

Optimization Analysis of Multiservice Architecture Concepts in Road Transport Telematics

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Transport telematic systems, also known as intelligent transportation systems, can be expensive to implement but the services they provide may offer substantial benefits. However, what services the system can provide depends on the architectural choices made, which also affects the cost of the system. We propose an optimization model to support a more informed decision before investing in a multiple service transport telematic system. The model evaluates the possible choices of services and architectures, and aims to maximize the total net societal benefit. We argue that the optimization model can provide support for strategic decisions by highlighting the consequences of adopting different system architectures, including both societal value and cost. This can be useful for decision makers, such as governments, road transport telematic service providers, and commercial road freight transport operators.

Keywords Architecture; Evaluation; Integer Linear Programming; Modeling; Optimization; Transport Telematic Service

INTRODUCTION

Intelligent transport systems (ITS) are today considered a suitable approach for addressing surface transportation problems, for example, reduction of road fatalities. The effectiveness of such approaches can be seen in terms of the benefits of implemented transport telematic services (TTSs). TTSs can deliver important benefits, such as improved emergency response, reduced travel times, and emissions. TTSs can coexist on the same telematic system. We view a transport telematic system as consisting of an architecture specification and the resulting TTSs. Several approaches have been used to address the benefits of individual TTSs, most notably cost benefits analysis (CBA) despite many shortcomings that are associated with CBA (Bekiaris & Nakanishi, 2004; Leviakangas & Lahesmaa, 2002; Levine & Underwood, 1996). Methods used in the assessments of transport systems are seen to be limited for the assessment of ITS

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systems (Brand, 1999) mainly because ITS are focused on soft concepts such as information accuracy, responsiveness, and so on. A platform or telematic system architecture that can deliver multiple TTSs may result in higher net benefits. Examples of anticipated platforms are the European Electronic Tolling system based on the Global Navigation Satellite System (GNSS) (Leinberger, 2008) and the emergency call platform (Dimitrios & Bouloutas, 2007). These platforms have the characteristic that many TTSs can be developed through an extension of existing functionalities. The choice of architecture influences the possibility of efficiently implementing TTSs. Further, the cost of implementing and using functionalities, the benefits of TTSs, and limitation in resources, make it difficult to determine a set of beneficial TTSs for a given architectural choice. Hence we use optimization to account for these trade-offs.

The purpose of this article is to develop an optimization model that can support strategic decisions about choices of telematic architectures that support multiple services (multi-service architectures [MSAs]). The choice of TTSs to prioritize for implementation is modeled as an optimization problem that maximizes net societal benefit. Different TTSs utilize different types and capacities of resources as shown in Table 1. A case study in the sixth section illustrates the use of the optimization

Table 1 Data rate requirements for communication and processing ITS data, with typical ranges of data rates for ITS applications.

Type of resource supported	Parameter value interval	Usage ($U_r \geq O, r \in R$) in Mbps
Data communication	0.5 kbps to 11 Mbps	0.0015
Voice communication	4.8 kbps to 32 kbps	0.002
Video/picture communication	3 Mbps to 6 Mbps	0.004
OBU data transfer rate	250 kbps (up-link), 500 kbps(down-link)	0.005
OBU data processing/storage	6.4 kbps	0.005
Distributed server processing	500 Mbps (4 GHz)	0.2
Centralized server processing	2000 Mbps (8 GHz)	0.05
INFORBEACON ARIB-STD T75	Transmission (1024 kbps) position frequency 1/10 KM	0.01
Satellite positioning	250 bps (down-link)	0.005

model. The benefit of modeling MSAs and TTSs is to improve our understanding of their potential effect on society. Further, modeling can help our understanding of the dependencies that exist between multiple TTSs and therefore improve how we assess potential benefits of such TTSs. This article proposes a model that supports the analysis of choices of MSAs, based on available TTSs, resource capacities, and functionalities needed to achieve TTSs. Different types of resources and resource capacities will lead to different costs, all shown in Table 2, for each alternative MSA. Resource utilization and costs of realizing each functionality contributes to the costs of realizing TTSs. This is somewhat similar to work done by Shaoyan and Chuanyou (1998) in evaluating the cost of data communication services, except that they focused on establishing tariffs. Results of the proposed optimization model in this article consist of a selection of various TTSs and MSAs according to perceived total net societal benefits. While this work may not lead to answers connected to the challenges that face the implementation of MSAs, it provides a method that can support high-level decisions by highlighting the consequences of adopting given architectures, from a system perspective, including both societal benefit and cost. In the rest of this article, the first three sections, respectively, provide definitions of the key terms used, introduce related work, and discuss MSAs for TTSs. In the fourth and fifth sections an optimization model is proposed, which is then applied to a case study. In the sixth, seventh, and eighth sections, results and analysis, conclusions and future work, and acknowledgments are presented, respectively.

Definition of Terms

Functionalities

Functionalities such as map matching, global positioning, and so on (Table 3) are the basic properties that can be implemented in a system and, when combined together, can achieve a TTS. It is assumed that essential functionalities for achieving each TTS can be specified. Such functionalities can be used commonly by TTSs incurring different costs.

Transport Telematic Service (TTS)

A transport telematic service (TTS), such as navigation, road user charging, intelligent speed adaptation, and so on (Table 3), is a product or activity, targeted to a specific type of ITS user, addressing given user needs (ISO/TR 14813-1, 2007). A TTS is specified by its functionalities, and provides value to society, incurring different costs as shown in Table 4.

Multiservice Architecture (MSA) for a Transport Telematic System (TTS)

This is considered to be the conceptual specification of transport telematic system architecture. The functionalities provided can be shared by different TTSs. We connect the MSA specification to functionalities by allowing a certain set of resources. Examples are thin client (Bernhard, 2003) to thick client

Table 2 Resources (R), capacities ($\tilde{U}_r \geq 0, r \in R$), and unit costs ($\Phi_r \geq 0, r \in R$) used in the case study.

Resource	Resource type	Capacity $\tilde{U}_r \geq 0, r \in R$	Unit cost in € $\Phi_r \geq 0, r \in R$
Communication	Sensor data modems (R1)	36 kbps	150
	Audio data modems (R2)	3 Mbps	250
	Video data modems (R3)	4 Mbps	400
Processing	OBU equipment (R4)	6.4 kbps	500
	Distributed computer network (R5)	500 Mbps	2000
	Centralized computer network (R6)	2000 Mbps	5000
Positioning	INFORBEACON based on DSRC (R7)	10 Mbps	1000
	Satellite e.g. GNSS (R8)	0.25 Mbps	500

Table 3 Full names of TTSs (represented by set S) and functionalities (represented by set F).

Full name of TTS abbreviations							
AWI	Accident Warning Information	FM	Freight Mobility	ODM	On-Board Driver monitoring	RG	Route Guidance
ADL	Automated Driver Logs	GEO	Geo-fencing	OSM	On-Board Safety & Security Monitoring	SGM	Sensitive Goods Monitoring
DP	Driver Planning	GI	Goods Identification	PYD	Pay as You Drive	SM	Staff Monitoring
DTI	Dynamic Traffic Information	IRM	Information About Infrastructure Repair and Maintenance	RTT	Real Time Track & Trace of Goods	TAR	Theft Alarm and Recovery
EC	E-Call	XXL	Information on the transportation of XXL Cargo	RED	Remote Declaration	TOH	Transport Order Handling
ETM	Emission Testing and Mitigation	ITP	Information on Truck Parking	RM	Remote Monitoring	TRO	Transport Resource Optimization
EDI	En-Route Driver Information	ISA	Intelligent Speed Adaptation	RHW	Road Hindrance Warning	VF	Vehicle Follow-up
ETA	Estimated Time of Arrival	NAV	Navigation Through a Route Network	RUC	Road User Charging (RUCA- advanced version)	WI	Weight Indication
Full name of functionality abbreviations							
as	Accident Sensors	dd	Driver data	mp	Map position and updates	src	Short range communication (e.g. DSRC)
asg	Alarm signal	gp	Global (absolute) Positioning	m	Monitoring	sd	Signal delay
at	Automatic Trigger	gds	Goods damage sensors	no	Network optimization	tfc	Tidal flow control and traffic priority
cv	Camera vision	gd	Goods data logging	obu	On-Board Unit	ts	Time Stamping
da	Data anonymity (encryption)	hs	Human sensors	odd	Origin-Destination Data	wf	Weather Forecast
db	Data Broadcast	ids	Infrastructure damage sensors	rm	Ramp Metering	vds	Vehicle damage sensors
ds	Data Storage	ind	Infrastructure data logging	rc	Route congestion	vd	Vehicle data/ID logger
du	Data updates	lp	Local (reference) Positioning	di	Driver interface	vs	Vehicle speed
dt	Digital tachographs	mh	Maintenance history data logger	ed	Emission data logger	vc	Voice communication

(Mckinnon, 2006) architectures, centralized, vehicle-to-vehicle-based architectures (Sakata et al., 2000), and so on (Table 5).

Related Work

Evaluation of ITS architectures is a subject of interest that has been addressed by many studies, such as Bristow et al. (1997), Persson et al. (2007), Tai-ying (2008), and Wees and Hertzberger (2000). All these studies have been aimed at understanding benefits of ITS using different methods. Most approaches used can be seen as formative or summative depending on the goal behind the evaluation (McQueen & McQueen, 1999). We differ from existing evaluation approaches, in that we are looking at the net benefit in the context of multiple TTSs. The task of evaluating architecture options is, in principle, concerned with how to identify, quantify, and compare

for all alternatives, all impacts, on all people and organizations, in all affected areas, over all time (Bekiaris & Nakanishi, 2004). However, in practice such an evaluation goal is optimistic due to the complexities involved, especially for MSAs. Thus, it is important to abstract conceptual architecture system characteristics for evaluation (Xu et al., 2006) to help understand the potential impacts of a real system.

Wees and Hertzberger (2000) uses discrete event-based simulation to abstract and identify interacting components and states for ITS evaluation. Their work did not consider the evaluation of multiple, coexisting TTSs, as their tool was aimed at single TTS evaluation. Benefits of individual TTSs have been evaluated on the basis of indicators, such as traffic volume increase, emission decrease, system construction cost, and vehicle equipment cost for electronic fee collection (EFC) systems (Tai-ying, 2008). Models for specific indicators have been suggested, for example, reliability model for ITS systems (Kabashkin, 2007). It remains to be demonstrated that these indicators can be used

Table 4 Value ($V_i > 0, i \in S$), cost ($Cir \geq 0, i \in S, r \in R$), and functionality ($Mij = [0,1], i \in S, j \in F$) data used in the study.

TTS	Value	Variable cost	Functionality specification per TTS
AWI	37.3	24.8	as, asg, db, ds, dt, di, lp, odd, rm, rc, ts, wf, vd, vs
ADL	1.3	0.3	db, dd, lp, ts, vd, vc
DP	1.7	0.4	da, db, dt, dd, gd, lp, obu, odd, ts, wf, vd
DTI	5.5	25.4	as, db, du, dt, di, gp, ids, ind, mp, obu, odd, rm, rc, sd, tfc, ts, wf, vd, vs vc
EC	31.2	1.5	as, asg, at, cv, db, du, dt, dd, di, gp, gds, gd, hs, lp, mh, mp, no, obu, rm, rc, src, sd, tfc, ts, vds, vd, vs, vc
ETM	1.8	24.9	db, ds, di, ed, gp, lp, mp, m, obu, rc, src, vd
EDI	30.6	24.8	du, di, lp, mp, obu, odd, rc, src, tfc, wf, vs, vc
ETA	6.2	0.8	db, dt, gp, gd, m, no, odd, rc, sd, ts, wf, vs
FM	1.8	24.8	da, ds, dt, gp, gds, gd, m, obu, odd, src, ts, vd
GEO	1.4	24.7	asg, at, cv, db, dt, gp, m, rm, src, ts, vd
GI	1.5	0.6	at, da, db, du, dd, gp, gds, gd, mp, m, obu, odd, ts, vd, vs
IRM	8.3	0.6	gp, ids, ind, mh, mp, m, rc, src, wf
XXL	0.4	24.9	cv, db, dt, di, gp, gd, ids, ind, mp, m, obu, odd, rc, tfc, ts, wf, vd, vs
ITP	3.2	49.2	at, cv, db, di, ind, lp, mp, no, obu, src, ts, vd
ISA	31.0	24.8	asg, cv, db, di, gp, ids, mp, m, rm, rc, sd, tfc, wf, vs
NAV	36.0	24.7	di, gp, lp, mp, no, obu, odd, rm, rc, sd, wf, vd, vs
ODM	2.0	0.6	as, asg, db, dt, dd, gp, hs, m, obu, ts, vds, vd, vs
OSM	3.0	25.0	asg, cv, dt, di, gp, gds, gd, hs, mh, m, obu, src, vds, vd, vs
PYD	6.8	25.3	as, at, da, db, ds, dt, dd, gp, mh, m, obu, odd, rc, ts, wf, vds, vd, vs
RTT	5.9	0.8	db, du, dt, dd, di, gp, gd, mp, no, obu, rc, src, ts, wf, vd, vs
RED	1.9	0.7	cv, da, db, ds, du, dd, di, gds, gd, mp, obu, odd, src, ts, vd, vc
RM	8.0	25.0	as, asg, at, ds, du, gp, lp, mp, m, obu, src, ts, vds, vd, vs
RHW	37.5	1.1	as, asg, db, dt, lp, mp, no, obu, odd, rm, rc, sd, tfc, ts, wf, vs
RUC	14.4	0.7	da, ds, gp, ids, ind, mp, obu, rm, rc, tfc, ts
RUCA	10.7	0.6	da, lp, ids, ind, mp, rm, rc, tfc, ts
RG	1.9	24.7	di, gp, ids, ind, mp, m, no, obu, odd, rm, rc, tfc, wf, vs
SGM	16.2	24.8	da, db, ds, dt, dd, ed, gp, gd, mp, m, odd, rc, ts, wf, vd, vs
SM	1.0	24.7	da, db, ds, dd, gp, mp, m, odd, ts, vd, vs
TAR	37.6	25.1	asg, at, cv, db, ds, dt, dd, gp, gds, gd, hs, mp, rc, ts, vds, vd, vs
TOH	22.1	24.7	da, db, du, dd, di, gd, lp, mp, obu, odd, rc, ts, wf, vd
TRO	49.9	25.7	da, db, ds, du, dt, dd, di, ed, gp, gd, ind, mp, m, no, obu, odd, rc, sd, tfc, ts, wf, vd, vs, vc
VF	3.1	25.0	da, db, ds, du, dt, dd, di, ed, gp, mh, mp, m, obu, odd, rc, ts, vds, vd, vs
WI	4.1	24.8	asg, at, cv, du, di, gp, gds, gd, ids, ind, mp, m, src, wf, vs

for modeling and evaluating other TTSs. The work by Persson et al. (2007) considers the support for multiple TTSs (flexibility) and provides a qualitative evaluation of architecture concepts, but does not quantify such benefits. We assess MSAs according to quantified benefits and costs of TTSs.

The use of optimization requires that the cost and benefits of TTSs be quantified. While many studies on the evaluation of TTSs have not quantified benefits, approaches based on economic and goal evaluation methods have addressed the question of benefits quantification (Peng et al., 2000). Their study

Table 5 MSA specification by key features and corresponding resources allowed ($A_{rt}, t \in A, r \in R$).

MSA key feature	Resources allowed							
	R1	R2	R3	R4	R5	R6	R7	R8
Vehicle-to-vehicle communication	1,4,6							
Roadside to server communication	5							
Vehicle to server communication	3	1,2,3,5	6					
Vehicle to roadside communication		4,6	2,3,5				3,6	
Satellite to roadside communication	2							
OBU data processing				1,2,3,5,6				
Multiple server processing				4	4			
Single central server processing					3,6	1,2,5		
Satellite positioning							4	2,3,5
Data broadcast							2,5	

Note. The numbers in the resource columns indicate which MSA specification has a key feature that provides a given resource; e.g., specifications Z1, Z4, and Z6, indicated by 1,4,6 under R1, has a key feature called vehicle-to-vehicle communication that provide a resource of sensor data modems. Thus $A_{R1Z1} = A_{R1Z4} = A_{R1Z6} = 1$. Empty cell means no architecture was considered that provided the given resource based on the key feature.

provides a framework for benefit assessment using benefit trees. They observe that there is significant variation in the complexity and details of ITS evaluation methods. Such variation in evaluation approaches and choice of criteria has partly been explained by the dependency on the end user of the evaluation results (Thill et al., 2006).

As a consequence, most evaluation methods are based on very specific approaches, for specific end users, making it hard to compare results on a general level. This issue has been partly addressed by Thill et al. (2006) using the ITS Option Analysis Model (ITSOAM) for forecasting the benefits of ITS elements and estimating the deployment cost. They address decisions related to system benefits, in which each ITS application should be considered separately and their benefits evaluated independently of each other. Our view about benefits differs from their study, since we consider the context of the benefits, that is, dependencies, for example, on given TTS collection and on the given platform due to the common functionality usage.

TTSs sharing functionalities existing in MSAs will result in synergies and improved net benefits. Such synergies cannot be successfully studied using CBA for an individual MSA, since the sharing of functionalities and the dependencies of benefits between TTSs are not accounted for in the case of CBA. The use of optimization models for evaluating MSAs, as advocated in this study, has not been explored so far.

MODELING MULTISERVICE ARCHITECTURES FOR TRANSPORT TELEMATIC SERVICES

The specific characteristic for distinguishing between two MSAs can be called MSA key features, such as communication, processing, positioning, and so on. In the proposed optimiza-

tion model we interpret key features as availability of certain resources that are used by functionalities of different TTSs, as shown in Table 5. Key features influence the availability of different types and levels of resources.

Multiservice Architecture Choices

Several choices of architectures (MSAs) can be used to achieve different types of TTSs depending on the types of functionalities allowed or not allowed by such architectures (Xu et al., 2004). In this study we choose to interpret an MSA concept as a combination of a set of features. As stated earlier, each key feature allows for a given resource or set of resources and capacities that are used by functionalities. Different types of resources and resource capacities are used by TTSs through their functionalities. If such resources are not available then the functionality cannot be achieved or it is achieved with an extra cost. Generally, selecting or deselecting (yes/no) a key feature means that certain resources are made available to functionalities of different TTSs as illustrated in Figure 1. We further illustrate specific combinations in the case study, together with the types of resources and associated capacities.

Resources Modeling for Transport Telematic Services

Different MSAs allow different functionalities based on two aspects: the type of resource required by the functionality and the associated capacity requirements; for example, sensor, video, audio data may requires 0.5 Mbps, 1 Mbps, or 2 Mbps of communication band width respectively (Esteve et al., 2006).

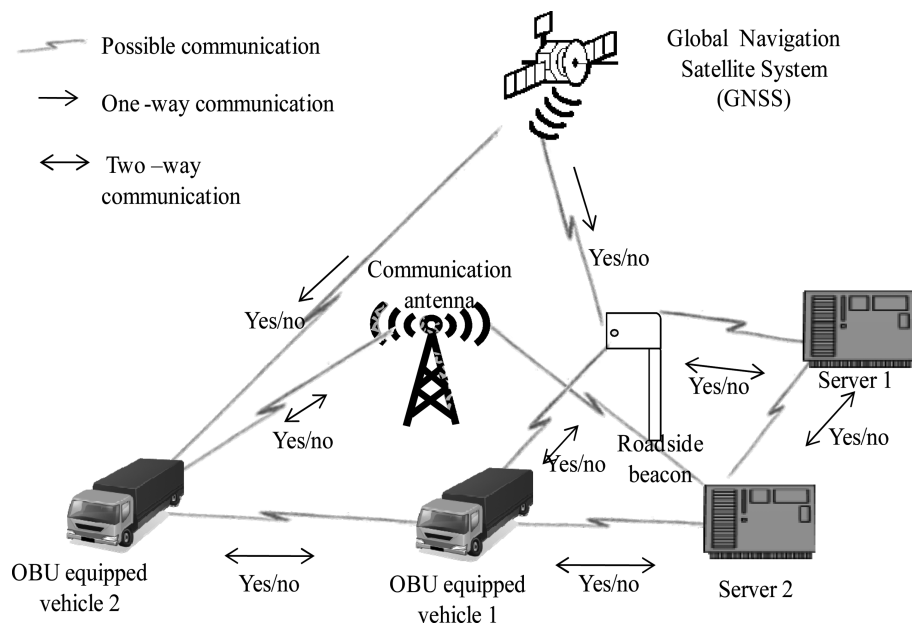


Figure 1 Illustration of the concept of MSA key features that provide functionality resources (color figure available online).

Communication

There are several ways of modeling communication. In this article, we have considered aspects related to communication capacity. For instance, one-way communication, such as data broadcasting, may require less bandwidth than two-way communication. We distinguish three types of data according to the communication capacity demand: (1) sensor data, for example, temperature, road conditions, number of vehicles; (2) audio data, for example, voice; and (3) video data, for example, road traffic cameras. For sensor data, communication bandwidth requirements are less demanding compared to video and audio data.

Processing

We consider the processing capacities of MSAs to depend on the type of technique (concept) used to achieve processing as follows:

- On-board unit (OBU) data processing: A small computer is fitted on-board the vehicle with the capability to process, display and store data (Bernhard & Wolfgang, 1996; Fukang et al., 2008).
- Single central server processing: The idea is that all information is processed by one server, or possibly by multiple servers that communicate with each other and share a database. A system with multiple servers sharing tasks can also be considered as centralized processing (Dimitrios & Bouloutas, 2000).
- Multiple distributed server processing: Though distributed processing can also be used to refer to a situation where tasks are shared between different computers, we consider that each server will completely execute its task without having to interact in real time with the other servers (Dimitrios and Bouloutas, 2000).

Positioning

One way to model positioning as a resource is to consider the possibility to achieve positioning using satellite or roadside beacons, the number of units, and the unit capacity.

- Satellite positioning: A receiver (in the vehicle) is used to pick up a signal and the position of the vehicle is determined based on the signal properties.
- Roadside equipment (INFORBEACON): An electronic device mounted on the roadside is used as a reference for positioning a vehicle. INFORBEACON can also be used for storing data and transmitting such data to other systems and hence can serve as a communication device.

Cost Modeling for Transport Telematic Services

The implementation of a functionality incurs a fixed cost. TTSs consist of functionalities utilizing different capacities of

resources at a variable cost in addition to the fixed costs of implementation; for example, the transmission of sensor data may require less communication bandwidth than the transmission of video data and hence incur different costs. Cost of resource utilization by TTSs can be modeled in several ways, for example, identifying resource requirements and estimating cost parameters. We have considered the cost of units or interfaces providing different functionalities that are available in the market for parameter cost estimates, as shown in Table 2.

Modeling Societal Values for Transport Telematic Services

In assessing the value of each TTS, it is assumed that the performance of the TTS meets the demands of its users with respect to accuracy and performance, that is, that the TTS is at its full potential. Consequently, we consider for each TTS the required functionalities for realizing its full potential. Further work on how user performance requirements may affect the quality and hence benefits of each TTS in the context of MSAs has been carried out (Mbiydzennyuy et al., 2010b). The value estimate for a TTS is based on its possibility to improve a number of performance saving indicators (PSIs) such as accidents, fuel consumption, delays, and so on, all of which are addressed by a separate study (Mbiydzennyuy et al., 2010a). In this case study, we have only used societal values and cost, mainly for illustrating the use of the optimization model and for providing some indicative results.

A PROPOSED OPTIMIZATION MODEL FOR MULTISERVICE ARCHITECTURE IN ROAD TRANSPORT

Optimization models represent choices as decision variables and seek values that maximize or minimize the objective function of the decision, subject to constraints on variable values expressing the limits on possible decision choices (Rardin, 2000). In this article, the decision choices are the type of MSA, TTSs, and their required functionalities, illustrated in Figure 2.

The proposed model aims to suggest the relationship between MSAs, resources, functionalities, and TTSs. Each MSA is a specification of a set of key features. We have concentrated on the resources for achieving key features. Hence each key feature involves either a single resource or a specification of a set of resource types and capacities. Each TTS functionality requires one or more resources. Once a functionality uses a certain type of resource, the result is that it generates a given amount of data. Each TTS is a specification of a set of functionalities.

The positive benefits are estimated from the societal value of a TTS and the costs from the functionalities utilized by the TTSs. Later in this article, we provide a complete mathematical formulation of the preceding relationships in an optimization model. We also consider a dependency parameter $D_{\hat{i}} \geq 0$, $i, \hat{i} \in S$, $i \neq \hat{i}$ (S a set of TTSs) to account for the decrease in marginal

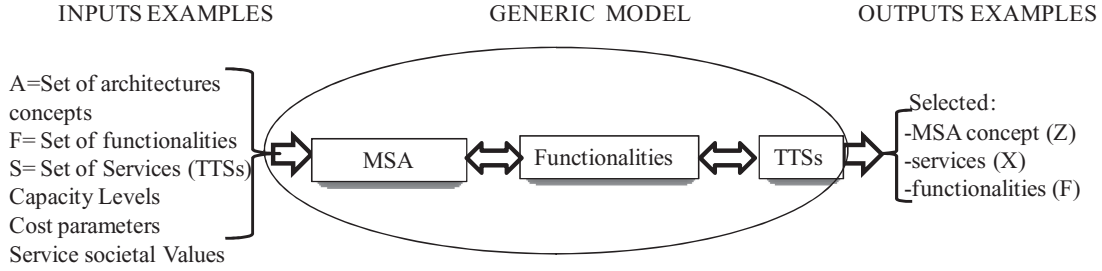


Figure 2 Generic model diagram illustration.

benefits of two TTSs that address a related aspect. For instance, if E-Call and Intelligent Speed Adaptation each reduce accidents by 0.15%, the total benefit will be slightly less than 0.3% due to a decrease in marginal benefits. Dependencies are computed by calculating a pairwise matrix for all TTSs if such TTSs address a common performance indicator. Assuming that (1) if there are two TTSs that require the same type of functionality, it is possible to design a system such that the TTSs can use the same functionality without having to implement it twice, and (2) each TTS can be implemented only in a given way, we propose the following optimization model.

Sets:

- S : Set of TTSs (shown in Table 3).
- F : Set of functionalities (shown in Table 3).
- A : Set of architectures (shown in Table 5)
- R : Set of resources (shown in Table 2).

Parameters: Parameters and set values indicated in parentheses are employed by the case study to illustrate the optimization model:

- $V_i, i \in S$ The value of each TTS (see Table 4).
- $C_j, j \in F$ The fixed cost of each functionality (see Table 4).
- $C_{ir} \geq 0, i \in S, r \in R$ The variable cost of each TTS for each resource (see Table 4).
- $P \geq 0$ Cost of communicating and processing 1 megabyte of data (rough estimate of $2.9 * 10^{-3}$ € per megabyte per year).
- $D_{\hat{i}\hat{i}} \geq 0, i, \hat{i} \in S, i \neq \hat{i}$ Pairwise dependency between two TTSs (discussed earlier).
- $T_{jr}, j \in F, r \in R$ 1 if functionality requires resource, 0 otherwise.
- $M_{ij}, i \in S, j \in F$ 1 if service requires functionality, 0 otherwise (see Table 4).
- $A_{rt}, t \in A, r \in R$ 1 if MSA allows resource usage and 0 otherwise (see Table 5).
- $U_r \geq 0, r \in R$ Data generated per resource unit (see Table 1).
- $Z_t, t \in A$ 1 if choice of architecture is considered, 0 otherwise (model solves one scenario at a time).
- $\tilde{U}_r \geq 0, r \in R$ Capacity per unit of resource, for example, OBU (see Table 2).

$$\Phi_r \geq 0, r \in R$$

$$E_j \geq 0, j \in F$$

$$\delta \geq 0$$

Variables:

$$x_i, i \in S$$

$$f_j, j \in F$$

$$y_{ij}, i \in S, j \in F$$

$$\tilde{f}_{jr} \geq 0, j \in F, r \in R$$

$$\vartheta_{\hat{i}\hat{i}} \geq 0, i, \hat{i} \in S, i \neq \hat{i}$$

$$\eta \geq 0$$

$$\psi_r \geq 0, r \in R$$

Objective to maximize:

$$Obj = \sum_{i \in S} V_i * x_i - \sum_{j \in F} C_j * f_j - \sum_{\substack{i \in S \\ r \in R}} P * C_{ir} * x_i - \sum_{r \in R} \Phi_r * \psi_r - \sum_{\substack{i, \hat{i} \in S, \\ i \neq \hat{i}}} \vartheta_{\hat{i}\hat{i}} - \sum_{\substack{j \in F \\ r \in R}} E_j * \tilde{f}_{jr} \quad (1)$$

Constraints:

C1: Whenever a TTS is 1, all its functionalities are also 1.

$$x_i * M_{ij} \leq f_j, i \in S, j \in F$$

C2: Whenever a MSA choice is 1, associated resources can be used by functionalities.

$$T_{jr} * f_j \leq A_{rt} * Z_t + \tilde{f}_{jr}, j \in F, t \in A, r \in R$$

C3: Whenever a pair of TTSs is selected, the dependency D is considered.

$$D_{i\hat{i}} * (x_i + x_{\hat{i}} - 1) \leq \vartheta_{i\hat{i}}, i, \hat{i} \in S, i \neq \hat{i}$$

C4: In order to estimate how much data is being generated, we will like to know when both a TTS and a functionality are selected.

$$(x_i + f_j - 1) \leq y_{ij}, i \in S, j \in F$$

C5: Whenever a TTS is selected (all its functionalities), we estimate the cost of managing the data generated by the TTSs, that is, processing and communicating.

$$c_{ir} \geq \sum_{j \in F} U_r * T_{jr} * y_{ij}, i \in S, r \in R$$

C6: To estimate the variable cost, we need to know how many units of resource are used by different TTSs.

$$\sum_{i \in S} c_{ir} \leq \tilde{U}_r * \psi_r, r \in R$$

C7: We limit the number of functionalities that are not supported by MSA resources.

$$\sum_{j \in F, r \in R} \tilde{f}_{jr} \leq \delta$$

C8: Finally we set a limit to the number of TTS currently considered in order to be able to study the sensitivity of the model (running from 2 to 32).

$$\sum_{i \in S} x_i \leq \eta$$

CASE STUDY ILLUSTRATING THE USE OF THE OPTIMIZATION MODEL

We illustrate one way of finding parameter values for the proposed optimization model. Here, we assume that the variable costs and resources of functionalities ($f_j, j \in F$) can be estimated in terms of data communicated or processed per TTS ($x_i, i \in S$). This allows for the use of data rates as a proxy for estimating parameter cost values. In the context of road freight transport by heavy goods vehicles in Sweden, the following assessments (estimates) provide data used in the optimization model.

Calculations of Resource Utilization by Transport Telematic Services

To estimate resource utilization by each TTS, we consider the total sum of the resource requirements (for all functionalities of the TTS) of type data communication, voice communication, and so on, as shown in Table 1. We assume a scenario where TTSs are accessing the resources simultaneously similar to a saturated network. Data utilization by different TTSs is obtained by

reviewing similar existing functionalities implemented in other systems (Esteve et al., 2006; Fukang et al., 2008). An example of typical ranges of data rates for ITS applications is shown in Table 1. Since most of the TTSs considered are centered on communication, processing and positioning, we derive the resource estimate as in Table 2, including rough estimates of each unit cost.

Cost Calculations for Transport Telematic Services

The cost of each TTS consists of the fixed cost and the variable cost. The variable cost depends on the capacity specification (data rates) of the TTSs.

Fixed Cost ($C_j, j \in F$)

The fixed cost of each TTS is the total sum of the fixed cost of all its functionalities. The fixed cost is the entry cost for initial acquisition of hardware and software for providing the functionality. Fixed-cost data sources are project documents related to different TTSs, for example, European projects such as e-IMPACT, CODIA, GOOD ROUTE, ARENA, and ISA trials in the United Kingdom and Sweden (ARENA, 2010; ECORYS, 2006; Kulmala et al., 2008; Malone et al., 2008), and so on. Other sources such as Landwehr and Krietsch (2009), Peng et al. (1999), Zhang (2007) and others are also used, and in some cases market pricing information is used. Unit costs for each functionality are considered; for example, fixed cost for an OBU is taken as 500 € (Mckinnon, 2006). All data are adjusted to the cost equivalent for the year 2011 due to inflation with discount rate = 5% as this value is typically used for ITS investment planning (Xu et al., 2004); that is, the OBU costs from 2006 will become 638.1 € (i.e., $500 * (1 + 0.05)^5$ €). In addition to the total cost of functionalities for each TTS, there are overhead costs and the cost of combining functionalities. This study focuses on the cost of functionalities.

Variable Cost ($C_{ir} \geq 0, i \in S, r \in R$)

The variable cost is associated with a fully functional TTS. In addition to the fixed cost, $C_j, j \in F$, associated to the resource units required, $\Phi_r \geq 0, r \in R$, we also include a variable cost directly associated with resource usage, $C_{ir} \geq 0, i \in S, r \in R$, based on the level of utilizing a particular resource $U_r \geq 0, r \in R$. The costs of communicating or processing a megabyte of data, P , is derived from the average data rate of 2000 MB/month communicated per user in Sweden in 2009 (PTS, 2009), which gives a rough average cost estimate of 4.9/2000 € /MB from mobile operators such as tre.se. This cost includes mobile terminal and VAT and hence our estimate for unit data handled by network is $2.9 * 10^{-3}$ € per megabyte per year. Considering each TTS is to be achieved independently of all the others, the estimated total annual cost is for a fleet of 65,000 (registered heavy goods vehicle (HGV) fleet in Sweden).

Societal Value Calculations ($V_i, i \in S$) for Transport Telamtic Services

The societal value of each TTS is calculated from the total cumulative percentage reduction of performance saving indicators (PSIs). To obtain PSI values requires aggregate estimates of the costs of accidents, fuel, time and distance, and so on, related to HGV transport for a given region. Different sources reporting statistical data in Sweden have been used to obtain these values, for example, road administration databases. The values of the TTSs are assessed per year. Details of these calculations are provided in Mbiydenyuy et al. (2010a). The data specification of the optimization model is shown in Table 4.

For each TTS we specify the total costs and the value calculated. The abbreviations for each TTS and functionality are defined as in Table 3.

Multiservice Architecture Specification

Following from Figure 1, each MSA specification is distinguished based on the type of resources provided, as shown in Table 5. The numbers in the resource columns indicate which MSA specification has a key feature that provides a given resource; for example, specifications Z1, Z4, and Z6, indicated by 146 under R1, have a key feature called vehicle-to-vehicle communication, which provides a resource of sensor data modems. Thus, $A_{R1Z1} = A_{R1Z4} = A_{R1Z6} = 1$. An empty cell means no architecture was considered that provides the given resource based on the key feature.

We have considered six candidate MSA concepts extended from previous work (Brasche et al., 1994; Persson et al., 2007). The value of $A_{rt}, t \in A, r \in R$ corresponds to the entries in Table 5 for each MSA specification. Thus, the availability of resources for each MSA is determined by the key feature (rows) and the corresponding resources allowed by the key feature (columns) as shown in Table 5. For each MSA, where relevant, we discuss a similar example, and summarize the key features for a given MSA in Table 5. We provide, next, a description for each MSA considered in Table 5.

- Vehicle-to-vehicle (V2V) with centralized communication (Z1): This is similar to a proposed emergency system known as eCall+ (Martínez et al., 2009), which is a variant of the eCall architecture. The eCall architecture has been considered as a potential MSA (Dimitrios & Bouloutas, 2007). Z supports R1, R2, R4, and R6 but not R3, R5, and R7. This same interpretation follows for the rest of the MSAs described in the following.
- Thin client with central server data processing (Z2): For this, vehicle position is recorded with the help of an OBU and communicated to a central unit that calculates the corresponding charge, for example, the Switzerland tolling scheme (Bernhard, 2003).
- Thick client with decentralized data processing (Z3): This is based on using satellites to track vehicles equipped with a receiver antenna or an OBU that is capable of processing data. The results are reported to the control unit for the infrastructure owner and TTS provider, such as the German tolling scheme (Mckinnon, 2006).
- Vehicle-to-vehicle (V2V) with decentralized communication (Z4): This is based on a distributed V2V communication ad hoc network with complete flexibility. A similar example is addressed in a study where vehicles are seen as autonomous units, with a possibility of allocating vehicles into groups using common communication protocols that can potentially share the same carrier frequency (Sakata et al., 2000).
- Vehicle to infrastructure (V2I) with decentralized communication (Z5): This is based on mounting roadside equipment that can provide functionalities to enable both communication and processing. A similar example is the Austrian toll system (Biffel et al., 1996; Mckinnon, 2006) based on a 5.8 GHz DSRC (CEN-DSRC) between the OBU and roadside equipment.
- Vehicle-to-vehicle to infrastructure (V2V2I) Hybrid architecture (Z6): This architecture combines the advantages of the V2V and V2I options that were just discussed. This is similar to the architecture described by Miller (2008), in which the author suggests the use of a single vehicle (supervehicle) for communication in a given zone, in charge of communication with a central server. It was shown that V2V2I can serve 2850 vehicles in each zone with only 13.4 kbs bandwidth transmission in both directions (Miller, 2008).

RESULTS AND ANALYSIS

In the context of freight transport in Sweden, the case study is aimed at showing the potential use of the model as support for evaluating different choices of TTSs that can be implemented together and, hence, support different system design choices. Such implementations will allow for sharing expensive infrastructure and associated functionalities such as positioning, communication, and so on. Existing functionalities (e.g., provided by a potential Swedish road user charging [RUC] system) will also be well utilized if TTSs are implemented together in packages. A scenario of the optimization model is solved with data from the case study using AMPL with CPLEX solver. AMPL provides a modeling interface and a high-level programming environment for building mathematical programming models. With a given data specification, CPLEX and AMPL will return global optimal solutions for convex optimization problems, such as the proposed optimization model. The following analyses are illustrated:

- Q1. What type of TTSs are selected, if in one case we consider a basic specification of a RUC system and in another case we use an advanced specification (RUC A)?

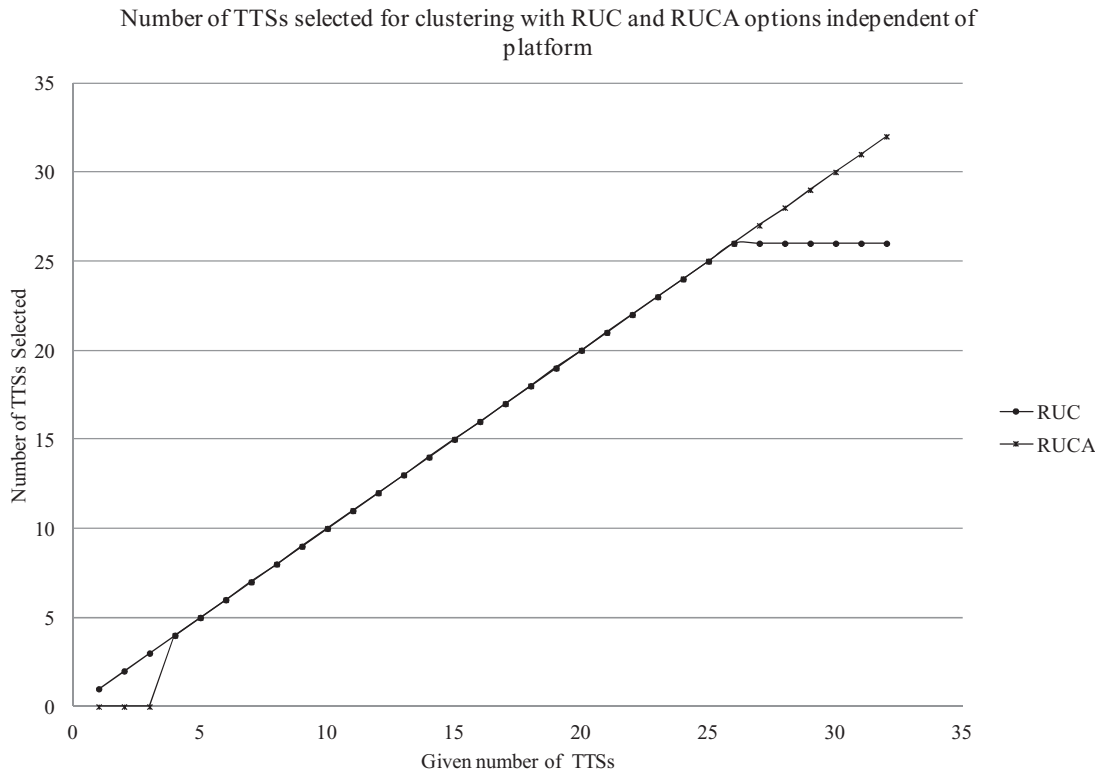


Figure 3 Number of TTSs selected with RUC and RUCA alternatives.

Q2. What is the effect of forcing a particular TTS to be implemented—for example, RUC, RUCA, and so on?

Q3. What is the effect of enforcing different MSA specifications?

The basic RUC system, according to the Swedish RUC ARENA specification (Sundberg et al., 2007), consists of the following functionalities: global positioning (e.g., based on GNSS, GPS), secured vehicle smart card register (obu), vehicle data differentiating between vehicle class (vd), time of the day (ts), and road type (mp). Additional requirements not considered are interoperability with EETS systems and compliance control. The advanced versions (RUCA) have, in addition to the RUC, the capability to control congestion (rc) by redirecting traffic to specific roads (rm) and road infrastructure data (ind) collection. Detailed results for each of the preceding cases are discussed next.

Effects of Different TTS Specifications

The selection of TTSs here is independent of MSA, and hence there is no limitation on resources. The number of TTSs selected based on synergies with RUC and RUCA alternatives is shown in Figure 3.

In the experiment set up for this scenario, we introduce RUC and run the model. We then introduce RUCA and run the model again. Of 32 TTSs considered in the model, RUC and RUCA alternatives resulted in the selection of 26 applications and 32 ap-

plications respectively. The difference between the selected applications was in IRM, XXL, ISA, RG, WI, and DTI that were not selected with RUC, whereas with the RUCA alternative, these applications showed positive synergies and hence were selected. In the graph, we run the optimization model with a restriction on the number of TTSs (η) from 2 to 32 (horizontal axis) and plot this against the number of applications selected by the model (vertical axis). Figure 3 further shows that there are potentially better synergies with RUCA than RUC, since RUCA selected more TTSs than RUC.

The most significant difference is that RUCA selects more TTSs than RUC for $\eta = 2$ to 32. RUC did not select DTI, XXL, IRM, ISA, RG, and WI, while RUCA did. All selected TTSs had a different selection order and hence different priorities when RUC and RUCA were considered: for example, for RUCA, the first 10 TTSs selected are EC, RHW, TAR, TRO; AWI, NAV; EDI; SGM; TOH; PYD, while with RUC we have EC, RHW, TAR; AWI, NAV, TRO; EDI; SGM; TOH; PYD. A comma (,) separates TTSs selected simultaneously, while a semicolon (;) indicates a successive selection of TTSs.

Effects of Enforcing Different TTSs

In this scenario we force the selection of a given TTS by setting $x_i = 1, i \in \{RUC, RUCA\}$. From the results, the total net benefit for RUCA will be negative until more than five applications are included, as can be seen in Figure 4. This is in

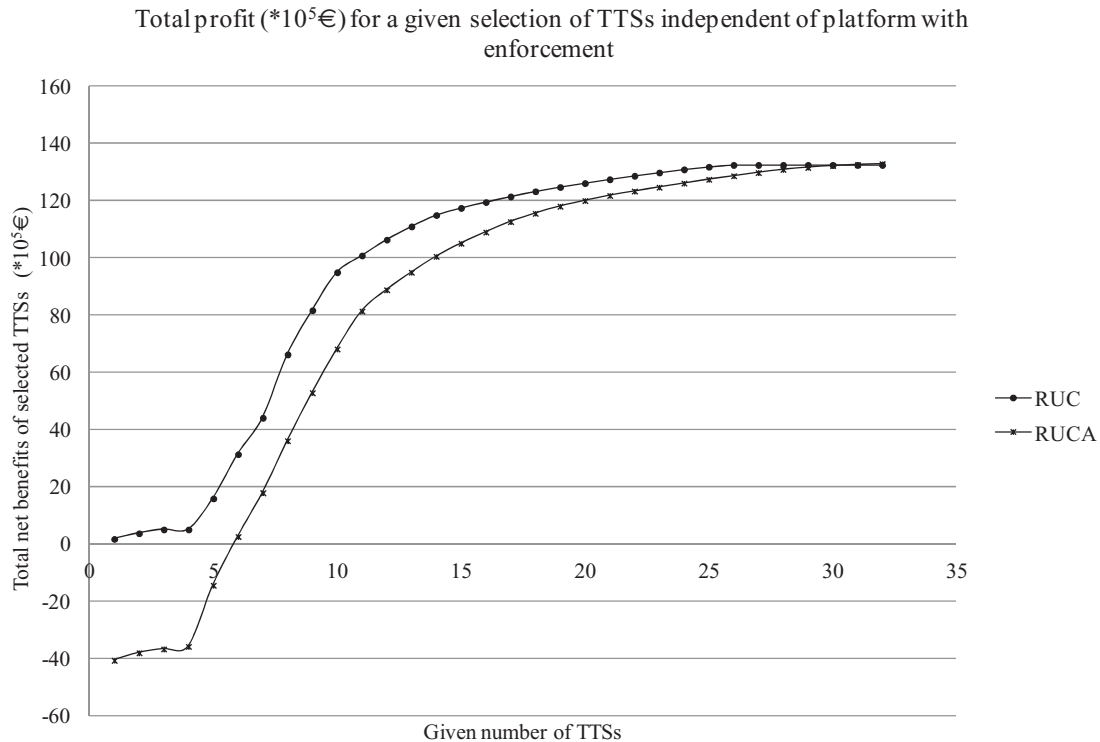


Figure 4 Net benefit variation with enforcement for RUC and RUCA.

line with results from Figure 3, since the selection of applications for RUCA did not take place until more than three applications were included. From Figure 4, it can be seen that enforcement is likely to lead to a negative total net benefit for RUCA if only a few TTSs are allowed. The enforcement of RUCA influences the combination of AWI, EC, NAV, RHW, TAR, and TRO to be selected with a negative net profit. The functionalities of RUCA that contribute to this include global positioning (e.g., based on GNSS, GPS), secured vehicle smart card register (obu), vehicle data differentiating between vehicle class (vd), time of day (ts), road type (mp), capability to control congestion (rc) by redirecting traffic to specific roads (rm), and road infrastructure data (ind) collection. This is because the model selects TTSs based on available functionalities.

The proposed model can also be used to study the consequences of mandating certain applications by law, such as ISA and EC, in order to understand their impacts in the context of multiple potential applications.

Effects of Enforcing an MSA Specification on Selected TTSs

First we consider the number of TTSs selected when different MSA restrictions are enforced. The current results were obtained with some soft constraints, where we allowed for a selection of two additional functionalities not supported by the architecture resources (at additional costs). The results show that Z3, similar to a thick client with decentralized data pro-

cessing, could support more TTSs than any of the other MSAs considered (32 of 32). Also a hybrid V2V2I architecture, Z6, can support nearly as many as Z3 (29 of 32). Coincidentally, Z2 and Z5 selected the same number of TTSs (13 out of 32) even though they are specified with different resources. This may have resulted from the level of detail of resource modeling. Z1 and Z4 selected the lowest number of TTSs. The progressive selection of applications with given restrictions (from 2 to 32) is shown in Figure 5.

Results of the total net benefit of selected TTSs show that Z3 is most beneficial relative to the other MSA specifications. In order of benefits priority, the most appealing TTSs for Z3 are TRO, EC, RHW, SGM, TAR; AWI. Z6 also indicates the potential to accommodate a number of TTSs similar to Z3 except that ETA and PYD are now included instead of EC and RHW in the top selected TTSs. Z2 and Z5 can both support 13 TTSs from the list of 32. In order of benefit priority, Z2 supports similar TTSs (in top selection) as Z3 except that PYD and ADL (as in Z6) but also ETA and DP are now included while EC, RHW, SGM are not supported at any point in the selection. Z1 and Z4 cannot be chosen as suitable architecture for the 32 TTSs considered because they support very few TTSs. One possible reason why Z3 supports the highest number of TTSs as seen in Figure 5 is on account of the choice of functionalities included in the Z3 architecture specification. However, at the same level of net benefit, Z6 will support more TTSs (5 of 32) than Z3 (4 out of 32) as shown in Figure 6.

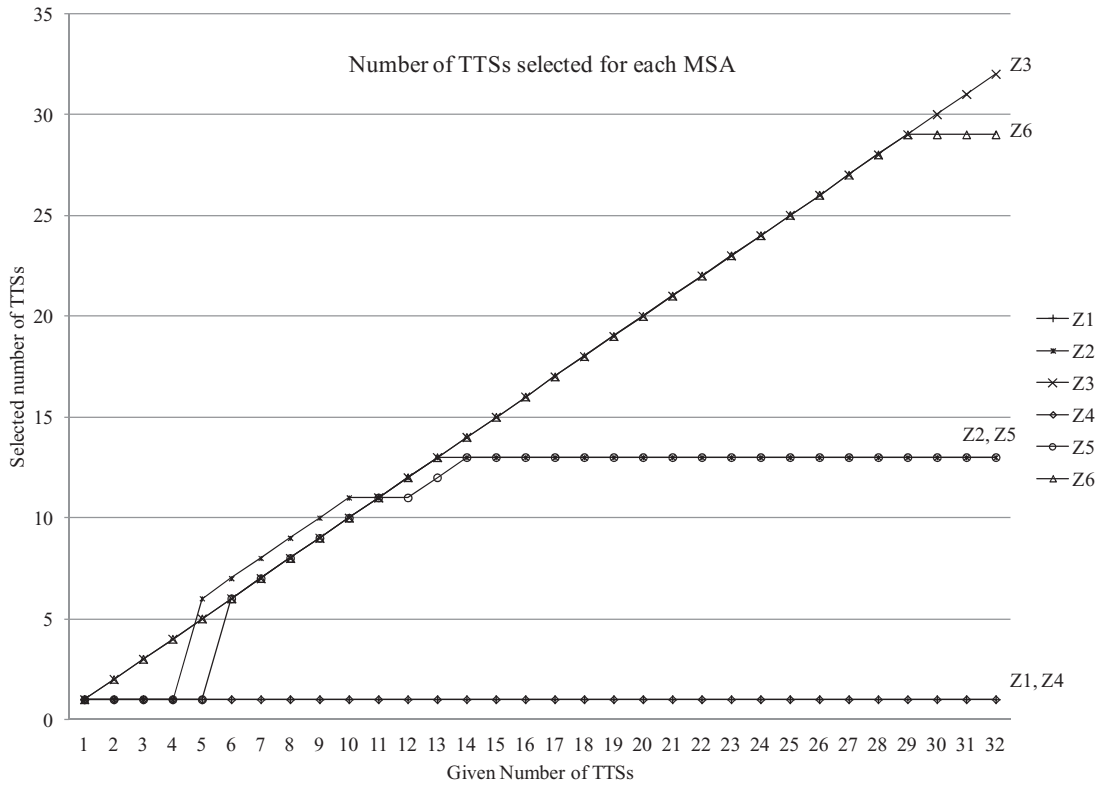


Figure 5 Selection of TTS for different choices of platforms.

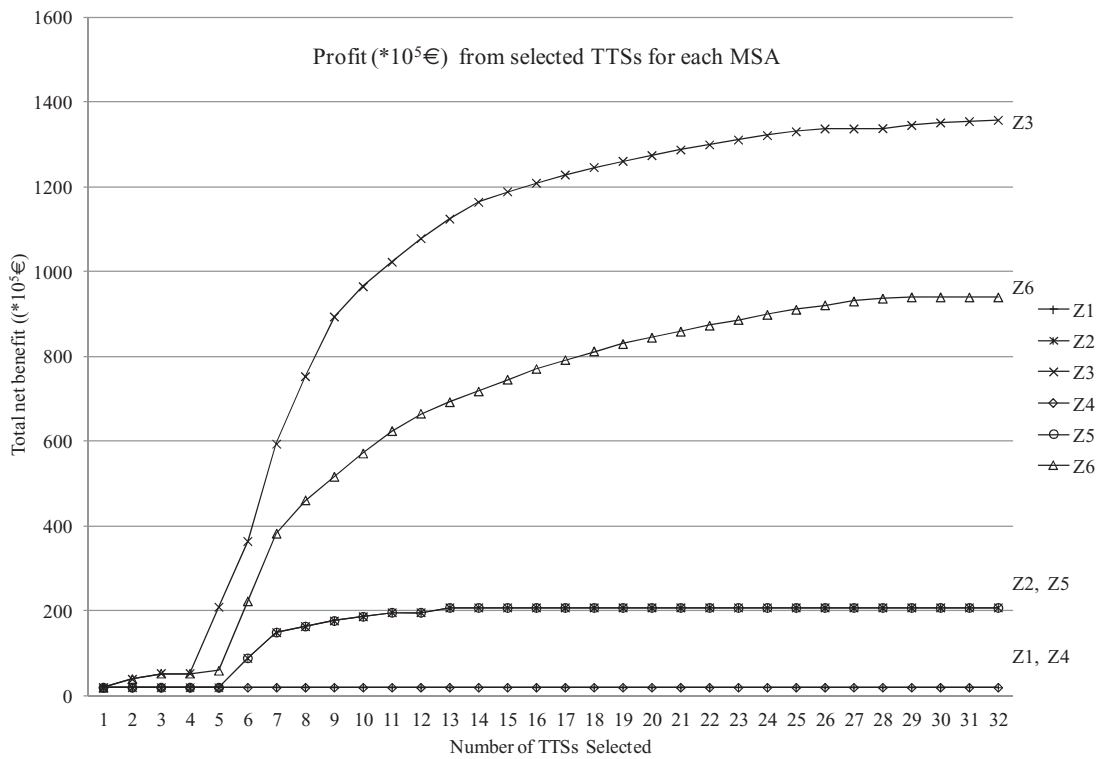


Figure 6 Total net benefit (objective function) of selected applications for different choices of MSA concepts.

CONCLUSIONS AND FUTURE WORK

This article has proposed a model that can be used to support strategic decision making related to the design and investment in MSAs and TTSs for road-based freight transport. Strategic decisions addressed by the model are those faced by policymakers, such as government authorities, to identify and invest in applications that will meet long-term transport policy objectives. The model can also be beneficial to telematic service providers and designers facing long-term decisions related to the implementation of telematic systems with multiple TTSs. We illustrated the model decision prescription capabilities by selecting potential beneficial applications from a given set of applications for road freight transport with focus on Swedish heavy goods vehicle (HGV) transport. By changing the conditions, we also illustrated that the model can be used to address “what-if-analysis” scenarios. To illustrate this, the model considered six different MSA concepts and their potential effects on possible TTSs that can be achieved from a net benefit perspective.

Studies that have addressed similar subjects to this study show varying results because of the use of different approaches; for example, Sjöström (2007) used qualitative analysis to show that road status monitoring, hazardous goods monitoring, transport service payment, and tracking and tracing of cargo are likely suitable applications for a thin client, while speed alert, preferred network guidance, and traveler information services were recommended for a thick client. Kim et al. (2005) proposed a telematic system platform and demonstrated its suitability for supporting real time traffic information, location, and entertainment services. These results differ from the suggestions in our study since the criteria used are not the same. However, most of the studies demonstrate that a common platform for multiple applications will lead to higher net benefits, though they have used different approaches for analyzing such benefits. In the future, the model can further be validated by improving the quality of data, experimenting with different case studies, incorporating quality of service factors, exploring alternative TTS implementations, and studying additional constraints on resources such as communication and processing.

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