabout
	Connection link of auxiliary road

Among a great number of road categories, the following terminologies are particularly relevant for this thesis work, and therefore, deserve a detailed introduction:

1) Dual carriageway - It is a highway in which the two directions of traffic are separated by a central barrier or strip of land. As a main link, it is specialized as road links with two sides.
2) Single carriageway - It is a road without physical separation between opposite traffic flows. As a main link, it is specialized as a road link with only one side. It includes a single line, or one-way road.
3) Freeway - It is defined as divided highway with limited access such as a motorway, a main road. It belongs to the dual carriageway.
4) Motorway - It is defined as high-speed highway or called expressway with limited or unlimited access. Most motorways are digitalized as dual carriageways.
5) Main road or major road - It is defined as a road in the second highest class. For example, almost all national highways and some provincial highways except motorways are main roads in China. Most main roads are digitalized as dual carriageways.
6) Secondary road - It is a road in a lower class than main road and consists of some provincial highways and important county roads. Parts of secondary roads are digitalized as dual carriageways.
7) Minor road - It is a road in the lowest class of all roads.

As Figure 5.5 shows, links 1, 2, 3, 4 are connection links, and links A, B, C, D and E are main links. Among them link-A and B are two sides of a dual carriageway, link-C and D are single carriageways, and link-E is an inner link of the intersection and a part of the single carriageway. Comparing with that an inner connection link (e.g. link-4 in Figure 5.5) connects two sides of a dual carriageway, an inner link of intersection connects not only two sides of a dual carriageway (e.g. link-A and B in Figure 5.5), but also the main link stroke it belongs to (e.g.

Link-C and D in Figure 5.5). Considering its connection functions, inner link of intersection (a type of main link) is explained together with connection links.

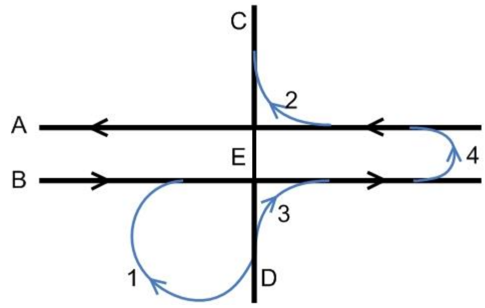


Figure 5.5 Samples of main links (A-E) and connection links (1-4)

There are seven types of connection link and the related inner link of intersections in terms of their functions as explained in Table 5.5 and demonstrated in Figure 5.6.

Table 5.5 Types of connection links

No.	Type	Function description	Comment
1	Directional ramp	It connects arterial roads of usually the same function class at a complicated junction of motorways in both rural and urban area.	It is the transition section between two motorways, and has the same pavement materials and structure, so actually it is a part of arterial roads but not named or identified as arterial roads in database.
2	Entrance/exit of motorway	It has the obvious function to connect motorway with another road.	It has usually a clear identification of link attribute. It is easy to recognize if a toll station exits on it.
3	Non-directional ramp	It mutually connects two-level (at height) crossing roads (a main roads, not motorway, always exits) except directional ramp.	It is almost with clear identification of link attribute and easy to recognize, and always connect to overpass or bridge.
4	Maneuver link	A short-cut link provides for a right-turn only when the vehicle is running on the right side. A special link provides for a P-turn or for a left-turn including a U-turn lane when a vehicle running on the right is to turn to the left. (left-hand drive in a similar way)	It connects same level (at height) crossing roads, which is different from ramp. It is usually with clear identification of link attribute, but not clears about the U-turn from an inner connection link.
5	Connection link of auxiliary road	It parallels to a main road to connect the main road with another road together combining ramps or maneuver links.	It is a part of ramp stroke or maneuver stroke.
6	Roundabout	It consists of a set of circular junction links in which road traffic must travel in one direction around a central island.	Whether a big roundabout junction or small roundabout intersection, they continue the direction of the main road.
7	Inner connection link	It connects both sides of dual carriageway, usually U-turn.	It is the exclusive to the U-turn as a maneuver link.
*	Inner link of intersection	It does not exist independent in the real world, just a digital representation where two or more roads cross or meet.	It is absolutely a part of main road and always with the left turn regulation. 4-way intersections are the most common.

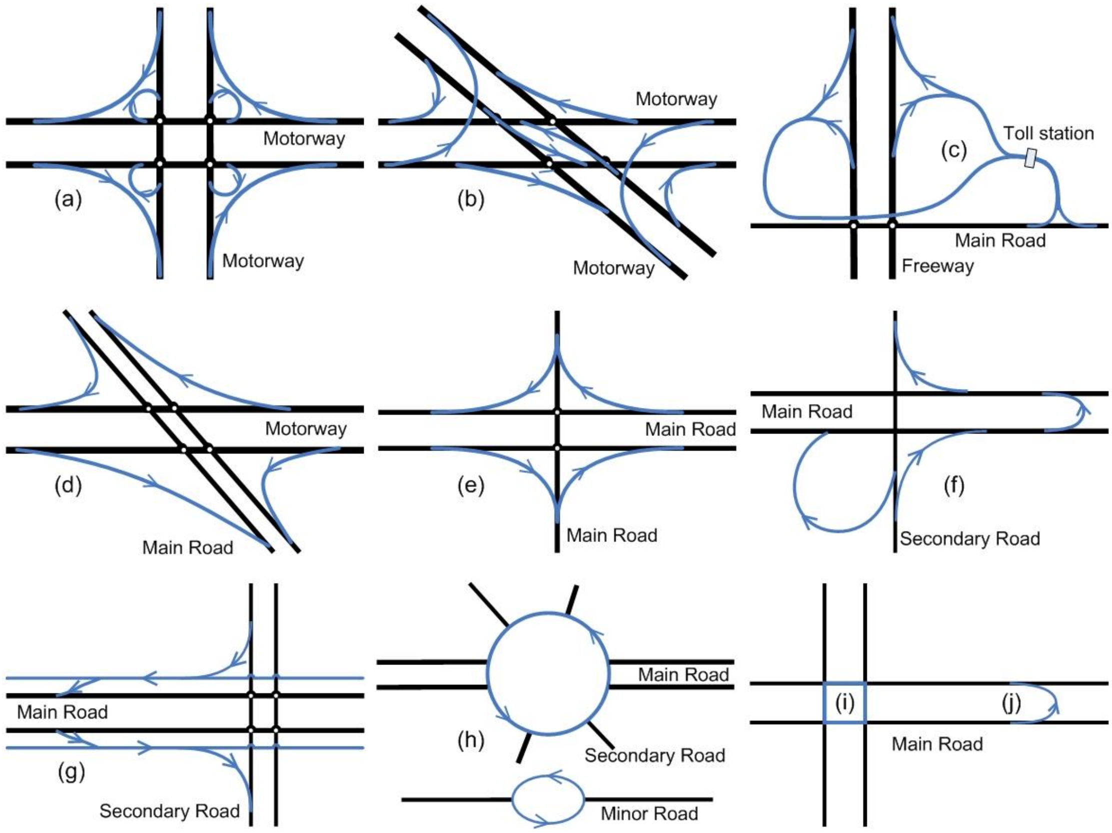


Figure 5.6 Schematic diagrams of connection links (in blue)

(a) Directional ramp at a crisscross; (b) Directional ramp at an irregular junction;
(c) Entrance/exit of a motorway with a toll station; (d) Entrance/exit of a motorway;
(e) Non-directional ramp; (f) Maneuver link (g) Connection link of an auxiliary road;
(h) Roundabout; (i) Inner connection link; (j) Inner link of intersection.

In addition, an auxiliary road is parallel to a main road (no motorway) and runs along one side of the main road. It can relieve the traffic flow in case of Figure 5.7a, guide to a service center or depot in case of Figure 5.7b, and connect the main road to another road, which is called connection link of auxiliary road (e.g. Figure 5.6g). The service area (e.g. Figure 5.7a) and parking area (e.g. Figure 5.7d) are branches from a freeway. Along with the guidance road to a service area or parking area, they connect back to the freeway rather than another link.

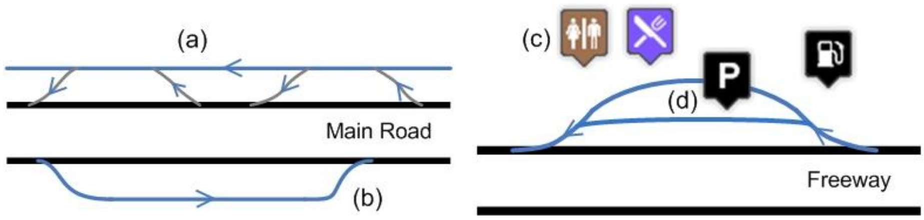


Figure 5.7 Samples of service link (in blue)

(a) Relief link of auxiliary road;
(b) Service link of auxiliary road;
(c) SA; (d) PA.

5.3.2 *Recognition of connection link*

In some geographical source data with enough rich information in good quality, the semantic attributes are used for recognizing different types of connection links. But for bad-quality source data which has just reached the threshold for navigation data authoring, the semantic attributes usually have no value or wrong values. Consequently, the spatial characteristics, relations and regulations are used to help recognize them. Detailed recognition proofs are represented in Table 5.6.

Table 5.6 Characteristics of connection links

No.	Type	Attribute (usability)	Spatial characteristics	Relation & regulation
1	Directional ramp	Ramp flag (sometimes, connecting vertical cross motorways)	Curved link with many forms	Connecting with motorway, excluding PA & SA. Building up strokes of all connection links: both ends are motorways.
2	Entrance /exit of motorway	Access flag (usually) Ramp flag (sometimes)	Curved link with many forms	Connecting with motorway, excluding PA & SA. Building up strokes of all connection links and judging if one end is motorway; the other end is not motorway.
2	Non-directio nal ramp	Ramp flag (usually)	Curved link with several forms	Connecting with dual carriageways usually, at least one. Building up strokes of all connection links, and judging if it connects two different two-level crossing roads.
4	Maneuver link	Maneuver flag (usually) P-turn flag (sometimes)	1/4 circle curve shape of the short-cut links of right-turn. 3/4 circle curve shape of short-cut links of P-turn. U-turn curved shape	For short-cut links: connecting with main roads, mostly including a dual carriageway. Building up strokes of all connection links, and judging if it connects two crossing roads on same level. For U-turn: checking the intersection nearby, and judging if corresponding right-turn short-cut link and left-turn forbidden exist.
5	Connection link of auxiliary road	Auxiliary road flag, Special road name (sometimes)	Parallel to the side of a main road	Parallel to main roads in urban area.
6	Roundabout	Roundabout flag (usually)	A round or ring shape	
7	Inner connection link	U-turn flag (usually)	U-turn curved shape	Comparing with maneuver link, there are no corresponding right-turn short-cut link and left-turn forbidden.
*	Inner link of intersection	Inner link flag (usually)	Straight link	

Their functional types of connection links are very well reflected in their spatial characteristics, relations and traffic regulations. It is empirically possible to traverse all road links so that all necessary connection links can be identified. This idea can be converted into a more efficient automated process as illustrated in Figure 5.8 with the following steps:

1) Recognize three types of main links except inner link of intersection. It is easy to identify motorway and dual carriageway by semantic attributes such as road class and road form along with the geometric, topological and distributional characteristics. Single carriageway can be separated from connection link and service link by attributes such as road name, road form, construction information, flag of connection link or service link, and traffic information. Usually the single carriageway has no traffic regulations, but connection link and service link have traffic limit, for instance, connection links are always one-way road.
2) Recognize roundabouts by attribute that the roundabout flag is nearly right recorded. Roundabout is a special spatial form that sometimes exists at the end of a main link and plays a transitional role from a main link to a connection link.
3) Check all connection links directly connecting to main links (including connected roundabouts) under in the order from motorway, dual carriageway to single carriageway. As each type of main link connects with different specified types of connection links, it is easy to arrange then taking the specified types into account. For example, directional ramp only connects to motorway, and all entrances and exits of motorway can also be picked up when checking motorway.
4) Chain the connection link from each main link with further links running in the nearly same direction into a longer stroke till another main link is touched. Referring to Figure 5.6g, connection link of auxiliary road can be chained into a stroke as a non-directional ramp or a maneuver link (see the dashed arrows in Figure 5.8).
5) Confirm the type of connection link by analyzing the two main links connected by the stroke.

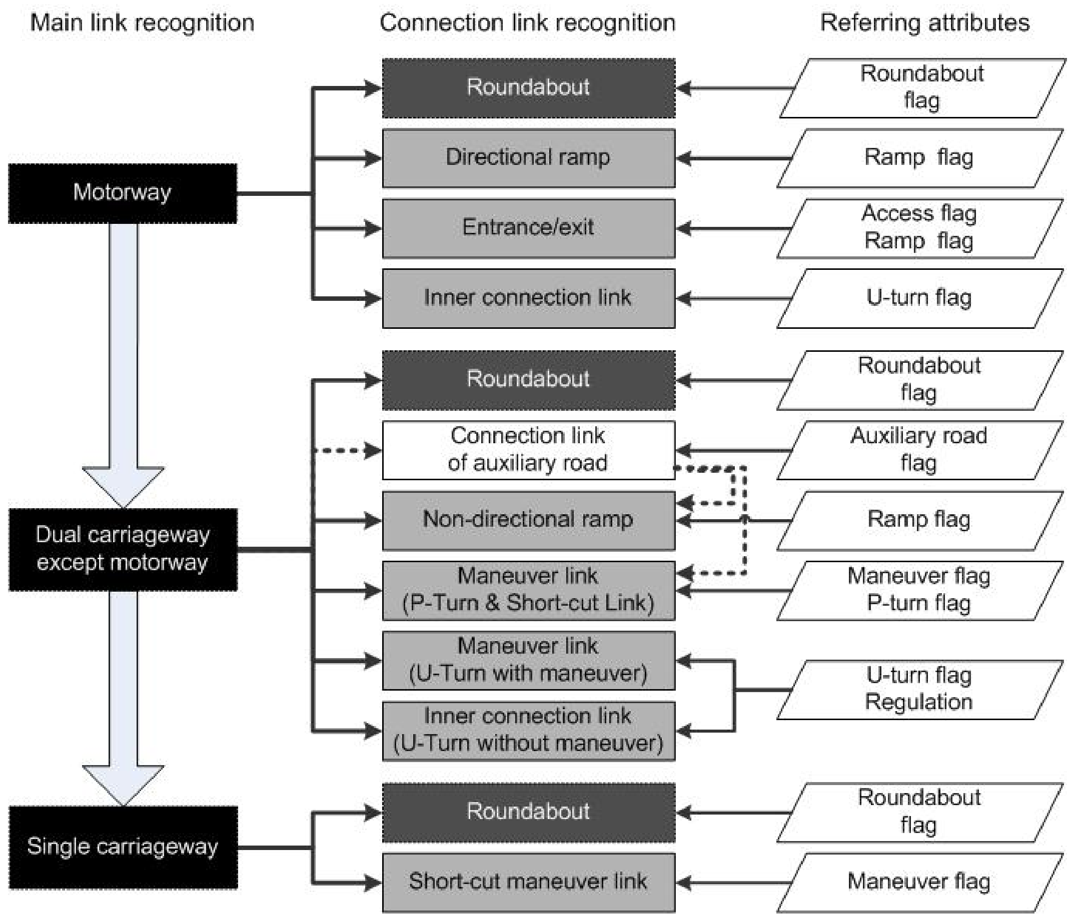


Figure 5.8 Recognition process of connection links

In addition, the method of connection stroke differs slightly from general stroke as a special application. In general stroke, a road link should exit in only one stroke. Referring to Figure 5.9, compared to the normal stroke B, connection stroke D contains link-2 and link-3, in the meanwhile link-3 exits in connection stroke C joining link-1 up. The reason why connection link is repetitively used is that, the connection stroke should ensure connection with two main links that help to confirm the types of connection link (stroke) and to cope with selection in scales.

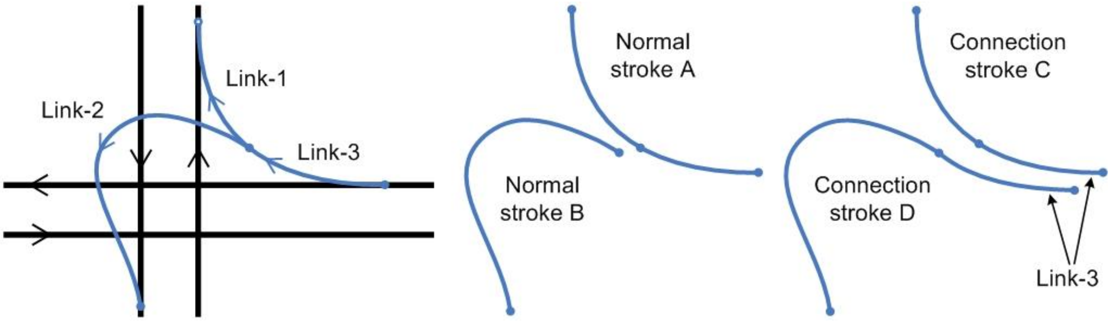
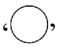


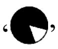
Figure 5.9 Normal stroke (A, B) and connection stroke (C, D)

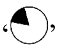
5.3.3 *Selection criteria of connection links*

Table 5.7 lists the selection criteria for each type of connection link and related inner link of intersection. Five classes of values are suggested, depending on the functional class of the main links it connects:

1) ‘’ means selection;

2) ‘’ means omission;

3) ‘’ means selection in most cases;

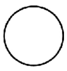
4) ‘’ means omission in most cases.

5) ‘’ means either selection or omission depending on the selection degree of the connected main links;

In the selection criteria of connection link summarized in Table 5.7, four general cases are perceivable:

1) Selection along with the most important connected road link in the highest functional class, e.g. roundabout in Figure 5.10a,b. A roundabout that connects many road links is usually characterized by pairs of strokes following the principle of natural continuity. If the roundabout is omitted together with the least important road links, there will be a gap between the important road links.
2) Selection along with the less important connected road link in the lower functional class, e.g. maneuver links in Figure 5.10c,d. These maneuver links connect two different main links of the same or different categories. If the less important road link is omitted in a higher layer, the connection link loses its function and therefore can be omitted as well. Ramp and entrance/exit of motorway also comply with this rule.
3) Selection along with the connected road links of the same functional class, for instance, inner connection link in middle layer and inner link of intersection connect two segments of a main link, and their selection helps maintain the consistency.
4) Omission in high layer directly, e.g. an inner connection link that connects both sides of a dual carriageway is not needed for long-distance route planning in high-layer road network.

Table 5.7 Selection criteria of connection links

No.	Type	High layer	Middle layer	Criteria & comment
1	Directional ramp			For high layer, mostly It's selected together with the connected motorways, except some local motorways. For middle layer, unconditional selection.
2	Entrance /exit of motorway			It's selected together with the connected main road, not motorway because the functional class of motorway is usually higher than that of main road. If the main road is retained in a layer, the entrance/exit should be kept to connect it with motorway. Otherwise it is omitted.
3	Non-directional ramp			It's selected together with the less important connected road. If a less important connected road is retained in a layer, the non-directional ramp should be kept to connect it with important road. Otherwise it is omitted.
4	Maneuver link			It's selected together with the less important connected road in the same way as with non-directional ramp.
5	Roundabout			It's selected together with the most important (highest level) connected roads to keep the connectivity. The roundabout that connects roads in three or more directions is so important that it is usually selected in middle layer. The roundabout that connects roads in only two directions for the purpose of speed control is usually omitted in middle layer.
6	Inner connection link			For high layer, it is omitted because it is not used for long-distance route planning. For middle layer, it is selected together with the connected road (both sides of dual carriageway).
*	Inner link of Intersection			It's selected together with the connected road. Actually it is a segment of the main road and same as the connecting road links.

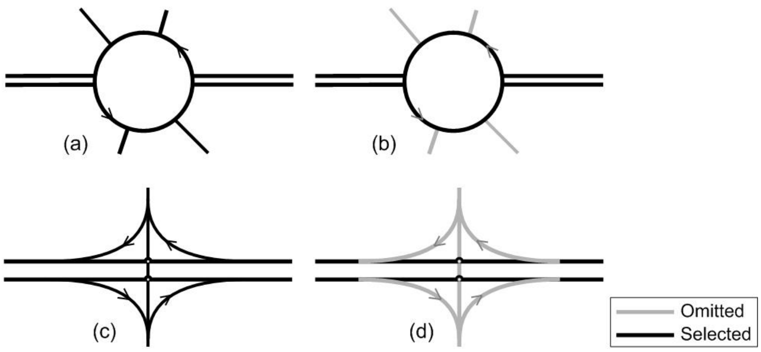


Figure 5.10 examples of selection by connection link

(a) A roundabout is selected when all main links it connects are selected;
(b) A roundabout is selected when some of main links it connects are selected;
(c) Maneuver links are selected when all main links they connect are selected;
(d) Maneuver links are omitted when one of main links they connect is omitted.

5.4 Selection by important cities

As mentioned in Chapter one, two common problems exist on a small-scale map of road network. One is the broken connectivity between the selected high-layer roads and the other is the ill-balanced distribution of these selected roads. Both problems can be resolved if the road selection takes important cities into consideration. Figure 5.11 demonstrates the process of finding high-layer roads for a test area (usually a province/state) for route-planning purposes.

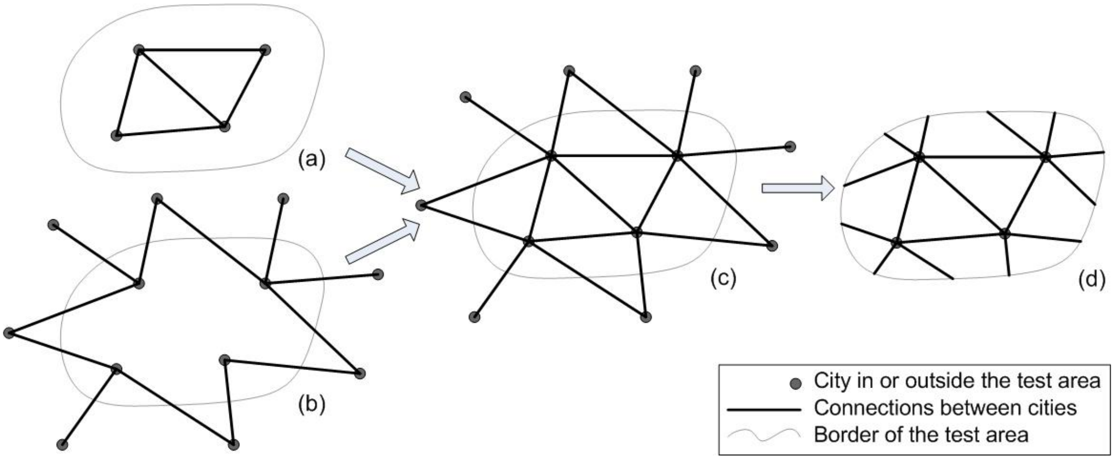


Figure 5.11 General selection by important cities

(a) Connections between important cities within the test area;
(b) Connections between important cities of the test area and other important cities beyond the test area;
(c) Combined connections of (a) and (b);
(d) High-layer roads selected by important cities for the test area.

This aforementioned process bears some similarity to the approach of Richardson and Thompson (1996) and Reynes (1997) that calculates the shortest paths between attractive points. But the idea here combines the functional classification with the network classification.

The functional classification makes the distinction among three categories of highways: arterial highway, collector road, and local road. The arterial highways provide direct service for important cities and larger towns which generate and attract a large proportion of trips. In network classification, the class is defined according to the relative importance of the constituting roads and ferries in the total road network. The roads of the highest class connect the most important cities on a continent and within a country. Both arterial roads and roads of the most important in a network have a similar inherent relationship with important cities and support the fastest access between them. This relationship holds for the functions of high-layer road network for navigation and long-distance route-planning algorithm. In addition, the hierarchical navigational road network has a corresponding relationship with road classes resulted from functional classification and network classification as shown in Figure 5.12. With the test data of Bavaria State, the road networks in corresponding layers are similar with each other as Figure 5.13 shows.

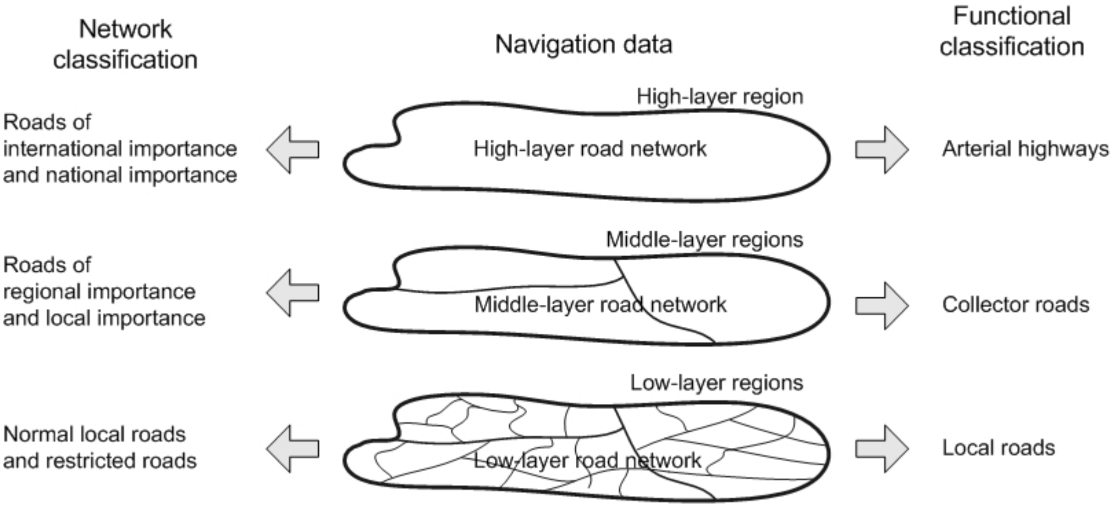


Figure 5.12 Correspondence between the hierarchical navigational road network with classes by network and by function

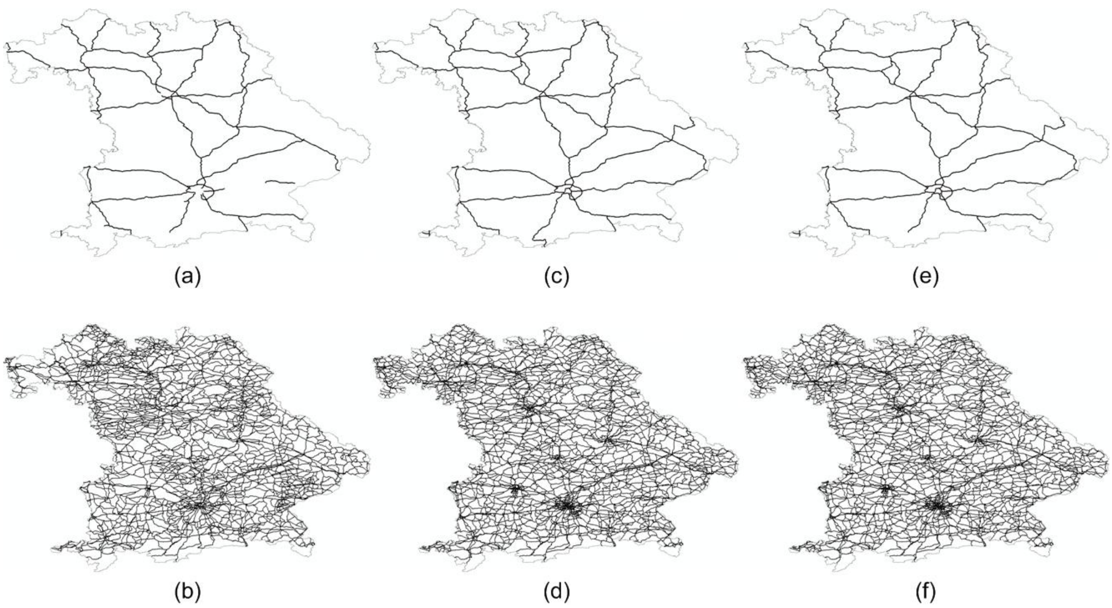


Figure 5.13 Examples of correspondence relationship

(a) Roads of international importance and national importance by network;
(b) Roads of regional importance and national importance by network;
(c) High-layer road network in car navigation data;
(d) Middle-layer road network in car navigation data;
(e) Arterial roads by function;
(f) Connection roads by function.

The key step of this method is therefore the selection of cities, which is obviously less complicated than the selection of roads, as the number of cities is much smaller than that of roads. The important cities can be recognized according to:

1) Passenger capacity and freight capacity which reflect the mobility volume of a city. Alternatively, urban population and economic aggregate can be used. Cities with particularly high traffic capacity are also selectable in spite of their relative small population or economic aggregate.
2) Administrative level. It is a very useful parameter, especially in China. There is a special level ‘prefecture’ between province and county. As social and economical resources are concentrated in cities at the provincial level and prefecture level, these cities are usually

regarded as important. Small cities at prefecture level and large county cities are omitted or selected under certain conditions.

3) Special functions. These include cities on the border with rapid development of trade, important towns in remote mountain areas, important port cities, and so on.

Furthermore, urban agglomeration is represented by the most important city. In Bavaria State, the most important cities are for example, Munich, Nuremberg (including Fuerth and Erlangen), Augsburg, Regensburg, Wurzburg (including Aschaffenburg) and Ingolstadt. In fact, it's important to find all related cities outside the test area because they provide good cues for the identification of a right number of important cities within the test area.

Figure 5.14 Selecting artifacts caused by proxy points in the road network for Munich

If each of the selected important cities is then assigned to a proxy point in the urban road network as the start point or the destination of a route-planning algorithm, usually, the proxy point can be the city center, a main coach station or an entrance/exit of motorway near the city. It is easily retrievable from POI information. However, some artifacts may occur. For example, in Figure 5.14, node-A is the city center of Munich, and node-B is the main coach stop. The extra roads in red that connect node-A and B to the arterial roads in bold black are selected as high-layer roads. This artifact is demonstrated in Figure 5.16 where Figure 5.16a should be the desirable selection and Figure 5.16b is not a desirable selection although it preserves connectivity to the proxy node of the city, while the beltway that is part of necessary arterial roads is not selected.

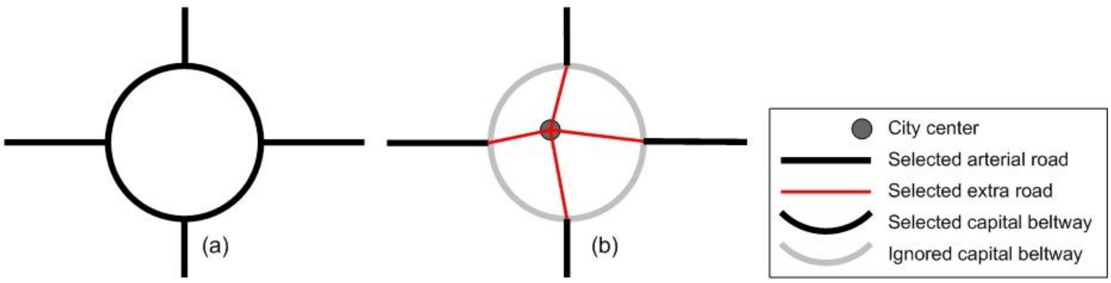


Figure 5.15 Schematic diagram of the selection artifact by proxy point

(a) Expected selection;

(b) Undesired selection that loses arterial roads and picks up needless extra road, although keeping the connectivity to the proxy point (city center).

Referring to Figure 5.15a, the arterial road in/near urban area can be selected by connecting related cities near. Consequently, the method of selection by important cities can be improved by the cities outside the test area as Figure 5.16 shows.

All the arterial roads marked in bold black in Figure 5.16a can be selected, taking the reference of the nearby cities. The high-layer roads in rural area in Figure 5.16b are same as those selected by all cities in and outside the test area in Figure 5.11d, moreover the high-layer roads in/near urban area can be selected correctly as Figure 5.15a shows. By the way, the proxy point of cities outside the test area can be selected as any type, even any node in the urban area, because no roads outside of the test area should be selected.

The cities outside the test area should be selected by analyzing the main routes from or to its neighboring regions. The transport information should therefore be collected and referred to. Empirically six cities or more outside a test area should be picked up in order to identify most arterial roads.

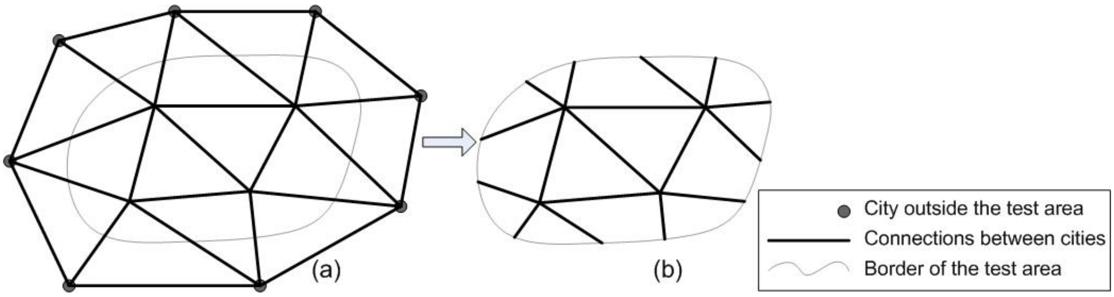


Figure 5.16 Improved selection by important cities

(a) Connections between important cities outside the test area;

(b) High-layer roads selected by important cities within the test area.

Furthermore, if the test region is located at the sea as shown in Figure 5.17, the city at a corner in the test area should be picked out as start point or destination. Usually, the exit of motorway or main roads near the city will be selected as the proxy point, so that the problem shown in Figure 5.15b can be avoided. In this situation, all important cities near the sea or other natural border in the test area and at least four cities outside the test area should be picked up.

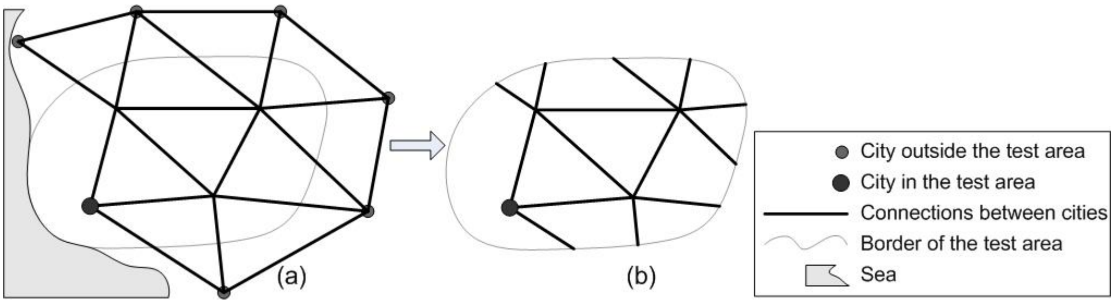


Figure 5.17 Complementary Selection by important cities

(a) Connections between each city in and outside the test area;

(b) High-layer roads selected by important cities within the test area.

In addition, as to large island area such as UK, Australia and Japan, all important cities near coastlines should be picked up, taking ferries into account.

To summarize, selection by important cities is the method to find the arterial roads by route-planning algorithm in which relative important cities are selected as the start points and destinations with the route-planning strategy - shortest time. In order to speed up the methods, only single middle-layer road network are used in this method.

5.5 Selection by OPCV algorithm

5.5.1 The concept of OPCV algorithm

Figure 5.18 shows the typical shortest way-finding problem when the optimal routing algorithm such as the accelerating A* algorithm is performed on a network partitioning based on an unreasonable hierarchical road network. Since a middle-layer road marked in grey in Figure 5.18a is not included in high layer, the accelerating A* algorithm will therefore follow the high-layer roads in red, thus provide a longer route in the end. In order to support accelerating A* algorithm to obtain the correct optimal route in green in Figure 5.18b, the inclusion of the necessary middle-layer road in the high-layer road network will lead to a more reasonable hierarchical road network. This is the task of an Optimal Path Comparison and Validation (OPCV) algorithm.

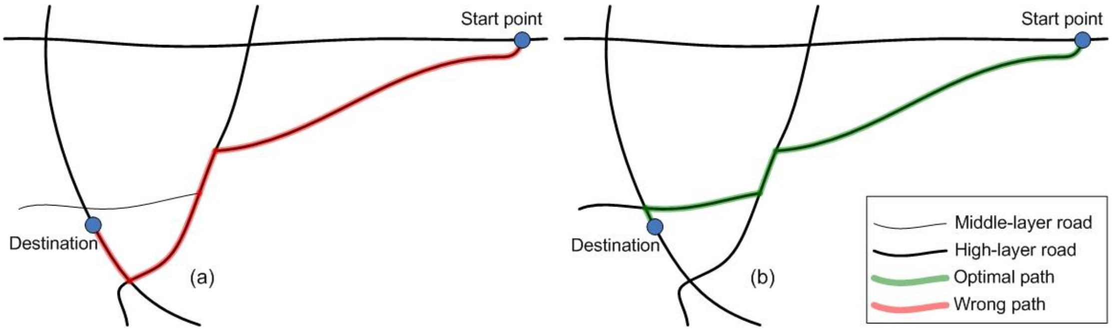


Figure 5.18 Typical problem caused by unreasonable hierarchical road network

(a) Suboptimal path when a necessary road is not included in high layer;

(b) Optimal path when the road is picked up into high layer.

The idea of the OPCV algorithm is inspired by a system test method for the examination of the route-planning function of a navigation unit. A routing task typically involves a given start point, destination and a route-planning strategy. It can be tested in two environments with different hardware, datasets and algorithms as shown in Figure 5.19. The correct results can be definitely calculated with A* algorithm working on a single layer of road network as proved by Hart et al. (1968). But the accelerating A* algorithm that aims at speeding up the searching process, thus works with network partitioning can not ensure the correctness of results, depending on how the hierarchy of the road network is established. If the results of two algorithms are different, there must be something wrong with the network partitioning for the accelerating A* algorithm.

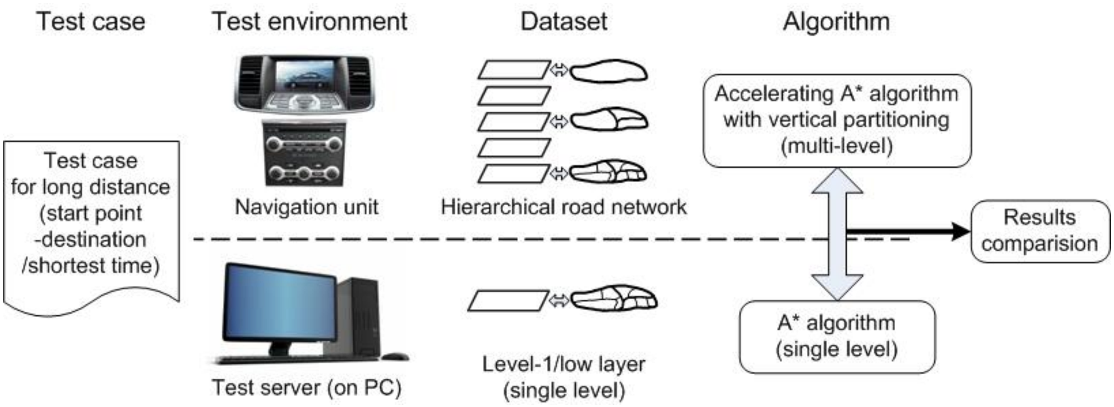


Figure 5.19 System test of a navigation unit

Theoretically, this test method can be used to uncover problems for any arbitrarily given routing task, but obviously it is inefficient to calculate the paths with so huge road links from the low layer. In order to increase the efficiency, a simulation environment on test server for a navigation unit with simplified databases can be created. Since only some necessary roads from the middle layer will be included to the high layer and it seldom happens that a road from the highest layer is connected with a road from the lowest layer, the roads from the low layer can be eliminated from the single-layer road network for A* Algorithm, while the hierarchical road network for the accelerating A* Algorithm will just consist of middle layer and high layer. In the test, all nodes in the test region and the nodes of the links outside the test region that are directly connected with can be selected as valid terminating points for the route calculation.

Figure 5.20 illustrates the automated test process of the OPCV algorithm for long-distance route planning and the shortest time as the route-planning strategy. The process is composed of the following steps:

1) Calculate all optimal routes with A* algorithm based on single-layer road network (middle-layer road network) which can be built up using the selection methods by individual attributes, road priority and road connectivity.
2) Calculate routes with accelerating A* algorithm (network partitioning) based on hierarchical road network with two layers (middle layer and high layer). The high-layer road network is built up using the selection method by important cities. Compared with A* algorithm, this method speeds up the process, but creates a small proportion of wrong or suboptimal routes because of the suboptimal hierarchical road network.
3) Compare the results from two algorithms, and recognize the differences where wrong or suboptimal routes exist.
4) Analyze the problems and adjust the hierarchical road network by including the necessary middle-layer roads to high layer. Road links in the road network may interfere with each other. After a road link from the middle layer is upgraded to the high layer, some other middle-layer road links may be modified accordingly.
5) Calculate the paths again with accelerating A* algorithm based on the adjusted hierarchical road network to verify and validate if all new routes are identical to the results from A* algorithm. The experimental results reveal that most optimal routes can be successfully verified, a few needs one or more iterations.

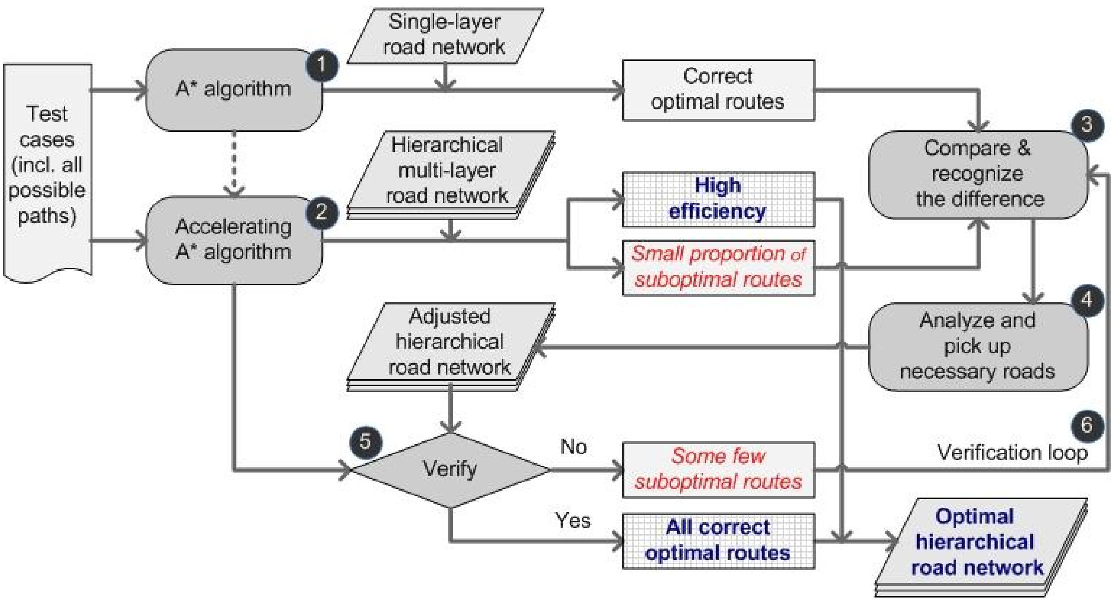


Figure 5.20 Process of the OPCV algorithm

(Undesired results in red and expected results in blue)

5.5.2 Initialization of OPCV algorithm for testing

The initialization of OPCV algorithm for testing aims to get the system prepared for the traverse of all possible paths in a test region (usually a province or a state) going through given start points and destinations. Two point sets are necessary for the configuration: One containing all nodes within the test region including the nodes on its border; the other containing some specified nodes outside the test region.

Route planning for long-distance travel is a research focus of the OPCV algorithm. Generally all paths of long distance should pass the nodes of high-layer roads on the border. Thus the nodes near the border outside the test region can be selected as the representative nodes (e.g. F, T and B shown in Figure 5.21. The reason that the nodes on the border are not selected is to keep the accelerating A* algorithm using the high-layer road network when the start point and destination locate in different middle-layer regions as the rule of the accelerating A* algorithm with vertical partitioning. Since some arterial roads may be missing in the high-layer road network, the proxy point of important cities around the test regions can be added to the point set to compensate the missing paths going through the nodes near the border. Moreover, it is tactically necessary to define a buffer zone encompassing the test region as shown in Figure 5.22 to ensure all paths can be checked. The buffer zone can be composed of the neighboring regions in the first and the second order. For example, Tyrol State of Austria is a direct neighboring region of Bavaria State of Germany, while Trentino-Alto Adige of Italy is a neighboring region of the second order.

As shown in Figure 5.21, different nodes are located in different regions and therefore bear different meanings. P represent a node on a middle-layer or high-layer road within or on the border of the test region; F represents a node on a dual carriageway near the border outside the test region with the direction towards the test region; T represents a node on a dual carriageways near the border outside the test region with the direction from the test region; B represents a node on a single carriageways near the border outside the test region; O represents a city in the buffer zone.

In order to keep the two-way access, all nodes in point sets should be used as both starting point and destination as the following sequence: (1) O->P; (2) F->P; (3) B->P; (4) P->O; (5) P ->T; (6) P ->B.

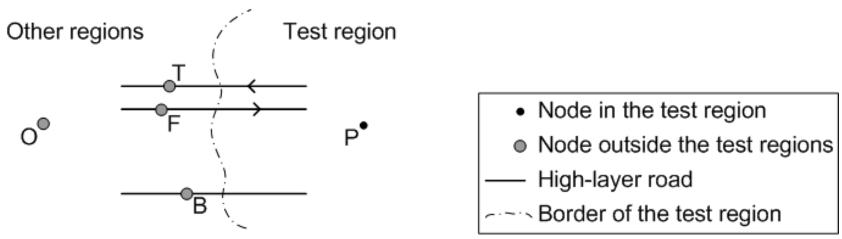


Figure 5.21 Setting of starting points and destinations

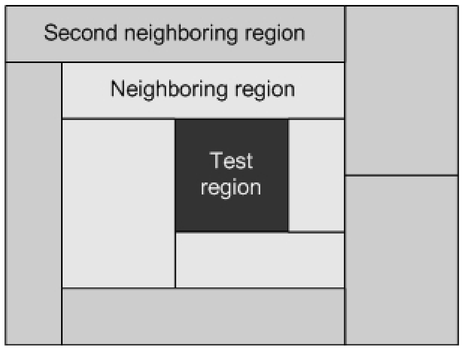


Figure 5.22 A schematic buffer zone encompassing the test area

5.5.3 Decisive path of OPCV algorithm

The case demonstrated in Figure 5.18 is in fact oversimplified. There are far more complex cases in the real road network. Considering the sketch in Figure 5.24, the question how to pick up all roads in optimal paths that are missing in suboptimal paths is not trivial. Figure 5.24f shows the anticipated results of adjusted high-layer road network after conducting the OPCV test. Although the new high-layer road network is fit for the accelerating A* algorithm, the road network is broken (e.g. Figure 5.24h) and many extra roads would reduce the efficiency of route planning. To circumvent this drawback, we propose to identify a decisive path firstly. A decisive path exists in two situations:

1) Along the course of an optimal path, alternative roads that start and terminate at certain intermediate nodes of the optimal path may exist. The section of the optimal path between these nodes is termed as decisive path. Some examples are shown in Figure 5.23 (Situation 1) and Figure 5.24 (the route between node-0 and 1).
2) Different roads may exist from the same start point or terminate at the same destination when the start point or the destination of a route is a node on a high-layer road. In such cases, the middle-layer road constitutes the decisive path in the optimal path. Figure 5.23 (Situation 2) and Figure 5.24 (the route between node-0 and 2) demonstrate two cases.

In addition, all decisive paths should start and terminate along the high-layer roads. Only in this way the connectivity with the original high-layer road network can be preserved. Once the decisive path is identified as shown in Figure 5.24g, other optimal routes, e.g. from start node-0 to node-3, 4 and 5 would also be found based on the new high-layer road network. In another word, when a decisive path is picked up into high-layer road network, the related problems with suboptimal route are easily solved.

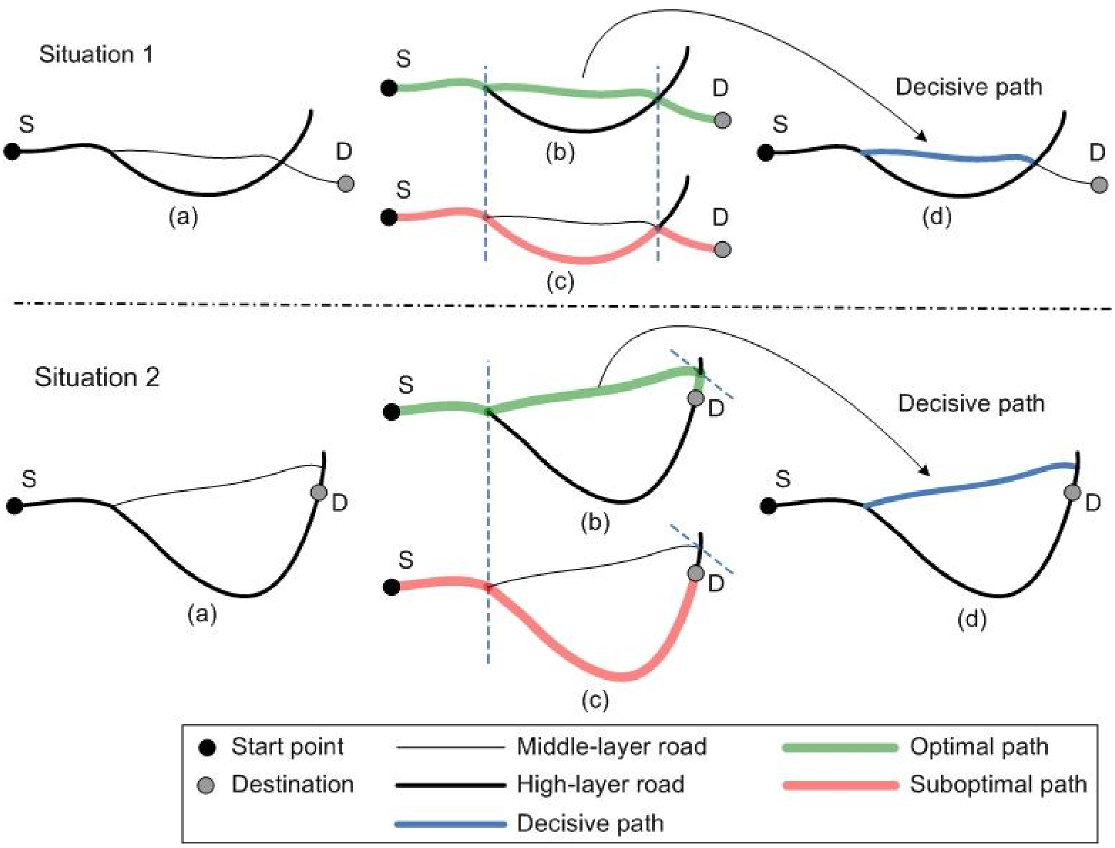


Figure 5.23 Two situations of decisive path strategies

(a) Two-layer road network for improvement; (b) Optimal path;

(c) Suboptimal path; (d) Improved two-layer road networks.

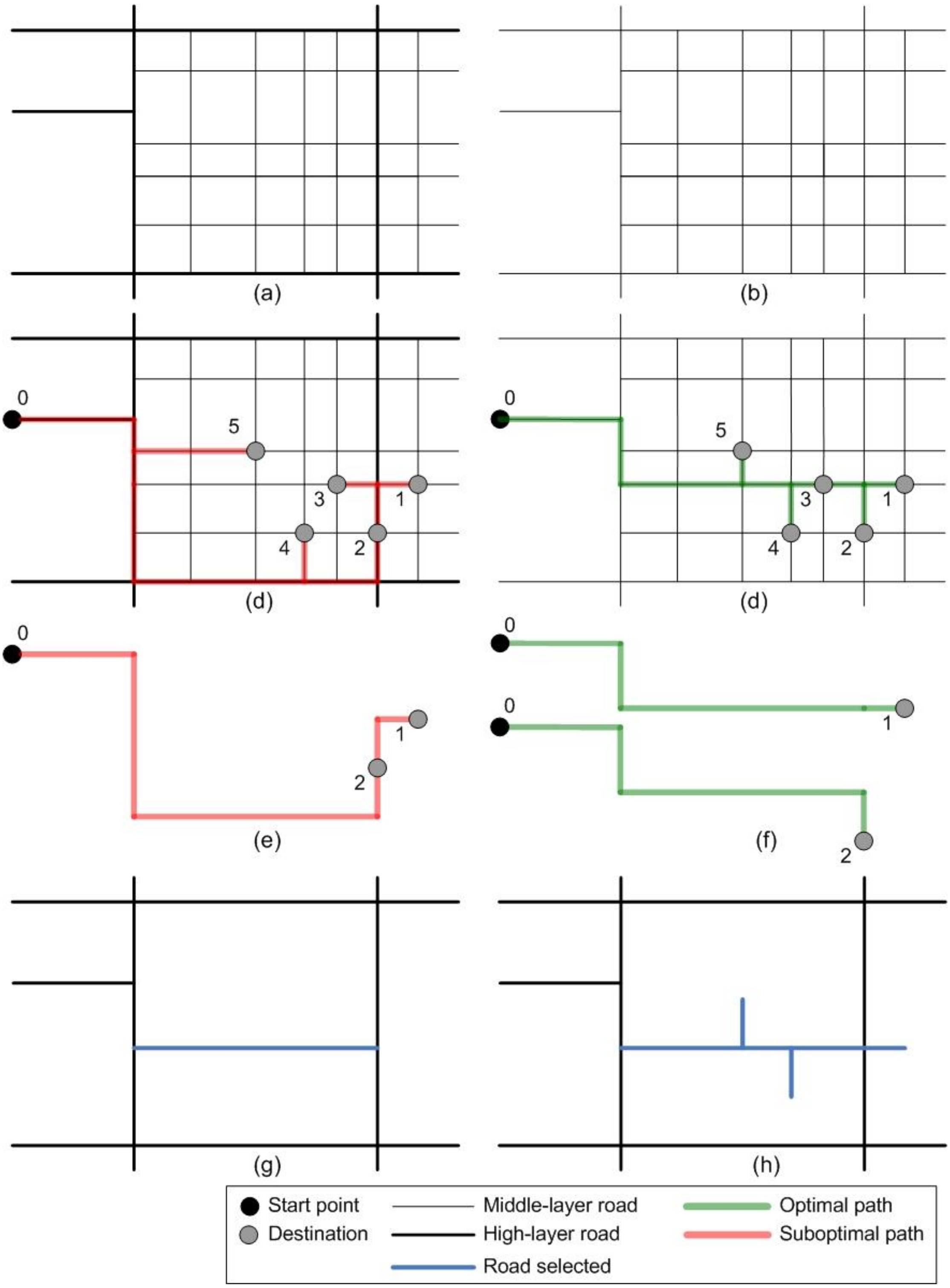


Figure 5.24 Examples of selection by OPCV algorithm

(a) Two-layer road networks (middle layer and high layer);

(b) Single-layer road network (middle layer);

(c)(e) Suboptimal paths calculated by accelerating A* algorithm;

(d)(f) Optimal paths calculated by A* algorithm;

(g) Roads selected by decisive path;

(h) Roads selected by picking up all different roads in optimal paths.

Chapter 6

Solutions and Implementation

This chapter is dedicated to the implementation of the selection approaches of road network in car navigation data authoring. So that all problems of road network for display and route-planning algorithms in an embedded car navigation system can be detected and solved by applying the methods discussed in chapter 5 in a combinational way.

The road datasets of Bavaria State and Northeast China are used as the test beds for the implementation. Because step to select road in level-3 consists of same processes as the steps in level-2 and level-4, we omit the expression for the steps in level-2 and level-4. Due to the different quality and scope of source data, the generalization process in Bavaria State are explained in detail, while for the test bed Northeast China we pay more attention on the selection method by connection link.

Finally, the reasonability of the test results is evaluated through comparison with existing road networks provided by commercial navigation data suppliers or following the requirements for map display and route-planning algorithms.

6.1 Generalization solution for navigational road network

6.1.1 Overview

As introduced in previous chapters, road networks for car navigation are structured at 5 to7 physical levels in display data and three to four layers in route-planning data. Usually, the larger the mobility area, the more the levels and layers are necessary for the management of the navigational road data. For both test areas selected for this study with the size of < 1000 000 km^2 and a length of < 1000 km for the longest route, five physical levels for display and three layers for route planning are set which is a usually case in most car navigation systems.

Figure 6.1 shows the flow diagram of the generalization process. The left part contains the road networks for display organized by parcels and three selection methods taking spatial constraints (road density, unchanged road shape and topology) into accounts. The right part illustrates the road network for route planning organized by regions and two selection methods constrained by connectivity, traffic regulation and optimization criteria of path-finding. There are three pairs of road networks in corresponding levels and layers between two types of road networks - level-5 vs. high layer, level-3 vs. middle layer and level-1 vs. low layer. The road features at these three display levels can find their corresponding road objects in the respective layers, but they have different attributes and relationships. For this reason, the selection in both road networks is conducted in a combinational way that considers not only spatial constraints but also semantic constraints.

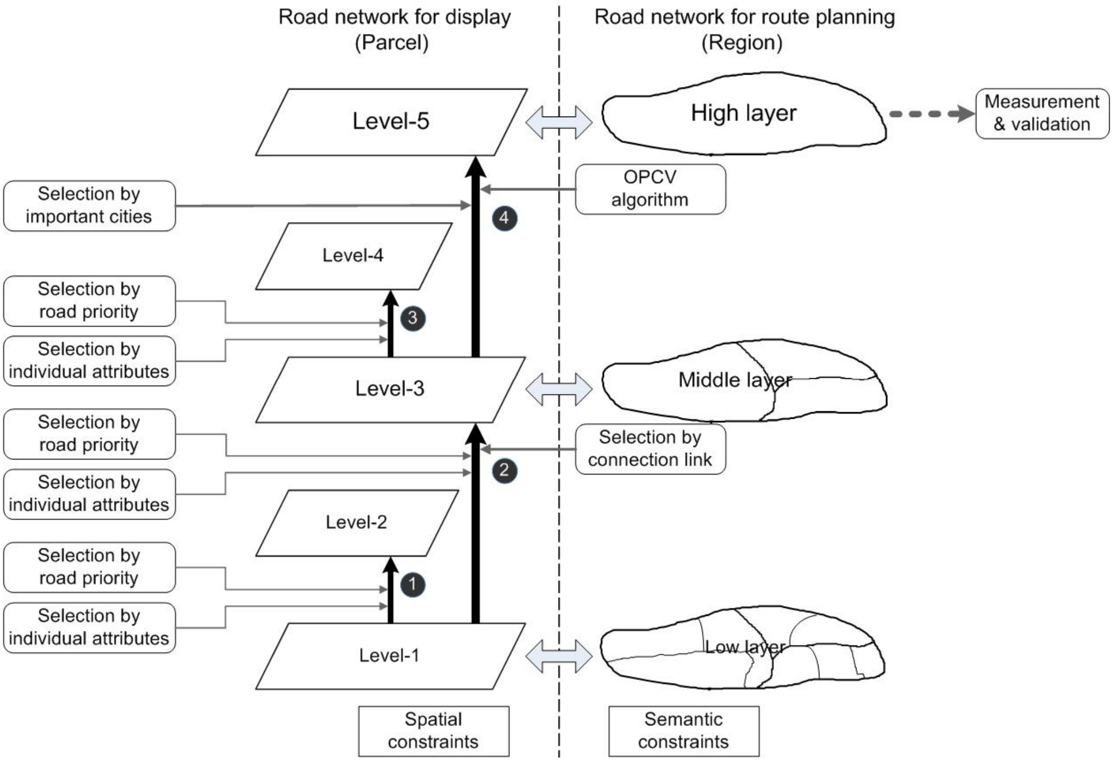


Figure 6.1 Generalization process of navigational road network

Four processing steps (1) - (4) in the flow diagram are realized by various selection methods. Selection by individual attributes and road priority is sufficient for the usual display purposes at level-2, level-3 and level-4. However the road network of level-3 is not able to support accelerating route-planning algorithm and preserve the connectivity due to the lack of connection links. Therefore, the necessary connection links are selected to ensure connectivity in step 2. Moreover, Step 2 works on level-1 road network rather than level-2 at which a part of necessary connection links was eliminated. For the same reason, Step 4 works on level-3 road network (middle-layer) and tries to overcome the problems of high-layer road network, i.e.

disconnect and unbalanced distribution, by applying the selection methods by important cities. The result data on level-5 has a very good visual display quality. Nevertheless, it does not pay attention to the requirements for optimal long-distance route planning in the navigation data authoring. For this reason, the selection method by OPCV algorithm is the key to ultimately solve this special problem, while all other selection methods can be regarded as supporting and preparation services for this key task.

6.1.2 Working environment for the development and test

1) The development was conducted in the following computing environment:
   - Hardware：Fujitsu CELSIUS W480 Tower (main board: Intel 3450, CPU: Intel X3430 2.4GHz, and memory: 4GB);
   - OS: Window 7 professional (32 bit);
   - Software: ArcGIS v8.3, PostgreSQL v8.3.14, PostGIS v1.4.2, Quantum GIS v1.5.0, and Visio Studio 2003.
2) The test with data from Germany and China took place in the following computing environment:
   - Hardware：CPU: ARM920T S3C2440 400MHz, memory: 128 MB, Flash: 64 MB, and Storage card: 2 GB;
   - OS: Window CE v5.0;
   - Software: navigation engine of Kotei Navi & Data (Wuhan) Corporation.

6.1.3 Preprocessing and input

The preprocessing of source datasets serves the purpose to identify all relevant attributes that recognize important roads and cities. In the digital datasets, neither all road objects are completely described by their attributes or all the attributes are completely assigned with values. Still, it is possible to make optimal use of the available attributes and the available values for a reliable selection. The preprocessed datasets are then specifically structured in the database.

(1) Data structure for individual attributes

Table 6.1 demonstrates how the operator (selection or omission) is dependent on the values or value ranges of the individual relevant attributes on the display level-2, 3 and 4.

The Sid is a serial id or number as the key index in database and usually automatically generated while starting from 1 and increasing as growth of 1.

Table 6.1 Data structure named as “individual attributes”

Sid	Level	Operator	Condition
1	2	0 (omission)	fow=14 (pedestrian zone)
2	2	0 (omission)	private_road=2 (private road)
3	2	1 (selection)	divided_state=1(dual carriageway)
…	…	…	…
18	3	0 (omission)	road_type=6 (parking place)
…	…	…	…
26	4	0 (selection)	frc<2(motorway and national highway)
27	4	0 (selection)	freeway=1(freeway)
…	…	…	…

(2) Data structure for road priority

The road priority can be regarded as a compound attribute based on different classification indicators and attributes such as speed and direction of traffic flow. The selection by road priority is efficient for display level-2, 3 and 4. and three records are stored in the data structure for each test area unit (e.g. Bavaria State in Table 6.2). That is, for display level-2, all roads of priority order from 1 till 72 at level-1 are selected, while for display level-3 all roads of priority order from 1 till 61, and for display level-4 only the first 34 priority levels are considered. These limits are derived from Table 6.13.

Table 6.2 Data structure named as “road priority”

Level	Priority	Classification 1 (N2C)	Classification 2 (NBC)	Classification 3 (FRC)	…
2	72	4	5	1	…
3	61	3	0	3	…
4	34	1	0	7	…

(3) Data structure for connection links

Connection links are described by all related attributes and their values, which combine the specified conditions referring to the corresponding type of connection link as shown in Table 6.3. Since not all conditions keep the 1:1 relationship with the types of connection links, a distinction is made for the type of condition with 1 to indicate a 1:1 relationship, and 0 for 1:n relationship.

Table 6.3 Data structure named as “connection link condition”

Sid	Type of connection link	Name of connection link	Condition	Type of condition
1	1	Directional ramp	ramp=1	0 (1:n)
2	2	Entrance/exit of motorway	ramp=1	0 (1:n)
3	2	Entrance/exit of motorway	fow=11	1(1:1)
4	3	Non-directional ramp	ramp=1	0 (1:n)
5	4	Maneuver link	ml=3	1(1:1)
6	5	Roundabout	roundabout=1	1(1:1)
…	…	…	…	…

(4) Data structure for important cities

Important cities are selected and represented by their proxy points. Cities within the road network of our test regions are spread across “city list” and “important city” as shown in Table 6.4 and Table 6.5. “city list” records the related information about each city including its name, the state it belongs to, the coordinates of its proxy point and the node identity corresponding to the proxy point, while “important city” records all identities of important cities related to (usually outside, sometimes within) the test State/Province. For example, all cities of Germany can be found in the data structure “city list”, and parts of related important cities in Bavaria State are listed in Table 6.5. The records in both tables are the input of the selection procedure by important cities.

Table 6.4 Data structure named as “city list”

City id	City name	State id	Coordinate X	Coordinate Y	Node id
1	Munich	1 (Bavaria)	…	…	…
2	Nürnberg	1 (Bavaria)	…	…	…
…	…	…	…	…	…
19	Stuttgart	2(Baden-w.)	…	…	…
…	…	…	…	…	…
50	Frankfurt	3(Hessen)	…	…	…
…	…	…	…	…	…
68	Erfurt	4(Thüringen)	…	…	…
…	…	…	…	…	…
99	Leipzig	5(Sachsen)	…	…	…
…	…	…	…	…	…

Table 6.5 Data structure named as “important city”

Sid	State id	City id
1	1 (Bavaria)	Stuttgart
2	1	Frankfurt
3	1	Erfurt
4	1	Leipzig
…	…	…

(5) Data structure for OPCV-algorithm

For the same reason, the data structure “opcv city” in Table 6.6 is designed for the selection method by OPCV algorithm, while the “city list” can be used to find the information of proxy point of each related city.

Table 6.6 Data structure named as “opcv city”

Sid	State id	City id

6.1.4 Selection and output

Since the thresholds or decisions for selection or omission have been embedded in the above explained data structures, the subsequent automatic generalization in terms of selection has become a task of data retrieval instead of computing. Some data structures are adopted to store the intermediate results.

The final result of the data retrieval is a hierarchical road network organized in navigational database. Each intermediate step of the hierarchy construction is stored as a traceable reference, such as “selection state”. Some records are demonstrated in Table 6.7. The items a-f record the results of each selection methods, and M, N record the final results in middle layer and high layer calculated by items a-d and e-f respectively. For item a, 0 means omission, and 1 is the default value and means not omission. Unlike item a, the default values of items M, N and b-f are set to 0 for no selection, and 1 means selection. The selection criteria for middle layer can be expressed as the formula “M= (a and (b or c)) or d”. For high layer, it is obviously that a road can be picked up into high layer when it is selected by important cities or OPCV algorithm, which is expressed as the formula “N= e or f”.

Table 6.7 Data structure named as “selection state”

No.	Road id	default	1	2	3	4	5	6	7
a	Omit by individual attributes	1	0	0	0	1	1	1	1
b	Select by individual attributes	0	1	0	0	1	0	0	1
c	Select by road priority	0	0	1	0	0	1	0	1
d	Select by connection link	0	0	0	1	0	0	1	1
M	**Middle layer**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**
e	Select by important cities	0	0	0	0	0	1	0	1
f	Select by OPCV algorithm	0	0	0	0	1	0	1	0
H	**High layer**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**

For the same reason, the stroke information of connection link is stored in data structure “stroke for connection link” as traceable reference as Table 6.8 shows. Three records represent a complete stroke of maneuver link, where “link number” indicates the number of the road links of the stroke and “sequence number” expresses the order of roads in the stroke consistent with its traffic flow.

Table 6.8 Data structure named as “stroke for connection link”

Road id	Type of connection link	Stoke id	Link number	Sequence number
…	…	…	…	…
101	Maneuver link	**50**	3	1
…	…	…	…	…
523	Maneuver link	**50**	3	3
…	…	…	…	…
1020	Maneuver link	**50**	3	2
…	…	…	…	…

6.2 Test bed - Bavaria State

The road dataset from Bavaria State has a high quality with almost complete attribute values of road network. Therefore, we can easily get integrated higher-layer road networks with good connectivity by using the attribute “net 2 class” and compare the results with the existing reference road networks for verification. The test dataset is provided by Tele Atlas version 200610 and covers 10 countries including Germany, Czech, Austria, Liechtenstein, Switzerland, Netherlands, Belgium, Luxembourg, France and Italy.

6.2.1 Selection among middle-layer roads by individual attributes

Section 5.1 has explained by the example in the northeast of Munich the reason for the selection of necessary roads and the omission of minor or low-class roads based on the method by individual attributes. Table 6.9 and Table 6.10 list the detailed attribute information and the distribution of different types of roads. Figure 6.2 shows the result in this area with 30.4% selected roads which is much more than the desirable selection proportion of the middle-layer road, although the distribution looks good.

Table 6.9 Selection of necessary roads in Bavaria State

No.	Function	Attribute	Count	Length
1	Arterial road	frc=0,1,2	85263	16081.4
2	High-layer road	n2c=0,1,2	217439	33823.8
		nbc=1,2,3,4,5,6	96271	17632.5
3	Driving speed	kph ≥70 km/h	101406	24134.2
SUM (the union set of three types of roads which intersect)			231661	37018.1

Table 6.10 Omission of needless roads in Bavaria State

No.	Function	Attribute	Count	Length
1	Low-class road	frc=7,8	1386242	213289.9
2	Low-layer road	n2c=5, 6	635162	144874.0
2	Invalid road	frc=-1	2611	128.7
3	Back road	back rd<>0	514502	130800.7
4	Pedestrian zone or walkway	fow=14, 15	68779	12996.6
5	Parking place, entrance and exit	fow=6,7,12	11769	843.5
6	Service road	fow=11	338	32.4
7	Private road	private rd=2	15196	1724.3
8	Road for authority	fow=17, 20	93	7.0
9	Closed in both sides	oneway=N	123064	22611.9
SUM (the union set of 11 types of roads, which intersect)			1389810	213605.0

Figure 6.2 Roads (in bold) selected from the middle layer by individual attributes in the northeast of Munich

6.2.2 Selection among middle-layer roads by road priority

The matrix in Table 6.13 shows altogether 83 priority levels ranked by relative importance. Each priority level corresponds to a number of roads to be selected if the priority level is taken as the threshold. In comparison to statistics in the navigation data of Nissan Europe 2009 in Table 6.11, four solutions marked in colors in Table 6.12 are identified as suitable alternatives, they correspond to the priority level-51, 60, 61 and 65. The length rates for alternatives 60 and 61 are closer to that in the reference data. The connectivity of road networks for alternative 51 and 65 is better preserved than the other three alternative solutions because roads with same value of N2C are completely kept. But as a whole, priority threshold at level-61 is the best solution as it keeps as many roads as possible in the allowable bounds of selection proportion of road length and road density, while 65 priority levels tend to select too many roads.

Table 6.11 Reference data of Bavaria State

State	Low-layer road links		Middle-layer road links			
	Count	Length (km)	Count	Count (%)	Length (km)	Length (%)
Bavaria	1551693	224838.1	197569	12.7%	29942.6	13.3%

Table 6.12 Selection solutions by road priority in Bavaria State

No.	Priority selection	Low-layer road links		Middle-layer road links			
		Count	Length (km)	Count	Count (%)	Length (km)	Length (%)
1	1-51	1996716	300618.9	214828	10.8%	33695.1	11.2%
2	1-60	1996716	300618.9	215977	10,8%	33826,5	11,3%
3	1-61	1996716	300618.9	242065	12.1%	37855.2	12.6%
4	1-65	1996716	300618.9	517881	25.9%	77309.0	25.7%

Figure 6.3 Roads (in bold) selected from the middle layer by road priority in the northeast of Munich

Table 6.13 Priority levels and the number of roads in Bavaria State

Priority	N2C	NBC	FRC	Count
1	0	1	0	5243
2	0	2	0	4736
3	0	2	1	574
4	0	4	0	1976
5	0	4	1	502
6	0	4	2	2
7	0	5	0	711
8	0	5	1	204
9	0	6	0	243
10	0	6	1	573
11	0	6	2	4
12	0	0	4	1
13	1	2	0	580
14	1	2	1	516
15	1	2	2	102
16	1	4	1	4602
17	1	4	2	220
18	1	5	0	37
19	1	5	1	13201
20	1	5	2	876
21	1	5	3	98
22	1	5	4	2
23	1	6	0	96
24	1	6	1	27683
25	1	6	2	2457
26	1	6	3	550
27	1	6	4	30
28	1	0	1	13
29	1	0	2	3
30	1	0	3	1562
31	1	0	4	504
32	1	0	5	16
33	1	0	6	5
34	1	0	7	22
35	2	4	1	141
36	2	5	1	42
37	2	5	2	60
38	2	5	3	219
39	2	5	4	31
40	2	6	1	963
41	2	6	2	18800
42	2	6	3	7214
43	2	6	4	1786
44	2	6	5	46
45	2	0	1	1
46	2	0	2	11
47	2	0	3	68649
48	2	0	4	47921
49	2	0	5	825
50	2	0	6	95
51	2	0	7	80
52	3	5	1	2
53	3	5	3	33
54	3	5	4	120
55	3	6	1	29
56	3	6	2	56
57	3	6	3	213
58	3	6	4	665
59	3	6	5	30
60	3	0	2	1
61	3	0	3	26088
62	3	0	4	268777
63	3	0	5	6578
64	3	0	6	373
65	3	0	7	88
66	4	0	3	18
67	4	0	4	610
68	4	0	5	164
69	4	0	6	88573
70	4	0	7	751541
71	4	0	8	154
72	4	5	1	2
73	5	0	4	250
74	5	0	5	9
75	5	0	6	306
76	5	0	7	499981
77	5	0	8	6
78	5	5	1	1
79	6	0	4	137
80	6	0	6	102
81	6	0	7	67813
82	6	0	8	66557
83	-1	0	-1	2611

6.2.3 Selection among of middle-layer roads by connection link

Thanks to the good data quality of the test bed Bavaria State, the selection methods by individual attributes and road priority can preserve connectivity to a large extent. Among all connection links, only 12 non-directional ramps and four maneuver links from low-layer network are upgraded to the middle-layer network. Table 6.14 lists the statistics of various connection links from the test bed Bavaria State. Nine related connection strokes where all connection links are upgraded are illustrated in Figure 6.4.

Table 6.14 Selection of Connection links in Bavaria State

Type of Connection Link	Low-layer road links		Middle-layer road links					
	Recognition		Selection by road priority		Adding by connectivity		Final	
	Count	Stroke	Count	Stroke	Count	Stroke	Count	Stroke
Direction ramp	521	189	521	189			521	189
Entrance/exit	9358	3825	9358	3825			9358	3825
Non-direction ramp	3195	3189	3064	3058	12	5	3086	3063
Maneuver link	4854	4848	2211	2205	4	4	2215	2209
Roundabout	5958	1133	3737	559			3737	559
Inner connection link	119	117	119	117			119	117

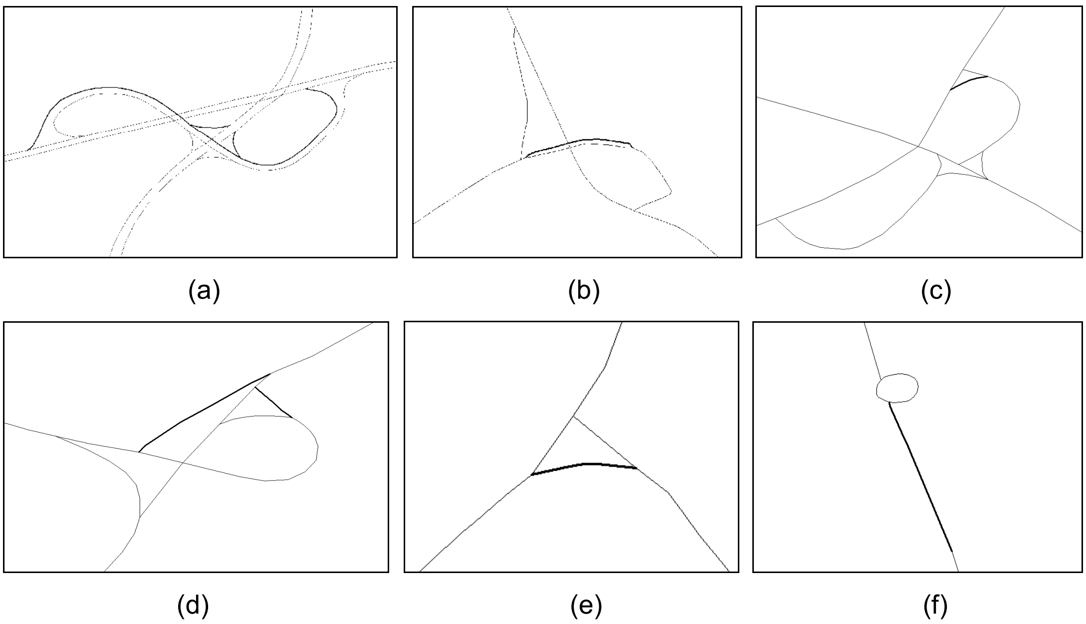


Figure 6.4 Selected connection links (in bold) in Bavaria State

(a) Three connection strokes consisting of 10 non-directional ramps between two dual carriageways by grade separation;

(b) A road link of a non-directional ramp overpassing a single carriageway;

(c) A road link of a non-directional ramp between two single carriageways by grade separation;

(d) A road link of a non-directional ramp (right one) and a maneuver link (left one) between two single carriageways;

(e) A maneuver link between two single carriageways;

(f) A maneuver link between a single carriageway and a roundabout.

After selection by the above three methods, 242084 roads remain in the middle-layer road network of Bavaria State as shown in Figure 6.5. The result for Munich is illustrated in Figure 6.6. These show the satisfying road network with allowable road density and good distribution for display, and all main roads between different regions in Bavaria State are also well kept, which can support accelerating route-planning algorithm. The test data with good quality allows an easy selection of the middle-layer road network by road priority.

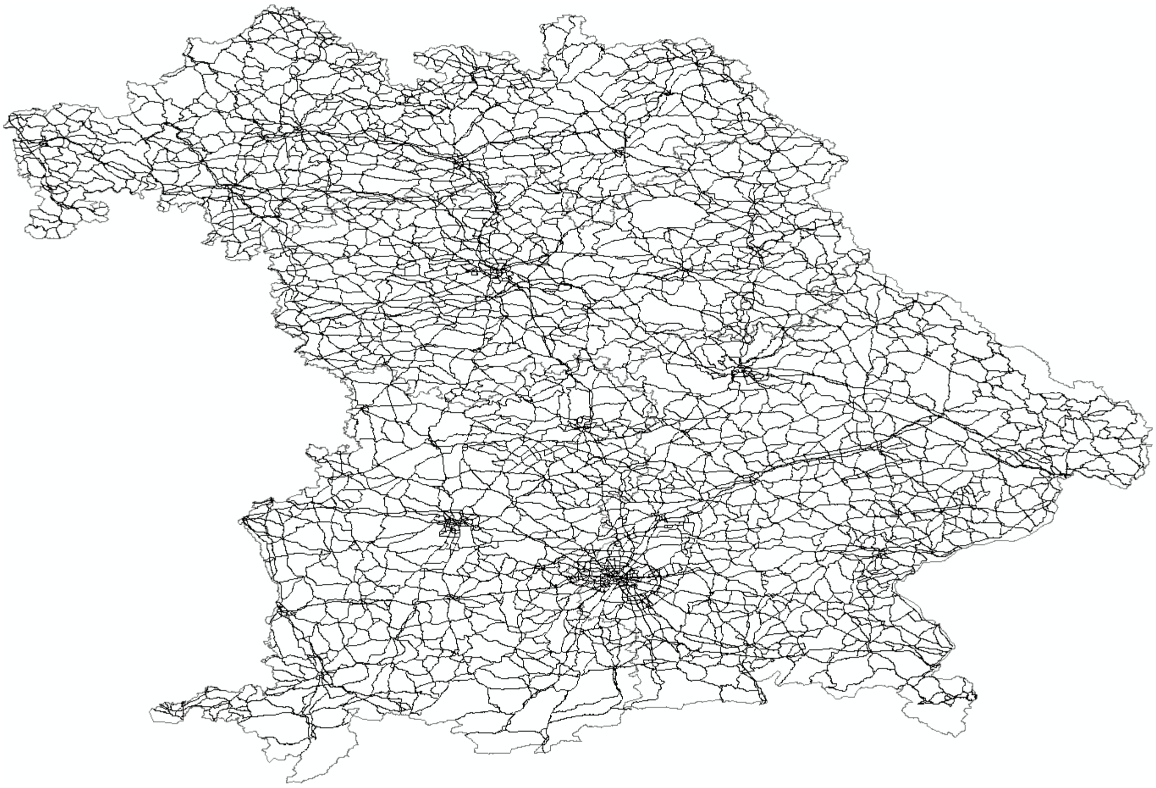


Figure 6.5 Integrated middle-layer road network of Bavaria State

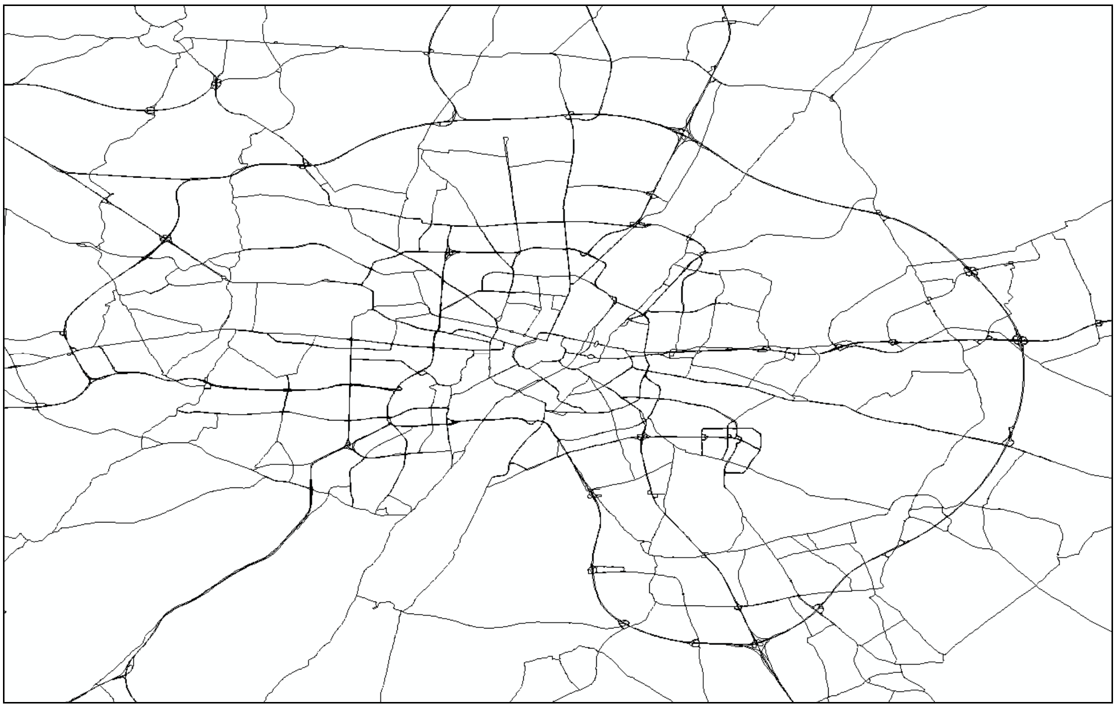


Figure 6.6 Middle-layer road network of Munich

6.2.4 Selection of arterial roads of high-layer road network

The following 13 Cities are selected in surrounding regions of Bavaria State according to the freight capability and spatial distribution, and their locations are also shown in Figure 6.7:

1) Chemnitz, Leipzig, Erfurt, Kassel, Frankfurt am Main, Mannheim and Stuttgart (Germany)
2) Zürich (Switzerland)
3) Vaduz (Liechtenstein)
4) Innsbruck, Salzburg, Linz (Austria)
5) Praha (Czech Republic)

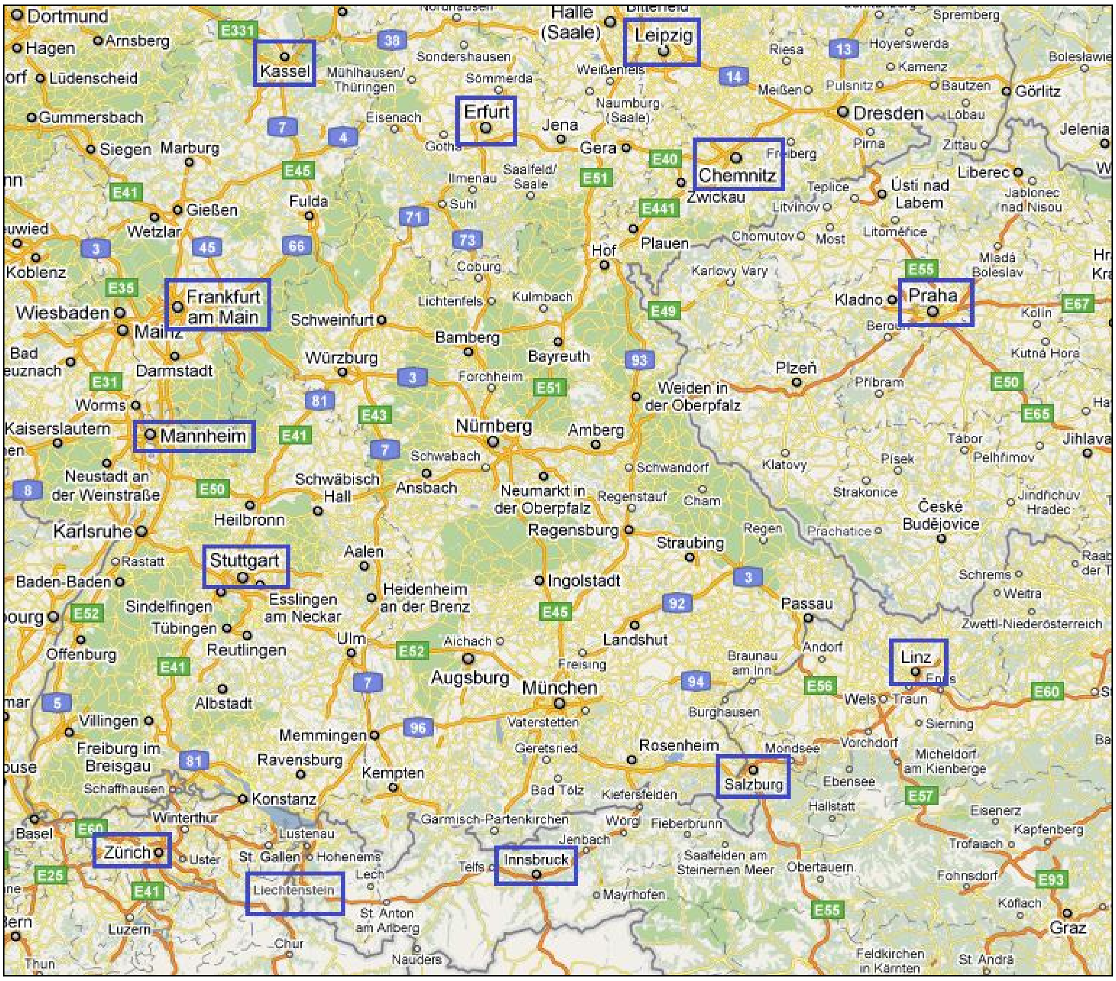


Figure 6.7 Selected cities (in blue frame) outside of Bavaria State on a Google map

By applying the route-planning algorithm all arterial roads that go though these selected cities are identified as shown in Figure 6.8. The arterial roads within Bavaria State are highlighted in Figure 6.9. Apparently the road network with all arterial roads has a good legibility and allowable road density. As a bi-directional route planning between all cities is possible, every node in the road network can be reached from any other node. However, a few arterial roads may go lost due to the complexity of the road network or the lack of city selection, which however can be compensated by OPCV algorithm.

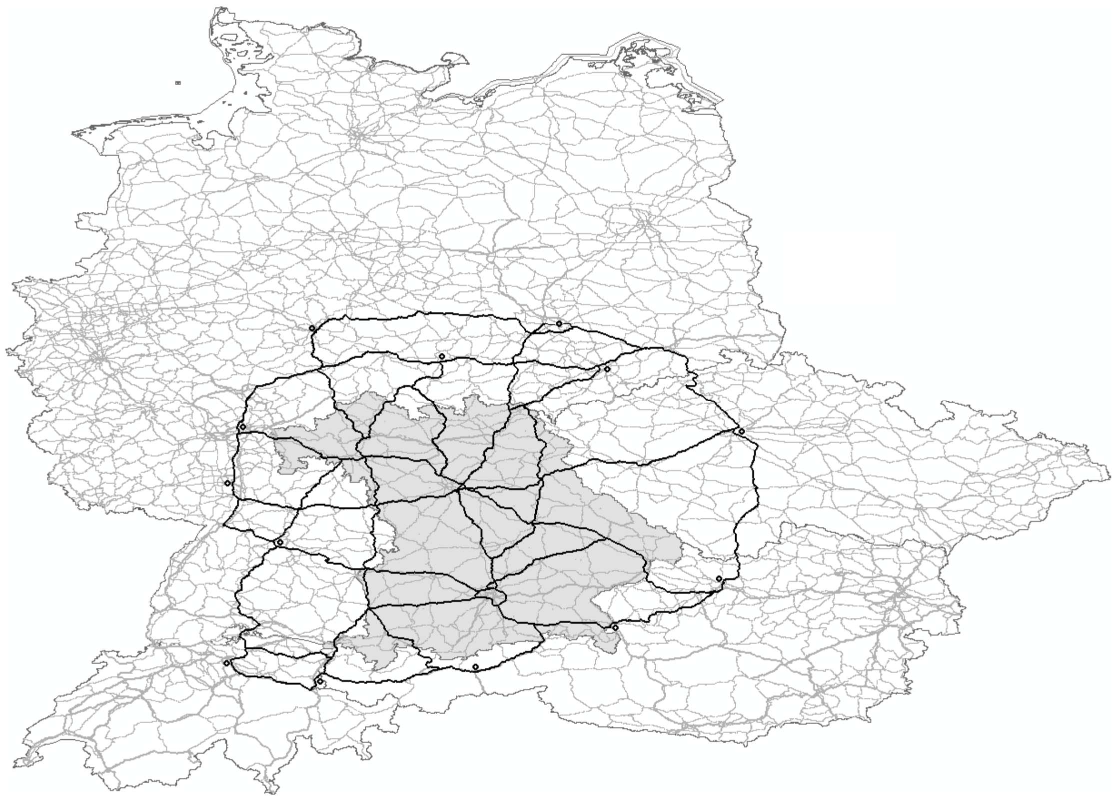


Figure 6.8 Arterial roads (in bold) selected by important cities (represented by small rings) in the encompassed areas (Germany, Czech, Switzerland, Liechtenstein and Austria)

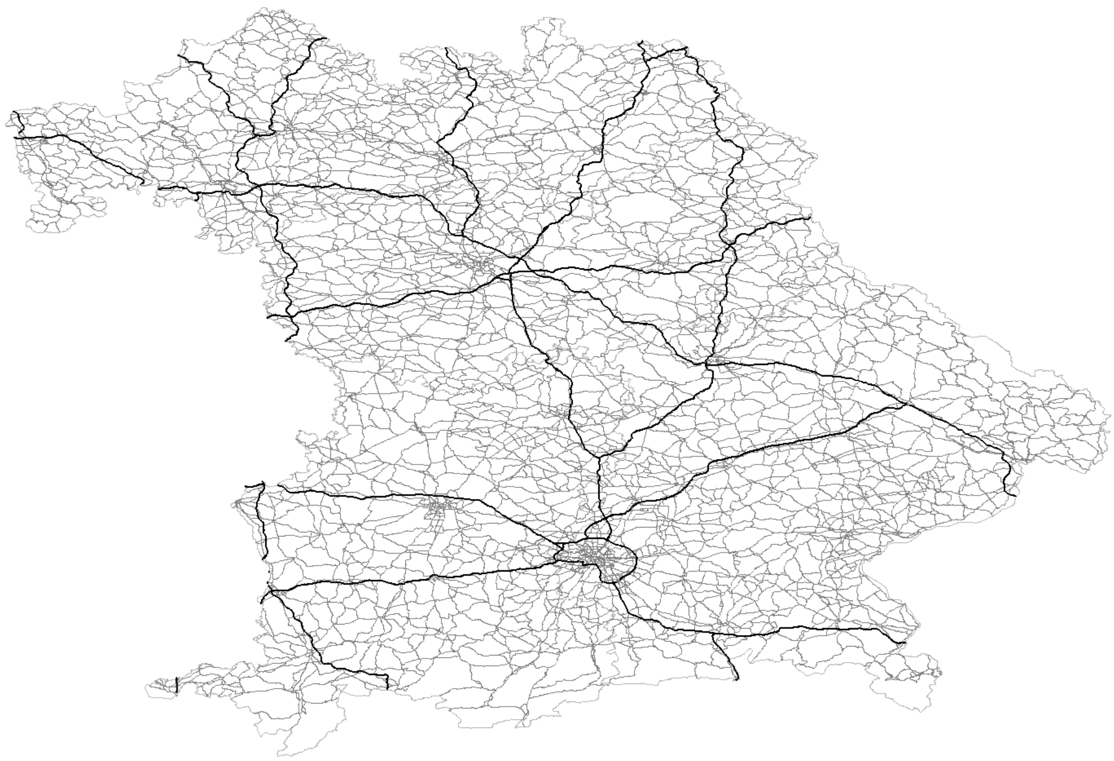


Figure 6.9 Arterial roads (in bold) selected by important cities in Bavaria State

6.2.5 Selection of decisive paths by OPCV algorithm

According to the initialization requirements of OPCV algorithm, two point sets are established for route-planning algorithms. One set contains all nodes of the middle-layer road network inside or on the boarder of the test region Bavaria State. The other set embraces:

1) 13 cities within the neighboring regions used in the selection method by important cities;
2) 12 cities within the second neighboring regions which are:
   - Berlin, Hamburg, Bremen (Germany)
   - Amsterdam (Netherlands)
   - Brussels (Belgium)
   - Paris, Lyon (France)
   - Milano, Bologna (Italy)
   - Graz (Austria)
   - Bratislava (Slovak)
   - Prague (Czech)
3) 52 nodes on the arterial roads near and outside the border of Bavaria State;
4) 6 nodes on the decisive paths near and outside the border of Bavaria State, which are obtained in the process of OPCV algorithm.

Seven decisive paths are detected by OPCV algorithm as shown in Figure 6.10 with overview of Bavaria State and Figure 6.11 with the enlarged view in Munich. In addition, several other roads are selected to reflect the urban pattern of Munich by “knee point” as Figure 6.11 and Figure 7.1 show. These roads are finally integrated embedded in the high-layer road network as illustrated in Figure 6.12.

The OPCV algorithm is a type of self-proving algorithm, so theoretically the road network of end result can support the corresponding accelerating route-planning algorithm for long-distance route. Technically, system tests can be triggered to confirm this characteristic.

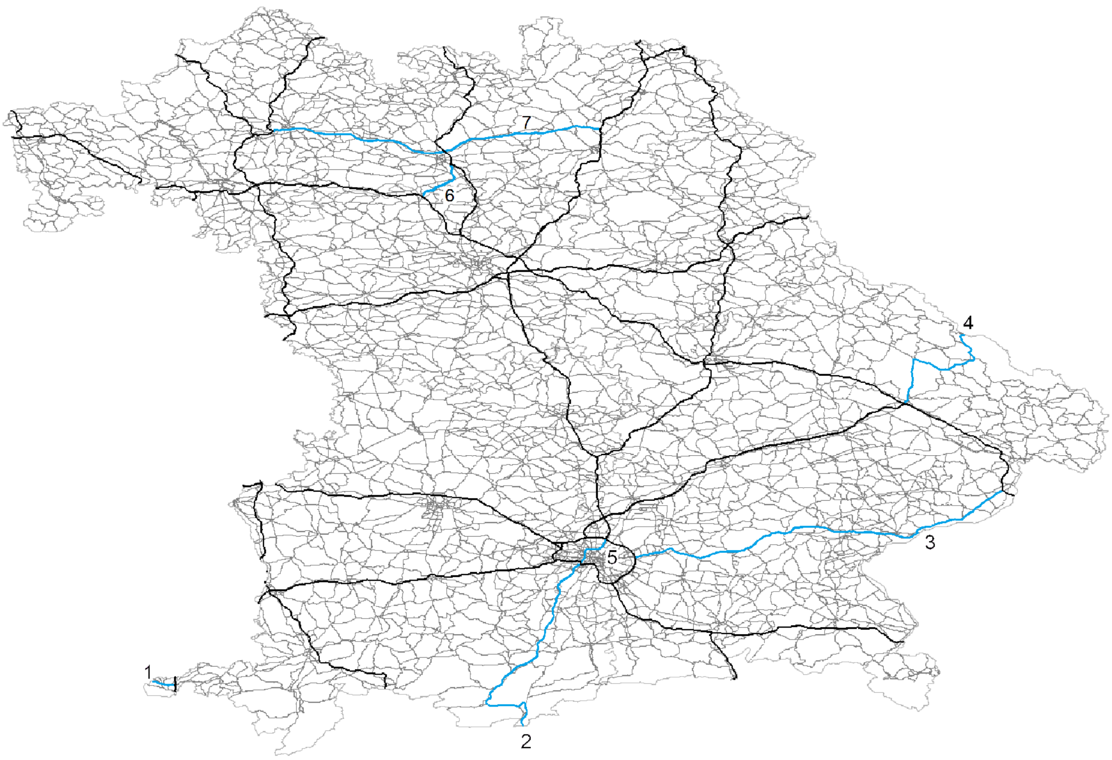


Figure 6.10 Decisive paths (in blue) detected by the OPCV algorithm in Bavaria State

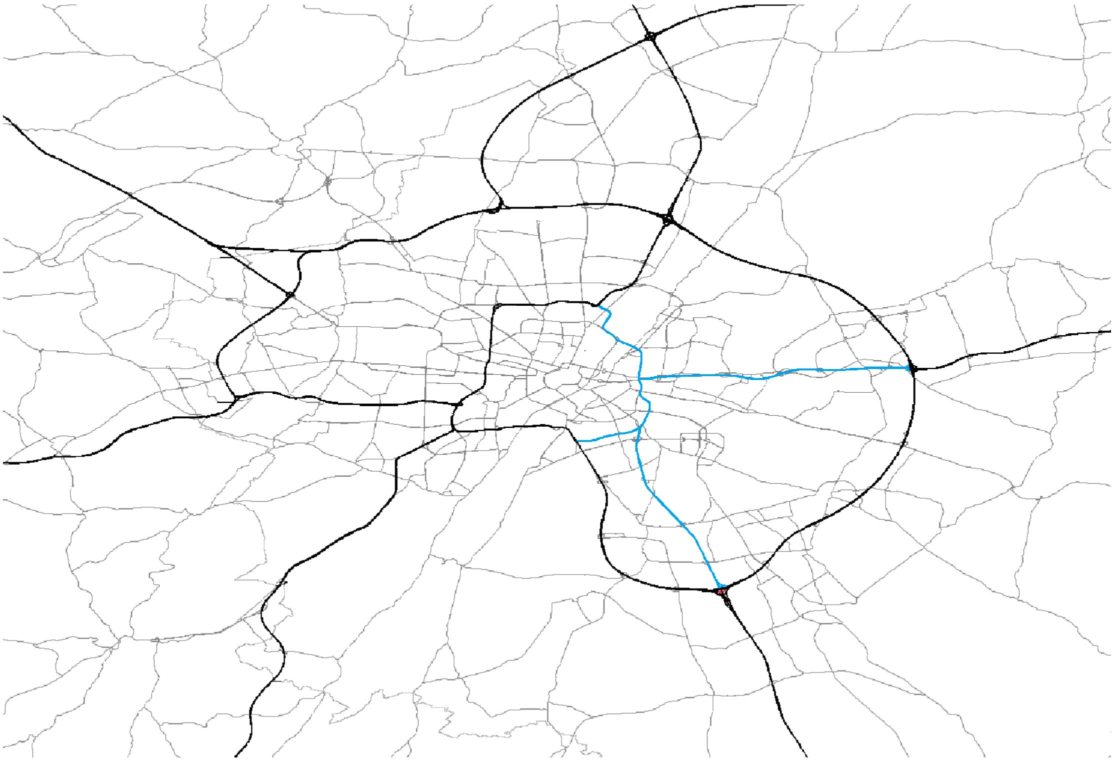


Figure 6.11 High-layer roads (in blue) selected by urban pattern in Munich

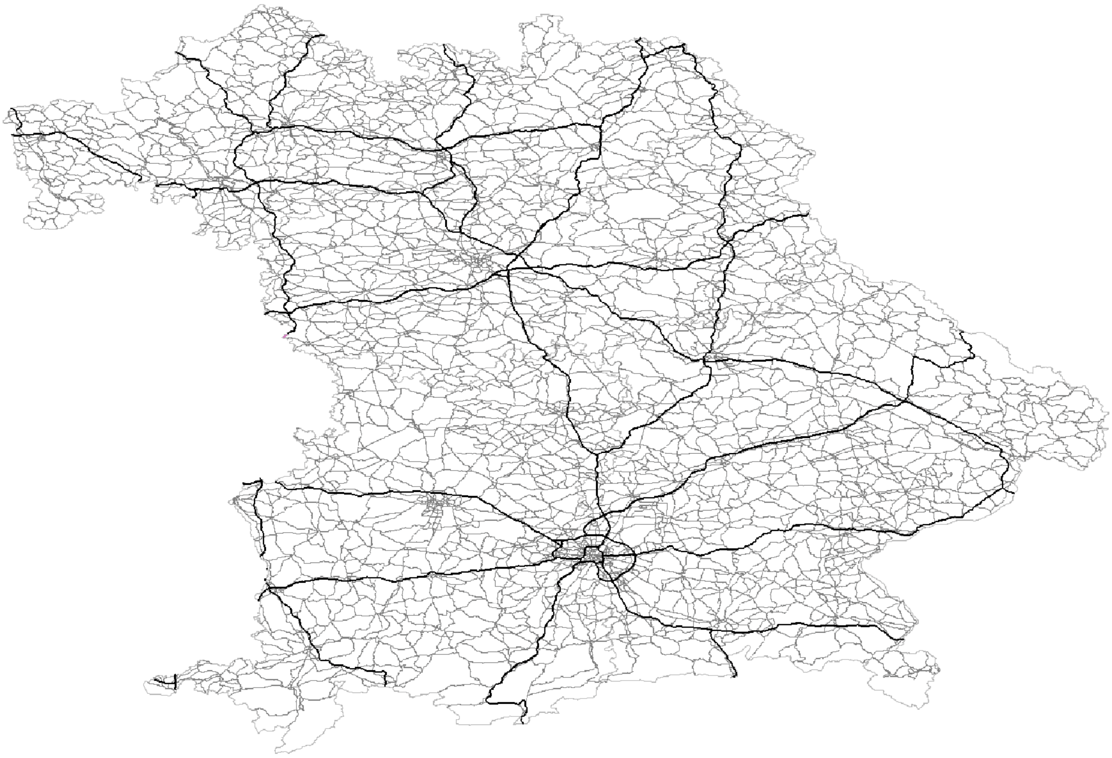


Figure 6.12 Integrated high-layer road network (in bold) in Bavaria State

6.3 Test bed - Northeast China

The dataset of test bed Northeast China covers three provinces - Heilongjiang, Jilin and Liaoning, as well as two neighboring provinces Neimenggu and Hebei. It is provided by Navinfo (the latest version 201010). The data quality is rather heterogeneous. The attribute values of road network are not sufficiently accurate, for example, connection links and their connected main roads are assigned almost the same class. And roads belonging to the highest display level reveal a rather unbalanced distribution pattern as Figure 1.4b shows. The discussions in following sections are therefore particularly focused on the connection links in the middle layer and two selection methods in the high layer for this test bed.

6.3.1 Selection of middle-layer roads

The important roads are selected by road attributes, such as freeway, national highway and provincial highway. The minor roads with incomplete or inaccurate attribute values are omitted. The detailed information about connection links is demonstrated in Table 6.15a-c. The differences between the results recognized only by attribute and those by all available information including pattern, traffic regulation, and connection relationship reveal the quality problems in the source data. The recognition and selection of connection links are operated at the same time by analyzing the relative position and connection relationship based on strokes.

Table 6.15 Detailed information of connection-link selection in Northeast China

(a) Heilongjiang Province;

Connection link		Recognize by attribute			Recognize by all information				
		Value	Count	Length	Add	Delete	Count	Stroke	Length
Roundabout		kind=0	2274	77.4	0	0	2274	487	77.4
Entrance/exit		kind=5	1973	558.8	218	9	2182	529	572.6
Ramp		kind=3,10	1069	262.6	-	-	-	-	-
	Direction Ramp	-	-	-	659	0	924	384	290.5
	Non-direction Ramp	-	-	-	89	0	893	697	147.6
Maneuver Link		kind=10	2385	316.8	109	39	2455	307	324.2
Inner Link		kind=4	17042	200.7	0	0	-	-	-
	Inner Connection Link	-	0	-	-	-	1151	1151	13.5
	Inner Link of Intersection	-	0	-	-	-	15891	10543	187.2

(b) Jilin Province;

Connection link		Recognize by attribute			Recognize by all information				
		Value	Count	Length	Add	Delete	Count	Stroke	Length
Roundabout		kind=0	1232	45.9	0	0	1232	235	45.9
Entrance/exit		kind=5	377	121.7	23	101	299	124	87.5
Ramp		kind=3,10	485	145.7	-	-	-	-	-
	Direction Ramp	-	0		104	0	165	86	73.6
	Non-direction Ramp	-	0		61	0	485	380	110.9
Maneuver Link		kind=10	4911	565.9	88	37	4962	521	573.7
Inner Link		kind=4	11954	127.2			-	-	-
	Inner Connection Link	-	0				2023	2023	20.25
	Inner Link of Intersection	-	0				9931	5396	106.944

(c) Liaoning Province.

Connection link	Recognize by attribute			Recognize by all information				
	Value	Count	Length	Add	Delete	Count	Stroke	Length
Roundabout	kind=0	2274	77.4	0	0	2274	487	77.4
Entrance/exit	kind=5	1973	558.8	218	9	2182	529	572.6
Ramp	kind=3,10	1069	262.6	-	-	-	-	-
Direction Ramp	-	-	-	659	0	924	384	290.5
Non-direction Ramp	-	-	-	89	0	893	697	147.6
Maneuver Link	kind=10	2385	316.8	109	39	2455	307	324.2
Inner Link	kind=4	17042	200.7	0	0	-	-	-
Inner Connection Link	-	0	-	-	-	1151	1151	13.5
Inner Link of Intersection	-	0	-	-	-	15891	10543	187.2

The middle-layer road network selected by individual attributes, road priority and connection link is illustrated in Figure 6.13. Liaoning dominated by hills and plains is the heavy industrial base of China, but Heilongjiang, an outlying province with mountains, has a vast territory with a sparse population. The distribution of road network is reasonable and fits the status of the three provinces, while the road density of Liaoning is denser than that of Jilin and Heilongjiang. Meanwhile it's necessary to remain a few stubble roads in Heilongjiang and Jilin that connect important towns in mountains. Furthermore, all main roads between districts of provinces are kept to support the accelerating route-planning algorithm.

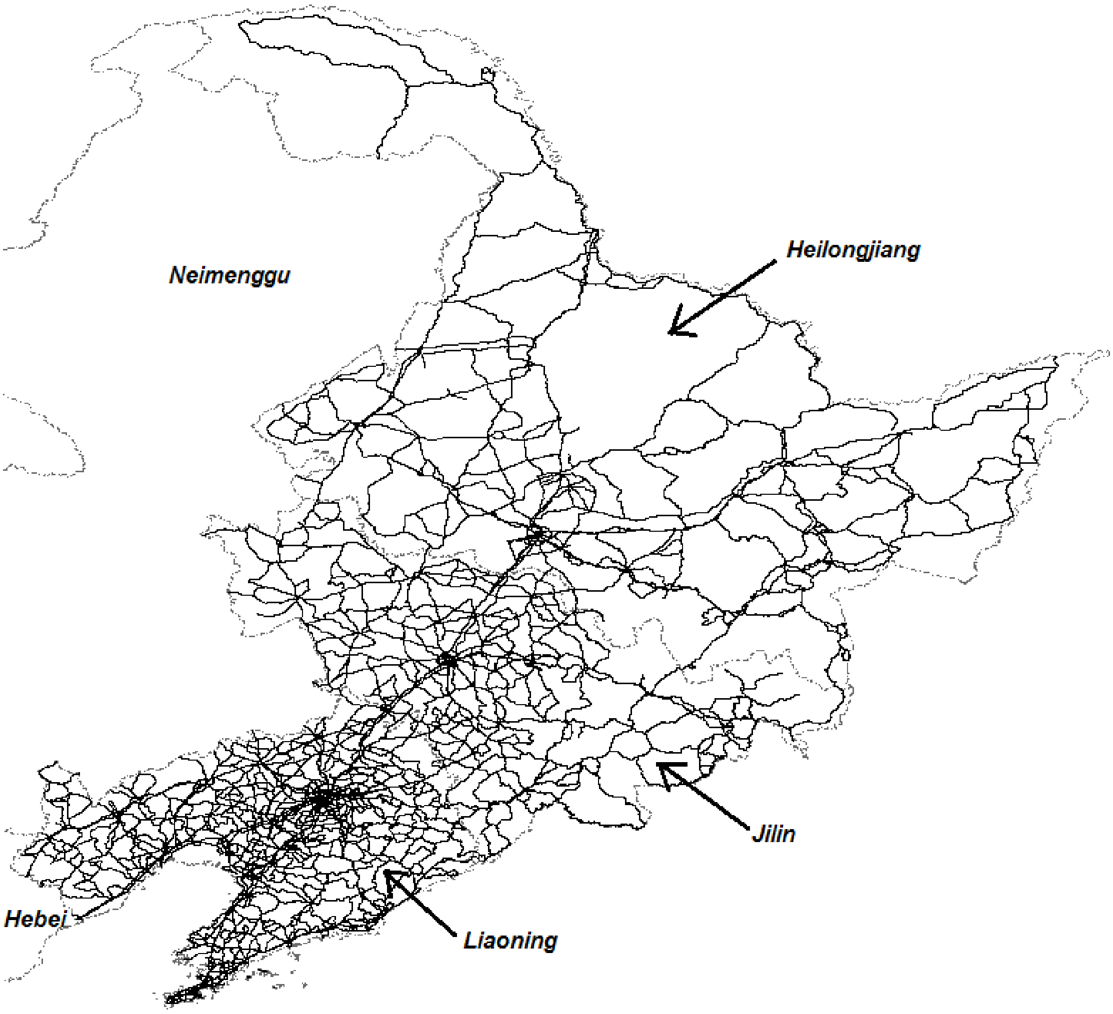


Figure 6.13 Middle-layer road network in Northeast China

6.3.2 Selection of high-layer roads

Unlike the test bed Bavaria State whose road network is well extended to neighboring states and countries, the road network in Northeast China is geographically obviously more restrained within the Chinese border instead of being well connected with North Korea and Russia, therefore, important cities are identified within the test bed and two neighboring Chinese provinces. Figure 6.14 shows the selected important cities for Liaoning province and Figure 6.15 shows the arterial roads in five provinces selected by important cities.

Figure 6.16 shows the decisive paths detected by OPCV algorithm in Liaoning and Jilin Province, while no decisive path exists in Heilongjiang Province as its road network is relative simply organized.

Finally the high-layer road network in Northeast China is integrated as Figure 6.17 shows. The high-layer and the middle-layer network road network reveal a similar distribution. Nevertheless, the road distribution in a few urban areas such as Shenyang, Changchun and Siping is complex, and several extra selected roads (e.g. the roads near Panjin and Liaozhong in Figure 6.16 are rather unusual. On a whole, the high-layer road network is fit for the long-distance route planning.

Figure 6.14 Important cities for Liaoning Province on a Google map

(Cities within Liaoning Prov. in green frame and cities outside Liaoning Prov. in blue frame)

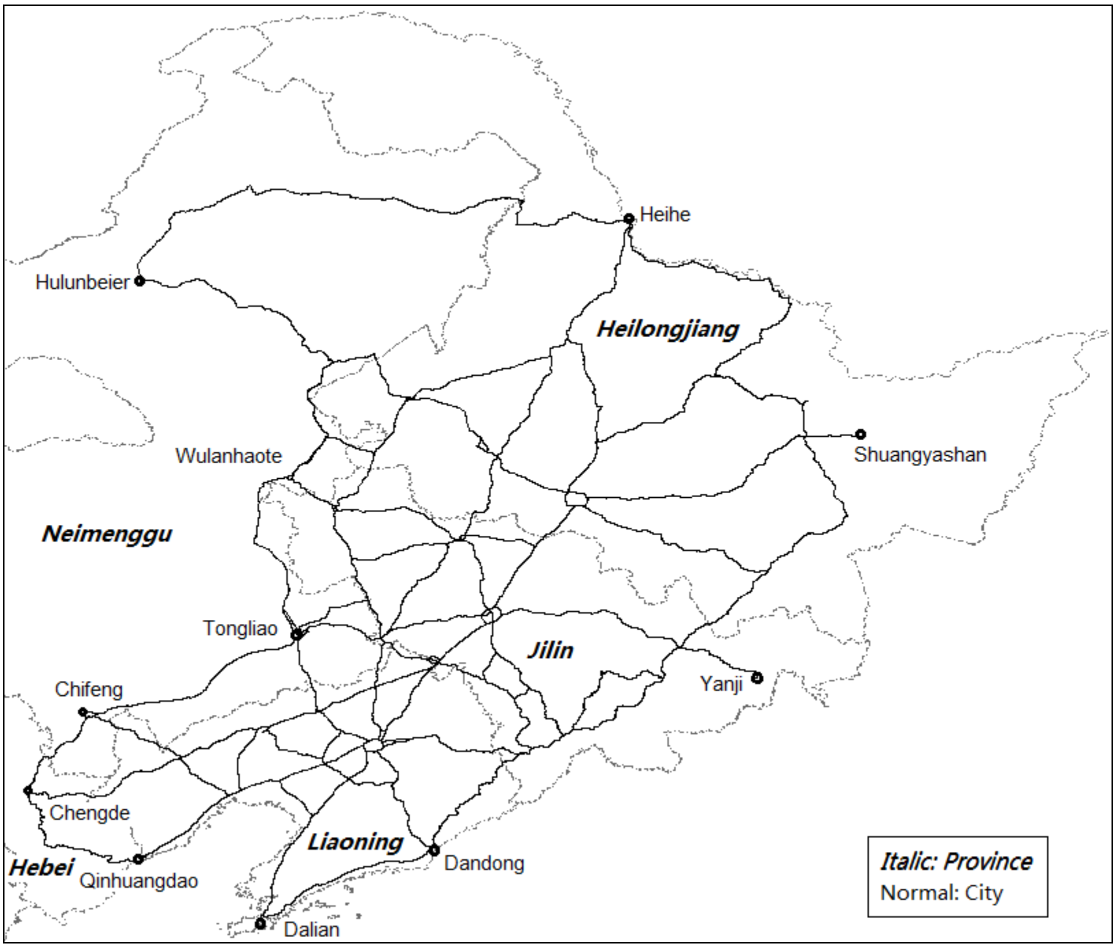


Figure 6.15 Arterial roads selected by important cities in Northeast China

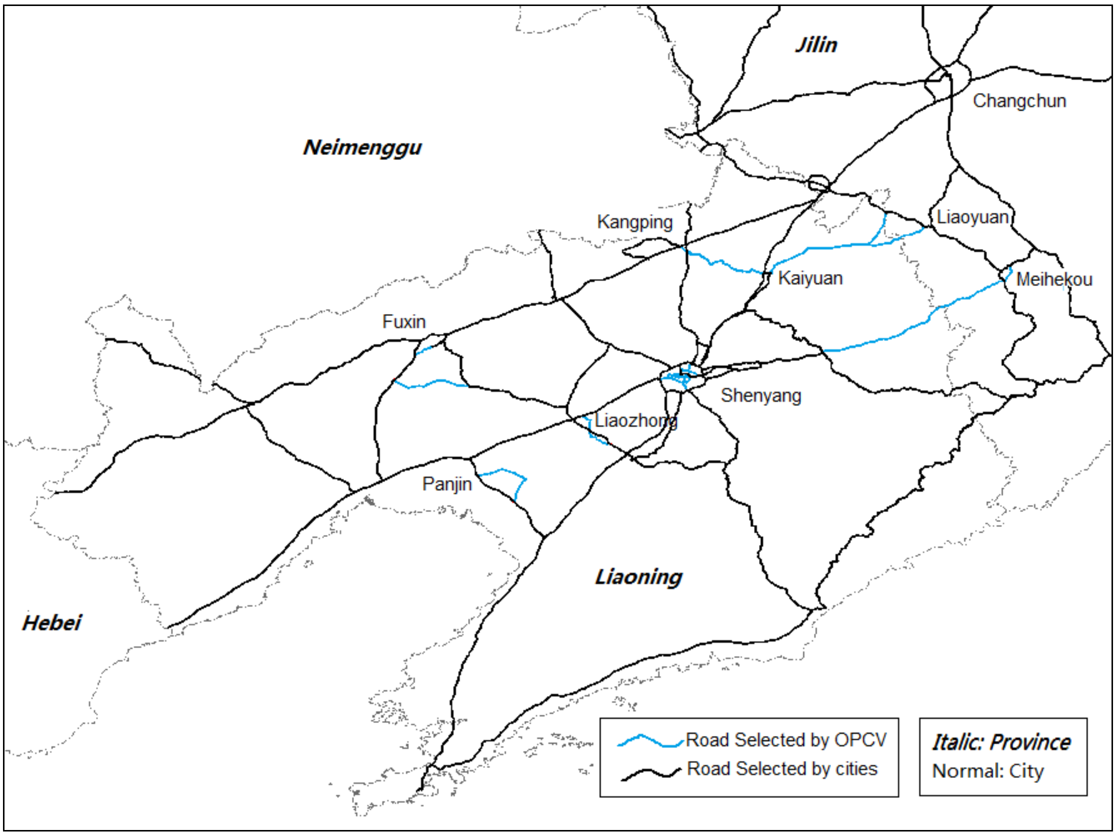


Figure 6.16 Decisive paths (in blue) in Liaoning and Jilin Province

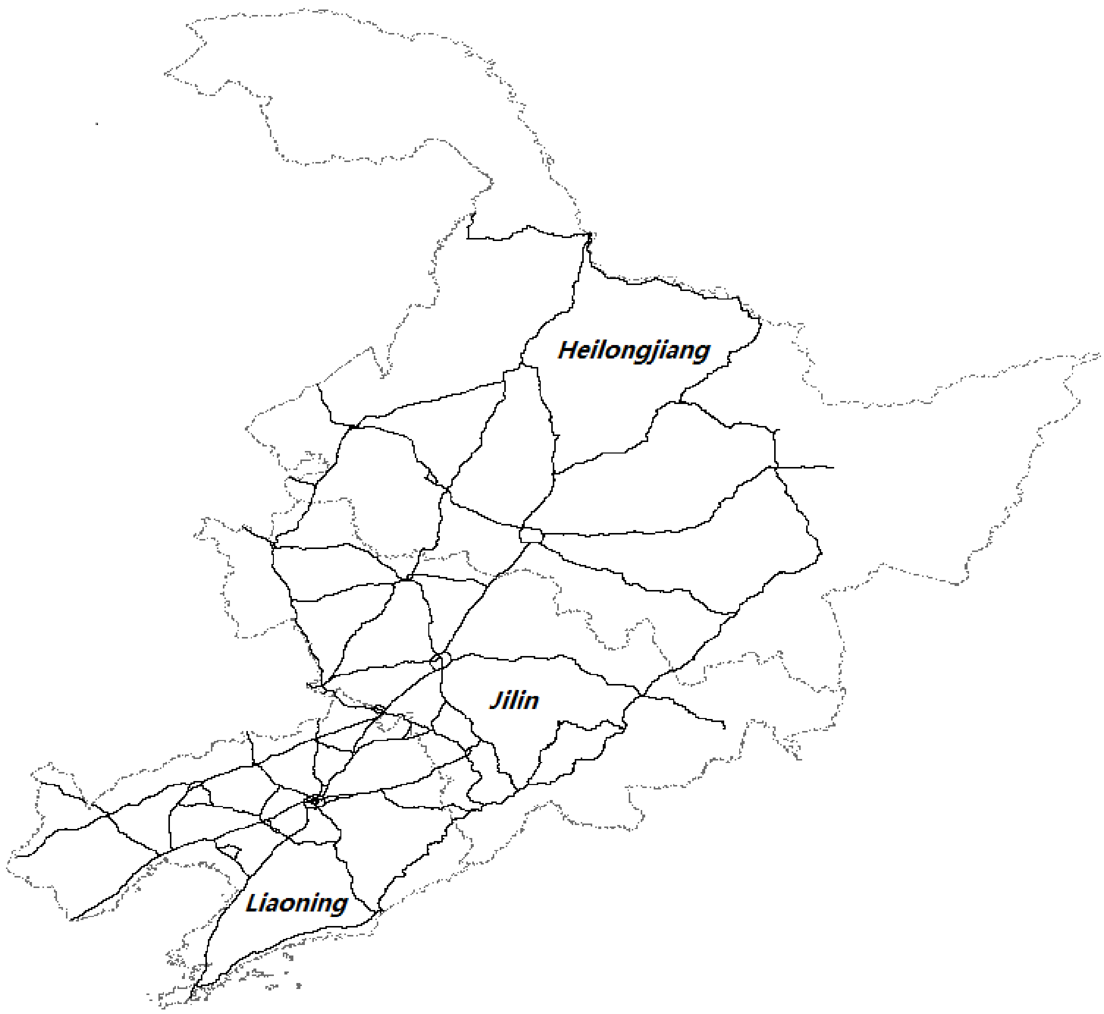


Figure 6.17 High-layer road network in Northeast China

6.4 Evaluation

The middle-layer and high-layer road network created for the above two test beds have obviously preserved the right road density and necessary connectivity for both visual display and navigation purposes.

Since the creation of the hierarchical road networks serves the main purpose to support efficient long-distance route planning in an embedded car navigation system, the thesis gives an in-depth analysis to the difference between our approach and the reference datasets from two test beds.

The results of our approach for test bed Bavaria State show a large similarity to those from Navteq's and Tele Atlas' which are tailored for navigation data authoring as shown in Figure 6.18, differences exist for five routes, in which the route in red is not included in high-layer road network of our new reproach and the routes in green are contained. The first column in Table 6.16 indicates five routes that disagree among the three high-layer road networks in Figure 6.18. Our results are all correct. In addition, the high-layer road networks of Navteq and TeleAtlas are used by many navigation system providers. The route-planning results of these providers are also correct because they use another route-planning algorithm based on a four-layer hierarchical road network.

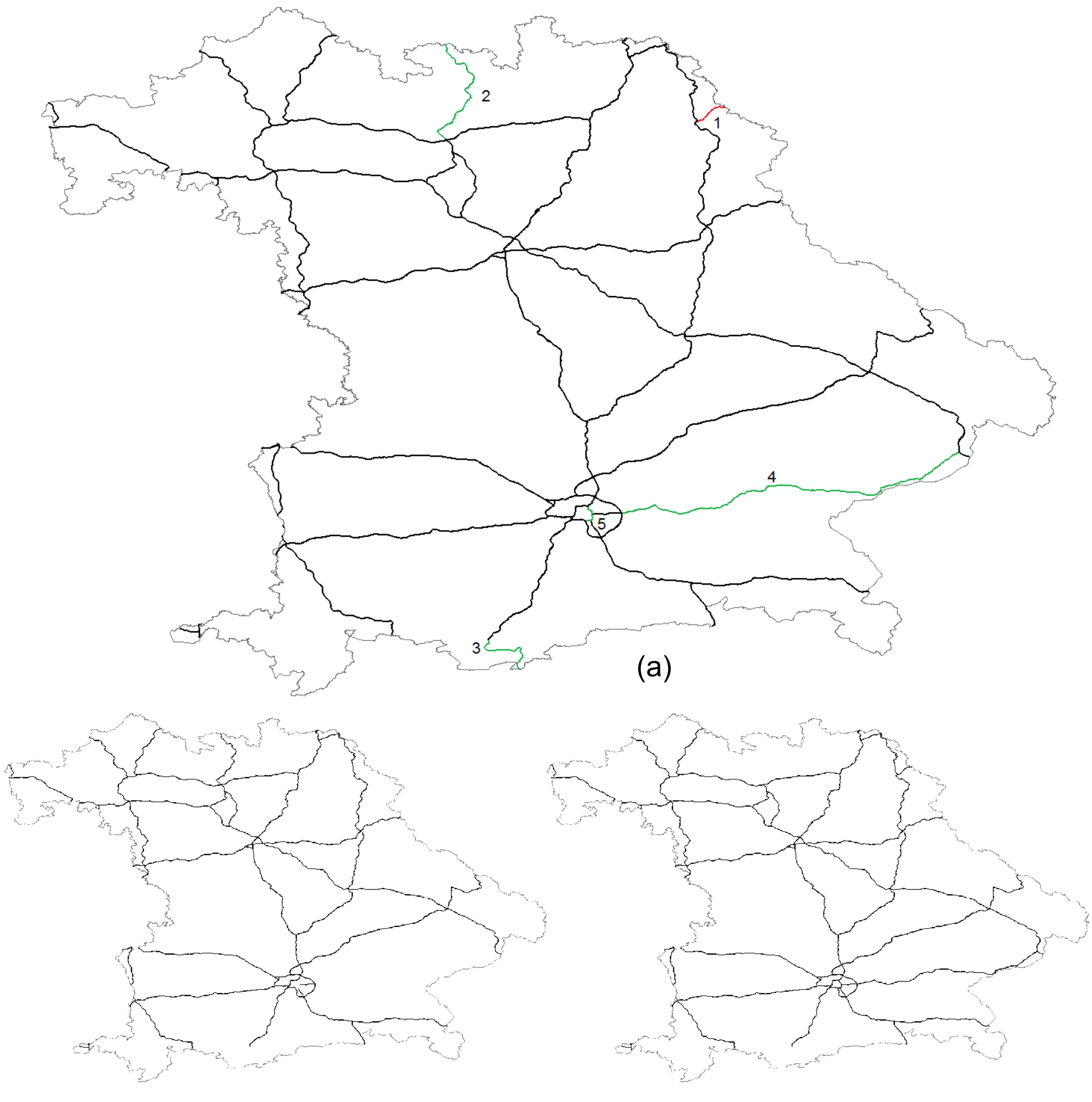
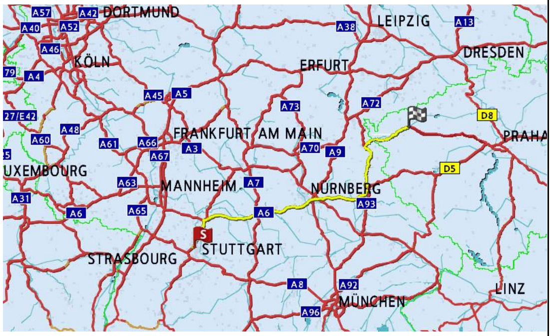


Figure 6.18 Comparison of high-layer road networks in Bavaria State

(a) Result of new solution; (b) Result of Navteq; (c) Result of Tele Atlas.

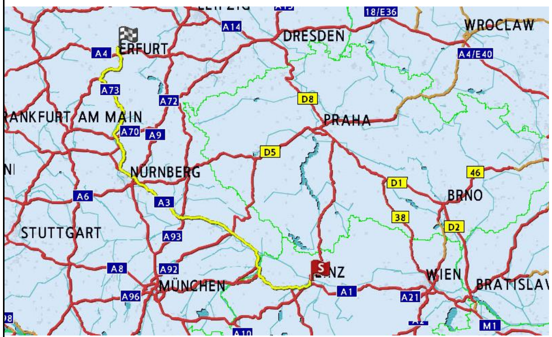
Table 6.16 Test cases and result analysis in Bavaria State

<table>
<tr><th>Route</th><th>Start point</th><th>Destination</th><th>Result</th><th>Analysis</th></tr>
<tr><td>1</td><td>Zurich,
Switzerland</td><td>Karlovy Vary,
Czech</td><td>New: OK
TA:OK
NA:OK</td><td>This route is needless and can thus be omitted because all paths are correctly found regardless of whether this road is selected in high-layer road network or not.</td></tr>
<tr><td colspan="3">

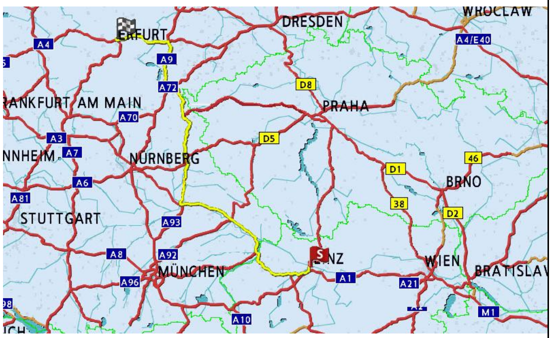
New: OK</td><td colspan="2">

TA:OK</td></tr>
</table>

Route	Start point	Destination	Result	Analysis
2	Linz, Austria	Erfurt, Germany	New: OK TA:NG NA:OK	This route is necessary because it's an arterial road between large regions from the functional perspective. Otherwise, the path is not necessary.



New: OK



TA:NG

Route	Start point	Destination	Result	Analysis
3	Bolzano, Italy	North of Garmisch-Partenkirchen, Germany	New: OK TA:NG NA:NG	This route is a decisive path. It's necessary to include the important main roads in mountains to keep the completeness. Also this road is detected by OPCV algorithm.

New: OK

NA:NG

Route	Start point	Destination	Result	Analysis
4	Wien, Austria	Forstinning, Eastern Munich, Germany	New: OK TA:OK NA:NG	This route is long and consists of A94 and main roads with high speed, So it's important for route planning. Also this road is picked by OPCV algorithm.

New: OK

NA:NG

<table>
<tr><th>Route</th><th>Start point</th><th>Destination</th><th>Result</th><th>Analysis</th></tr>
<tr><td>5</td><td>Milano, Italy</td><td>Innsbrucker Ring, Munich, Germany</td><td>New: OK
TA:OK
NA:OK</td><td>This route contributes to the recognition of the urban pattern of Munich, although it does not affect the correctness of long-distance route planning.</td></tr>
<tr><td colspan="5">


New: OK


NA:OK
</td></tr>
</table>

For the test bed Northeast China, our result (Figure 6.19a) has also revealed a better road density and distribution pattern in comparison to the source dataset from Navinfo (Figure 6.19b). Six typical long-distance routes are confirmed to be correct as Table 6.17 shows.

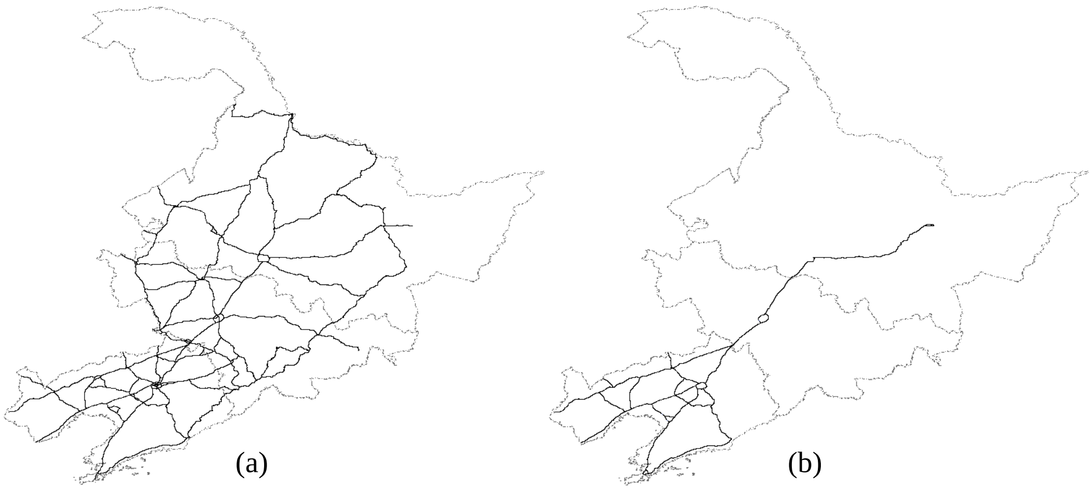


Figure 6.19 Comparison of high-layer road networks in Northeast China
(a) Result of new solution; (b) Result of Navinfo

Table 6.17 Test case and results in Northeast China

Route	Start point	Destination	Result
1	Huhehaote, Neimenggu	Tongjiang, Heiongjiang	OK
2	Shijiazhuang, Hebei	Yian, Heilongjiang	OK
3	Huhehaote, Neimenggu	Qianan, Jilin	OK
4	Jinan, Shandong	Yushu, Jilin	OK
5	Jinan, Shandong	Kuandian, Liaoning	OK
6	Shijiazhuang, Hebei	Faku, Liaoning	OK

Moreover, the route-planning speed on navigation unit was tested on two hierarchical road networks with different high-layer road network as shown in Figure 6.19 (a called new and b called ref). All nodes of each province are set as start points. Six destinations are selected as Figure 6.20 shows and each province has three corresponding destinations. So for each province, three set of routes would be tested: (1) Liaoning - Heihe, Shuangyashan and Yanbian; (2) Jilin - Dalian, Chaoyang and Heihe; and (3) Heilongjiang - Dalian, Chaoyang and Huludao. The statistics in Figure 6.21 demonstrates the efficiency of long-distance route planning based on 3-layer hierarchical road network (360,000 road nodes in Northeast China), The minimum time, maximum time and average time of all nine set of routes in three provinces based on our new high-layer road network are shorter than those based on reference road network.

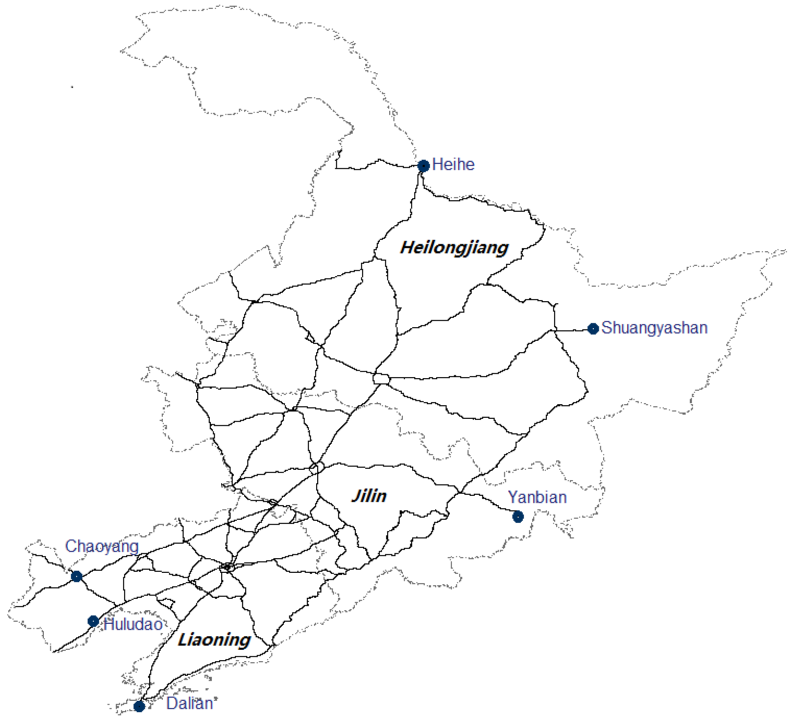
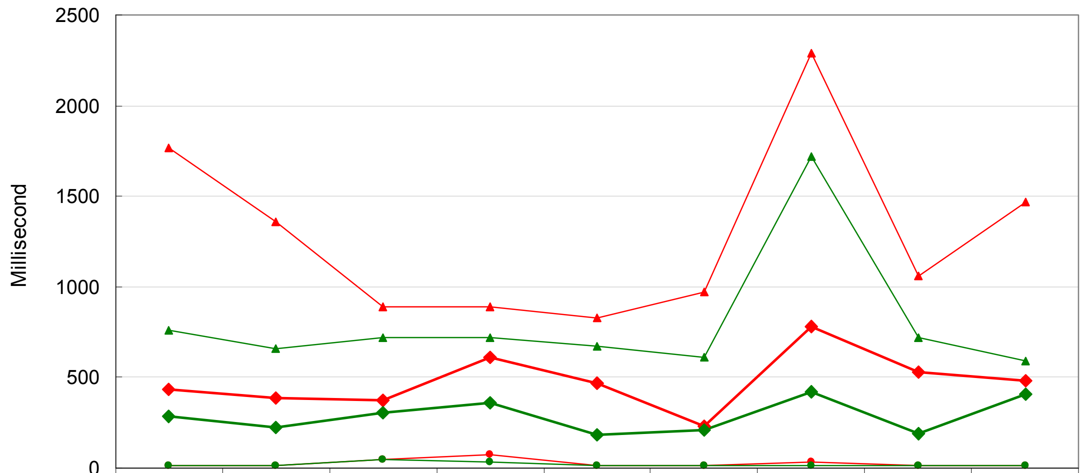


Figure 6.20 Destinations represented by navy blue points in Northeast China



	Liaoning -Heihe	Liaoning -Shuangy.s.	Liaoning -Yanbian	Jilin -Dalian	Jilin -Chaoyang	Jilin -Heihe	Heilongjiang -Dalian	Heilongjiang -Chaoyang	Heilongjiang -Huludao
Ref-Max.	1765	1360	891	891	828	969	2289	1063	1469
New-Max.	764	656	719	719	672	609	1718	719	594
Ref-Avg.	438	390	372	614	470	234	784	533	482
New-Avg.	287	222	303	357	182	209	422	188	410
Ref-Min.	15	15	46	78	15	15	32	15	15
New-Min.	15	15	46	31	15	15	15	15	15

Figure 6.21 Statistics of route-planning speed based on two hierarchical road networks

Chapter 7

Conclusions and Outlook

7.1 Conclusions

This thesis is devoted to the generalization of road network for the application in an embedded car navigation system which implies a number of special constraints in terms of limited hardware resources and computing capacity for map display and navigational services. It analyses various generalization operators of road network and characteristics of road network in car navigation data authoring. Based on the interpretation of road information available in commercial datasets, the author proposes improvements in five complementary selection methods and an automated solution for navigational road-network generalization to solve the two existing problems: (1) the connectivity of navigational road network is not always ensured taking traffic regulations into account, (2) distributional density of roads at higher abstraction layer is unbalanced or unreasonable, which hinders the efficiency of accelerating route-planning algorithms. The new approach creates two sets of hierarchical road network for an embedded car navigation system: one for map display and the other for route planning. In this way, it can satisfy not only general cartographical requirements for legibility conditioned by map scales but also the special requirements for navigational functions and performance.

Generalization of road network in car navigation data authoring as a special research field crosses three disciplines - cartography, navigation and transportation network. This work makes the following main contributions:

1) The thesis has shed light on the generalization characteristics of road network for car navigation data authoring that consist of the constraints, specific operators and algorithms, elements of validation standards required by navigation functions. The navigation data authoring is an automatic process that reorganizes the data structure and converts information among different contexts. The generalization of road network for navigation data authoring is essentially a model generalization. To guarantee the correctness of vehicle positioning, road matching, route guidance, and other navigational functions, the positions of road nodes, the road shape and the topology of road network should be preserved as far as possible. Road selection is therefore identified as the main generalization operator which does not introduce graphic artifacts and conflicts in the simplified road network. The existing road selection methods reported so far have been extended and elaborated in this work in order to makes full use of all available semantic attributes and values. Road name, speed category, direction of traffic flow, road type, construction information etc. are considered in an integrative and complementary manner. For example, various indicators of road class and other relevant attributes are combined to determine the road priority that allows the ranking of individual roads, thus a fine-tuned selection.

2) Since the bidirectional connectivity for traffic flow is fundamental for the route-planning algorithms, traffic regulations are considered in the selection process and the fitness for route planning is used as one of the most important quality criterion for the verification of the selection results. The thesis put forward the idea to use connection links as additional indicator for road selection to keep connectivity of road network. A main link forms the main part of a road and extends in a continuous direction to pass from one place (city/town/intersection) to another. A connection link usually brings two main links together, thus allows the mutual accessibility between the main links and prevents the road network from being broken. Due to their inferior classes quality and sometimes missing attribute values, connection links are often eliminated by conventional selection methods,

thus leads to disconnection among selected roads. In this work, various types of connection links are automatically recognized by their shapes, their relationships to the main links or other explicit attributes. A part of them is then added to the selected main links and the connectivity of resulted road network is thus preserved.

3) The service relationship between arterial roads and important cities is utilized as an efficient clue for road selection. On the one hand, the arterial roads provide direct service for important cities and larger towns which generate and attract a large proportion of trips. On the other hand, the roads with highest class in a network usually connect the most important cities on a continent and within a country. Therefore, the proxy locations of important cities are selected as anchor points to identify arterial roads and build up a high-layer road network with good connectivity and balanced road density. Road selection by means of city selection has substantially reduced the computational complexity.

4) Being inspired by the fact that the optimal performance of accelerating route-planning algorithms relies on whether the underlying road network is reasonably partitioned into vertical layers, a novel method of selection by OPCV algorithm is developed in this work. Using the self-proving OPCV algorithm in a simulated test environment, suboptimal routes found by the accelerating route-planning algorithms on an improperly partitioned road network can be automatically detected. Further, a decisive path that distinguishes the suboptimal route from the optimal one can be identified and added to the high-layer network. This leads to the improvement of vertical partitioning and finally the construction of a high-layer road network that allows the optimal route planning.

To summarize, the thesis provides a successful engineering solution of road generalization for an embedded car navigation system with a pair of automatically constructed and mutually related hierarchical road networks. This solution has unified five selection methods in the car navigation data authoring process. It allows real-time map display for given scale levels and optimal long-distance route planning at the same time. The experimental results with two test beds - Bavaria State and Northeast China - have verified the feasibility of the approach.

7.2 Future work

A number of further improvements on the basis of the engineering solution in this thesis are possible:

(1) Extension of selection methods

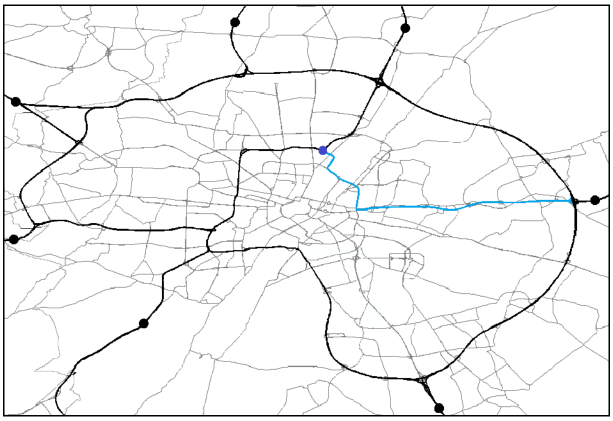
The selection methods by important cities and OPCV algorithm can satisfy the requirements of high-layer road network. Theoretically, they can work on the middle layer, but their efficiency is yet to be proved. The middle-layer road network contains far more medium-sized and small cities. Extensive survey is necessary to determine the relative importance of these cities, which in turn will influence the selection of roads. The selection by OPCV algorithm faces a similar situation with a large amount of data the algorithm has to operate. Although it is possible to traverse all routes between any given starting and terminating node, the computing efficiency is questionable and some special measures that help reduce the search scope need to be developed.

(2) More generalization methods of road network

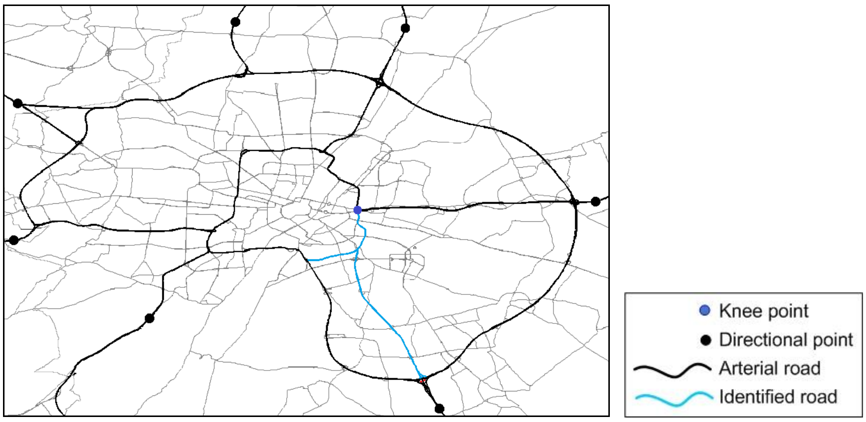
The thesis has handled five levels for map display, with each containing a certain number of road links and nodes resulted from the selection operator. In fact, there are many other constraints such as mesh density, road conflict and area ratio of road symbols which can be derived from the existing road information and satisfied by applying further generation operators.

The recognition of connection links by stroke or by road pattern in this thesis is based on the construction of strokes following the psychological principle of good continuation. Based on the deflection angles (Jiang et al. 2008), road class or road name (Jiang & Claramunt 2004) in formal methods, the general stroke construction can be facilitated with further semantic information, such as road attributes and traffic flow etc. Moreover, some semantic information should be used as important clues before the spatial information is involved.

Generalization of road network in urban area is a research hotpot recently. The road network in a city is formed or planned for some reasons. This background information can be used to guide the pattern recognition and preservation. To preserve the road pattern of Munich characterized by rings, for instance, the necessary roads between "knee point" and "directional points" on freeway outside the city need to be identified and included in the network as illustrated in Figure 7.1.



(a)



(b)

Figure 7.1 Road selection by knee point in urban area

(a) Search a decisive path between the first knee point and all directional points on freeway;

(b) Search other two decisive paths between the second knee point in the first decisive path and all directional points on freeway.

(3) Innovation of car navigation data format

As a market-oriented product, the car navigation system has to keep pace with the development of hardware capability and new technologies and find trade-offs among performance improvements (speed and performance of display, speed and correctness of route planning), functional expansions and cost efficiency. The innovations with car navigation data may go in two opposite directions as the two approaches (a) and (b) explained in Table 7.1 and illustrated in Figure 7.2.

Table 7.1 Two suggestions for an innovative car navigation data format

No.	Solution	Advantage	Disadvantage
a	Keep flat binary files. Completely separate road networks for display from route planning in higher layer.	Improve display performance and increase the speed of route planning after eliminating the correspondence between them. Cost down.	Hard to update, the same as the PSF of KIWI. Not use the new embedded technology.
b	Use embedded database to manage mass data. Merge the road network for route planning with that for display, while build up mirror image to construct a hierarchical road network for route planning.	Easy to update (insert, delete, modify) in database. Reduce the data volume and complexity. Improve display performance.	Not sure if it accelerates the route-planning procedure. Difficult to reduce the cost.

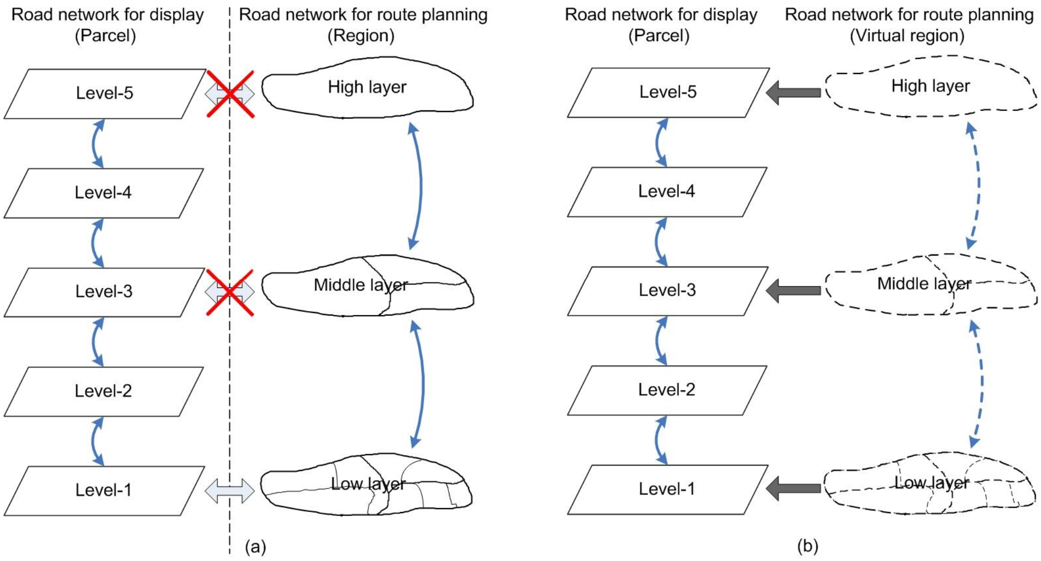


Figure 7.2 Two possible solutions for an innovative car navigation data format

(a) (b) Two possible innovation approaches corresponding to Table 7.1.

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Acknowledgements

I had a dream to study abroad early in senior middle school. Wonderful moments in several photos in a showroom from overseas alumni invoked my curiosity. When there was no chance to be an exchange student for our grade in graduate school, I felt very disappointed. Years later, I got a generous offer from Prof. Dr. Dunyao Zhu from Wuhan University who supported me with a PhD scholarship and sent me as the candidate to pursue the PhD degree at Technische Universität München (TUM), thus my dream came true. Although doing the degree has been challenging and enduring, I have luckily got great helps and supports from a lot of people.

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Prof. Dr.-Ing. Liqiu Meng. Taking my former work experiences into account, she wisely proposed the research topic that not only aims to solve the existing engineering problems but also promoted the related theoretical study. She knew how to guide me to the correct direction in the academic world especially when bottlenecks occurred. Always just a hit could be a precise key to open the gate to success, which cheered me up and made me become more and more self-confident. In particular, she is a very strict teacher. She reviewed this dissertation word for word and helped me to revise all faults one by one, which allowed me to ensure the quality of my thesis. In addition, I was deeply touched in that she is very kind and gave my family so much warm-hearted helps here. It is my fortunate and honor to be her student.

I would like to extend my sincerest thanks to my co-supervisors, Prof. Zhilin Lin from The Hong Kong Polytechnical University and Prof. Dirk Burghardt from Technische Universität Dresden for reviewing my work and giving me valuable comments.

I'm very grateful for the supports from all my colleagues at the Department of Cartography of TUM, especially Mrs. Luise Fleißner, Dr. Jukka Krisp, Dr. Hongchao Fan, Dr. Lu Liu, Mr. Christian Murphy for their generous help, scientific management and logistic support. The Department of Cartography has rendered me a comfortable learning atmosphere. I would never forget our grand times together.

I would like to express my gratitude to my company and Prof. Dr. Dunyao Zhu, the president of Kotei, who provided me such an invaluable opportunity to study in Germany. Many thanks should go to my partners: Data Engineer Yanggang Wang, Software Engineer Mingjie Yang and Test Engineer Jiangbo Hao, who worked overtime to help me finish the project together. Thanks a lot to many colleagues who supported me and concerned me. Yes, I learned that, a team we are.

I can't help telling my wife Man Chen how much I appreciate her endless support and understanding. When I started my PhD study in Germany, she was pregnant. Although I stand by her at the birth moment our son Cheng Gong, she took care of it alone later. After she came to join me in Munich, she actually has been looking after Cheng and me both. Her love has given me the great power to work harder and try to do better, while Cheng has brought us much joy. My home is where you are.

I am lucky to grow up in a loving family that is always a source of strength and fun. This thesis is also dedicated to my parents who have always stood by me and supported me.

Curriculum Vitae

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