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Diseño de un Sistema de Percepción del Contexto para el Entorno Intra-Vehicular

Tesis Doctoral

Presentada por:
Fernando Terroso Sáenz

Supervisada por:
Dr. Mercedes Valdés Vela
Dr. Antonio Fernando Skarmeta Gómez

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Design of a Context-Aware System for the Intra-Vehicular Environment

Ph.D. Thesis

Authored by:
Fernando Terroso Sáenz

Advisored by:
Dr. Mercedes Valdés Vela
Dr. Antonio Fernando Skarmeta Gómez

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A mis abuelos y yayos,
Jesús, Ascensión, Iluminado y Milagros.

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Capítulo 1

Resumen

1.1. Motivación y objetivos

Los Sistemas Inteligentes de Transporte (*Intelligent Transportation Systems*, ITSs) tienen como objetivo ofrecer soluciones a los problemas mundiales del transporte a través de las tecnologías de la información y las comunicaciones [6]. Durante los últimos años, se han realizado numerosas propuestas en el campo de los ITS para lograr viajes más seguros, eficientes, sostenibles y confortables tanto para los conductores como para los pasajeros.

Uno de los enfoques más importantes en el campo de los ITSs ha sido los Sistemas Avanzados de Soporte al Conductor (*Advanced Driver Assistance Systems*, ADASs). Un ADAS tiene como finalidad ofrecer ayuda al conductor de un vehículo cuando éste se ve envuelto en alguna situación peligrosa mientras conduce. En este sentido, muchas de las propuestas para el desarrollo de ADAS han seguido un enfoque basado en la Percepción de la Situación (*Situation Awareness*, SA) [12] dando lugar a los Sistemas Avanzados de Soporte al Conductor con Percepción de la Situación (*Situation-Aware Driver Assistance Systems*, SADASs). El término SA se enmarca en *"la percepción de los elementos, su significado y la proyección de su estado en el futuro cercano"* [14]. En el terreno de los ITSs, dicha definición puede adaptarse fácilmente sustituyendo el término *elementos* por el de *vehículos*. Por lo tanto, un SADAS tiene como objetivo principal detectar el rol de un vehículo con respecto a su entorno circundante. De esta manera, es posible anticiparse a ciertas situaciones peligrosas que puedan involucrar a dicho vehículo. Para ello, este tipo de sistemas toma como entrada datos provenientes tanto del interior como del exterior del vehículo tales como, por ejemplo, sensores de abordo o servicios web.

Un SADAS puede verse como un tipo de sistema de Percepción del Contexto (*Context Awareness*, CA). Un sistema CA tiene como finalidad percibir el contexto de una determinada entidad a fin de proveerla con información que le pueda resultar útil, en donde el contexto es cualquier tipo de información que caracterice la situación de dicha entidad [3]. En el caso de los SADAS dicha entidad es un vehículo. Sin embargo, la percepción del contexto para un determinado vehículo que los SADASs son capaces de realizar tiende a ser incompleta dado que suele centrarse en las características relativas a la seguridad del vehículo.

En este sentido, percibir el contexto de un vehículo de una manera más precisa y detallada sería extremadamente útil para permitir el desarrollo de servicios ubicuos vehiculares. La computación ubicua es un paradigma que tiene como objetivo el desarrollo de servicios que rodeen al usuario de forma no intrusiva [25]. Mediante este paradigma, sería posible desarrollar servicios vehiculares para mejorar no sólo la seguridad sino también la comodidad de los viajes por carretera. Teniendo en cuenta que los vehículos privados son todavía un importante medio de transporte, el hecho de desarrollar dicho tipo de servicios es notablemente interesante tanto para los usuarios finales como para los fabricantes. En este contexto, varios trabajos han propuesto el desarrollo de sistemas CA en un entorno vehicular que van más allá de los SADAS y que por tanto son capaces de percibir el contexto de un vehículo de una manera más detallada [11, 35, 42]. Sin embargo, dichos trabajos suelen centrarse en determinados dominios y ámbitos por lo que su percepción del contexto está condicionado por dicho factor. Por lo tanto, hasta la fecha ningún trabajo ha propuesto claramente una solución CA de propósito general cuyo objetivo sea la percepción global del contexto de un vehículo.

Considerando todas las circunstancias anteriormente descritas, la principal motivación de la presente tesis doctoral se centra en **el diseño de una novedosa solución de carácter general para gestionar el entorno de un vehículo que cubra tanto los aspectos teóricos como prácticos relacionados con la percepción del contexto vehicular**. Esta nueva solución CA dentro del contexto vehicular ha sido llamada *Intra-vehicular Context Awareness* (IvCA). En concreto, la presente tesis se centra en definir y estudiar la viabilidad de los elementos que resultan básicos para la total implementación de un sistema IvCA. Dicho sistema se ejecutaría como un sistema de abordo y sería capaz de proveer con información contextual de alta calidad de un determinado vehículo a un amplio rango de servicios. Con respecto al tipo de vehículo, este trabajo se centra en el entorno familiar. En este tipo de entornos, el vehículo es usado para acometer una serie de *itinerarios* frecuentes que cumplen un conjunto de tareas diarias tales como ir al trabajo o a comprar. Este uso de los coches uno de los más comunes en las sociedades desarrolladas [34].

Dado que la percepción del contexto vehicular es una de las tareas más importantes del presente trabajo, la tarea de dar una definición formal de dicho contexto se convirtió en primordial. De este modo, gran parte de los esfuerzos de esta tesis se han centrado en la definición de un modelo formal del contexto relacionado con un vehículo familiar. Puesto que dicha definición tenía como objetivo ser útil en un marco de propósito general, ésta debía contener un amplio rango de las características de un vehículo con diferentes niveles de abstracción. Estas características no debían ser sólo especificaciones técnicas sino también relacionadas con el uso y objetivos que un vehículo pudiera tener. Dado que un vehículo familiar suele ser usado para cubrir una serie de itinerarios, el proceso de modelado del contexto tuvo en cuenta dichos itinerarios como parte de la información contextual de un vehículo.

Aparte del modelado contextual, otro de los asuntos a los que esta tesis ha prestado especial atención ha sido el estudio de las posibles fuentes de datos que pudieran ser útiles para detectar el contexto vehicular. En este sentido, muchas de las propuestas que pueden encontrarse en la literatura sobre la percepción del contexto asociado a un vehículo dependen de la instalación en dicho vehículo de sensores o equipamientos de abordo muy específicos. En algunas ocasiones, dichos elementos pueden ser bastante intrusivos tanto para el conductor como para los pasajeros y, sobre todo, elevar el coste económico de la solución. Con el objetivo de evitar dichos problemas, surgió la necesidad de enfocar la presente tesis en la percepción del contexto mediante sensores o equipamientos de bajo coste que un vehículo común puede tener instalados de fábrica.

En lo que respecta al desarrollo del sistema, uno de los objetivos del presente trabajo era llegar a una arquitectura modular y por capas en donde cada capa percibiera el contexto con un determinado nivel de detalle. De esta manera se favorecería su extensibilidad y adaptación. Por este motivo, el desarrollo del sistema ha seguido un enfoque incremental definiéndose tres niveles de percepción tal y como se muestra en la Fig. 1.1. El primero de los niveles se centra en detectar el *movimiento* del vehículo (también conocido como su estado cinemático). Este tipo de información es un elemento clave en el contexto de un vehículo pues conocer si dicho vehículo está parado, acelerando, etc. proporciona una información muy útil acerca de su situación actual. Posteriormente, este nivel de percepción del movimiento fue extendido mediante una segunda capa para ampliar la percepción contextual mediante una serie de módulos encargados de detectar otras características del contexto. Dado que la presente tesis se centra en los vehículos familiares, esta segunda capa se centra en el contexto relacionado con los itinerarios habituales de un vehículo. En particular, se encarga de dos elementos esenciales que identifican a un itinerario: los ocupantes del vehículo y sus lugares más significativos.

Otro aspecto que resulta interesante detectar en un entorno vehicular son las condiciones del tráfico que rodean a un vehículo. Por ello, el sistema se extendió con una tercera capa encargada de gestionar la parcepción del tráfico como parte del contexto vehicular tal y como muestra la Fig. 1.1. En este sentido, existen multitud de soluciones que son capaces de detectar problemas de tráfico en una carretera de una manera muy precisa. Sin embardo, muchas de ellas dependen de sensores especialmente instalados en

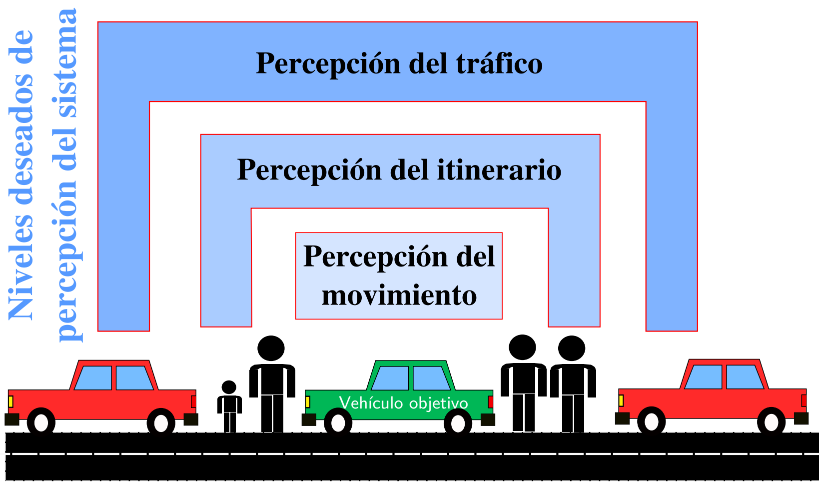

Figura 1.1: Niveles de percepción del sistema desarrollado.

diferentes partes de la infraestructura de la carretera. Por el contrario, la presente tesis doctoral tiene como uno de sus objetivos principales sacar el mayor partido posible al equipamiento de abordo de un vehículo. No obstante, es prácticamente imposible percibir las condiciones de tráfico que rodean a un vehículo sólo mediante el uso de sus sensores de abordo. Dicho objetivo sería factible si los vehículos circulando por una carretera compartieran entre ellos la información recogida por sus sensores de abordo para detectar el estado del tráfico en dicha carretera. De esta forma, el presente trabajo ha estudiado también un enfoque colaborativo con el objetivo de aumentar la percepción contextual de un vehículo mediante la información sobre el estado del tráfico circundante.

En resumen, los objetivos específicos de la presente tesis doctoral son listados a continuación:

1. Analizar el presente estado del arte de los enfoques CA en el campo de los ITS e identificar sus posibles debilidades a la hora de proporcionar soluciones de propósito general.

2. Establecer una definición formal y de propósito general del contexto relacionado con un vehículo familiar.

3. Identificar los sensores comunes de un vehículo útiles para percibir determinadas características del contexto vehicular.

4. Desarrollar un módulo de abordo capaz de percibir el estado cinemático de un vehículo a partir de sensores comunes como parte de su contexto.

5. Desarrollo de una herramienta de abordo no intrusiva para percibir la ocupación de un vehículo como parte de su contexto mediante el uso de sensores de bajo coste.

6. Desarrollo de un mecanismo de abordo capaz de detectar en tiempo real los lugares más representativos de los itinerarios frecuentes de un conductor.

7. Desarrollar un sistema para detectar en tiempo real las congestiones de tráfico relacionadas con un vehículo usando para ello la información proveniente de los vehículos circundantes.

8. Validación de las propuestas mediante una serie de pruebas de concepto con el objetivo de probar su idoneidad.

En definitiva, todos los objetivos arriba descritos tienen como finalidad ser lo menos intrusivos posible y sacar el máximo provecho de la información proveniente del equipamiento de abordo que un vehículo común tiene de fábrica con el fin de percibir el contexto vehicular.

1.2. Resultados

Como resultado de la presente tesis doctoral, se han realizado notables contribuciones. Una lista de los diferentes trabajos realizados puede consultarse en la sección 8.2. Algunos de ellos no están descritos en detalle en el presente manuscrito debido a la normativa para este tipo de presentación de tesis doctoral. La mayor parte de dichos trabajos consiste en estudios preliminares de las soluciones finales incluidas en el presente manuscrito. Sin embargo, todas ellas exponen interesantes propuestas.

La tabla 1.1 resume los objetivos enumerados en la sección anterior y sus resultados asociados así como una clasificación desde el punto de vista ingenieril. Además, las citas de los trabajos en donde cada resultado particular fue presentado han sido también incluidas en dicha tabla. A continuación, se expone una descripción de los resultados asociados a cada uno de los objetivos.

En lo relativo al objetivo 1), descrito en la sección anterior, se realizó un estudio de los enfoques actuales para percibir el contexto vehicular. En concreto, el presente trabajo se ha centrado en las soluciones SA que pueden encontrarse en la literatura. Así, un completo estado del arte sobre los SADAS ha sido expuesto como resultado. Dicho estudio concluye que las actuales soluciones basadas en SA no perciben de manera general el contexto de un vehículo dado que están principalmente diseñados para tareas de seguridad.

Respecto al objetivo 2), el estudio realizado para el objetivo anterior nos permitió identificar las dimensiones del contexto vehicular que estaban o no cubiertas por las actuales soluciones SA. Posteriormente, dichas dimensiones fueron empleadas para definir las características globales del contexto relativo a un vehículo y, finalmente, llegar hasta una definición formal del mismo. Dicho modelo ha sido la guía del resto del trabajo realizado en la presente tesis.

Una vez que el modelo contextual fue definido, el siguiente paso era considerar cómo era posible percibir dicho contexto. Para ello, se llevó a cabo un estudio acerca de los diferentes sensores y equipamientos que un vehículo común incluye por defecto. Esto nos llevó a descubrir que era posible acceder a un amplio abanico de los sensores de un vehículo mediante la interfaz *On-Board Diagnostic II* (OBD-II) [2]. Básicamente, ODB-II hace viable el acceder a un gran número de sensores y unidades instaladas en diferentes partes del motor, carrocería e interior de un vehículo. Por lo tanto, un gran rango de fuentes de datos estaba disponible para detectar el contexto vehicular. Finalmente, mediante el presente estudio el objetivo 3) fue completado.

En lo relativo a los objetivos relacionados con la fase de diseño, el primer mecanismo para la detección del contexto desarrollado como parte de la presente tesis fue el relacionado con el estado cinemático de un vehículo que permitió cumplir el objetivo 4). El estudio previo acerca de las fuentes de datos vehiculares expuso que era posible detectar el estado cinemático de un vehículo mediante la información proveniente de alguna de sus unidades de abordo. Debido al ruido e imprecisión que los datos provenientes de estas unidades pueden contener, la presente tesis doctoral optó por seguir un enfoque basado en la lógica difusa [46] para detectar el estado cinemático de los vehículos. El procedimiento seguido para dicho enfoque consistió en los siguientes pasos. En primer lugar, la herramienta para combinar algoritmos de *soft-computing* descrita en [41] se mejoró con más capacidad computacional para posteriormente implementarla en forma de *Application Programming Interface* (API). El resultado de este trabajo puede consultarse en [55]. A continuación, esta API se utilizó para desarrollar una primera propuesta para la detección de maniobras longitudinales en un entorno vehicular mediante un enfoque basado en el modelado difuso [51]. Por último, una mejora de dicha solución ha sido incluida en el presente manuscrito.

El objetivo 5) ha sido completado con un nuevo mecanismo no intrusivo que tiene como objetivo detectar la ocupación actual de un vehículo. Dicho mecanismo se basa en la hipótesis de que es posible percibir la ocupación de un vehículo en base a las interacciones habituales entre los pasajeros

Objetivo	Resultado	Clasificación
Objetivo 1: Analizar el presente estado del arte de los enfoques CA en el campo de los ITS e identificar sus posibles debilidades a la hora de proporcionar soluciones de propósito general.	Estado del arte de los sistemas CA en el entorno vehicular [51–53,56]. Definición y diseño del concepto IvCA [52].	Estudio
Objetivo 2. Establecer una definición formal y de propósito general del contexto relacionado con un vehículo familiar.	Modelo del contexto intra-vehicular [52].	Modelado
Objetivo 3: Identificar los sensores comunes de un vehículo útiles para percibir determinadas características del contexto vehicular.	Identificación de los sensores vehiculares comunes y de bajo coste susceptibles de usarse como fuentes de datos contextuales [51–53, 56].	Análisis
Objetivo 4: Desarrollar un módulo de abordo capaz de percibir el estado cinemático de un vehículo a partir de sensores comunes como parte de su contexto.	Módulo para la detección de las maniobras longitudinales de un determinado vehículo basado en el modelado difuso [51, 55, 56].	Diseño
Objetivo 5: Desarrollo de una herramienta de abordo no intrusiva para percibir la ocupación de un vehículo como parte de su contexto mediante el uso de sensores de bajo coste.	Módulo basado en patrones para el descubrimiento de la ocupación vehicular [52, 53].	Diseño
Objetivo 6: Desarrollo de un mecanismo de abordo capaz de detectar en tiempo real los lugares más representativos de los itinerarios frecuentes de un conductor.	Landmark discovery algorithm [52].	Diseño
Objetivo 7: Desarrollar un sistema para detectar en tiempo real las congestiones de tráfico relacionadas con un vehículo usando para ello la información proveniente de los vehículos circundantes.	Módulo CEP para descubrir congestiones de tráfico [49, 50, 54].	Diseño
Objetivo 8: Validación de las propuestas mediante una serie de pruebas de concepto con el objetivo de probar su idoneidad.	Batería de test basados en simulación y el mundo real para estudiar la idoneidad de las propuestas [52, 54, 56].	Validación

Cuadro 1.1: Objetivos de la tesis doctoral y sus resultados junto con las citas a los trabajos donde son descritos.

y el propio vehículo cada vez que los primeros se montan o apean del segundo tales como abrir o cerrar las puertas. Estas interacciones pueden detectarse mediante sensores de bajo coste instalados en puertas, ventanas o cinturones de seguridad. En concreto, el mecanismo propuesto se centra en la búsqueda de una serie de patrones predefinidos en el flujo de datos proveniente de dichos sensores que permiten obtener información acerca de la ocupación de un determinado vehículo. En este sentido, el mecanismo propuesto en la presente tesis continúa el trabajo presentado en [53] solucionando determinados problemas intrusivos.

La detección de los lugares frecuentados por un vehículo que implica el objetivo 6) se ha logrado mediante un enfoque basado en clustering. En concreto, se ha desarrollado un nuevo algoritmo basado en el concepto de clustering por densidad. Este nuevo algoritmo, llamado *landmark discovery algorithm*, es capaz de detectar los lugares significativos de los diferentes itinerarios de un vehículo en tiempo real y con diferentes granularidades. Dicho algoritmo soluciona los problemas detectados en otros trabajos de clustering basado en densidad lo que lo hace idóneo para ser usado como parte de la equipación de abordo de un vehículo.

Respecto al objetivo 7), esta tesis propone un innovador mecanismo para detectar las congestiones de tráfico en una carretera basado en la tecnología de Procesamiento de Eventos Complejos (*Complex Event Processing*, CEP). CEP es un novedoso paradigma diseñado para operar en entornos distribuidos con grandes tasas de generación de datos. Un ejemplo de este tipo de entornos son las redes vehiculares o *Vehicular Ad-hoc Networks* (VANETs). Las VANETs son una importante plataforma que permite a los vehículos en movimiento compartir información entre ellos. Además, este tipo de redes ha sido ampliamente estudiado en la literatura y se ha convertido en un importante punto de interés en el campo de las comunicaciones. Por lo tanto, parecía idóneo usar dicho tipo de red para cumplir el presente objetivo. Como resultado, la presente tesis introduce una solución basada en CEP capaz de procesar la gran cantidad de información que una VANET, bajo ciertas condiciones, puede llegar a generar. Además, dicho mecanismo es el resultado de una línea de trabajo que se ha centrado en el desarrollo de soluciones CEP en el campo ITS [49, 50].

Con el propósito de satisfacer el objetivo 8) todos los mecanismos propuestos en el presente trabajo han sido testeados mediante una serie de experimentos. En concreto, se han empleado tres enfoques diferentes a la hora de componer dichos experimentos: mundo real, simulación y enfoque híbrido. Mientras que en los experimentos con el enfoque mundo real se han empleado únicamente datos recogidos de entornos reales para validar los mecanismos, el enfoque basado en simulación se basó en datos artificiales con el objetivo de generar el flujo de entrada que el mecanismo a testear espera procesar. Para ello, se han desarrollado diferentes plataformas que combinan simuladores ya existentes. Para los experimentos híbridos también se ha hecho uso de simuladores pero, en este caso, los datos generados se han basado en bases de datos del mundo real recogidas previamente. El enfoque híbrido ha sido empleado en caso de que se tuvieran datos del mundo real pero su cantidad no fuera la suficiente para construir un experimento sólo a partir de dichos datos. Por último, usar uno u otro enfoque ha dependido básicamente de la disponibilidad de datos del mundo real que el mecanismo a estudiar espera recibir como entrada.

Los resultados de los diferentes experimentos llevados a cabo prueban que todas las soluciones presentadas en esta tesis doctoral fueron capaces de conseguir niveles de percepción muy precisos de diferentes características de un contexto vehicular. Además, en alguno de los casos, el mecanismo desarrollado mejoró los resultados de otras propuestas de la literatura. A modo de conclusión, todos los objetivos de la presente tesis han sido cumplidos. Como resultado, las bases para un sistema vehicular CA plenamente desarrollado han sido definidas de manera satisfactoria. Esto ayudará al desarrollo de futuras aplicaciones ubicuas en el entorno vehicular al poder hacer uso del contexto percibido por nuestra solución. Esto permitirá que el transporte por carretera sea más confortable, seguro y sostenible.

1.3. Conclusiones y Trabajos Futuros

El desarrollo de servicios de abordo en el entorno vehicular es una importante línea de trabajo en el campo de los ITS. En este marco, la percepción del contexto es un factor primordial a la hora de desarrollar servicios más avanzados y complejos. En este sentido, la mayor parte de las propuestas en la literatura para percibir el contexto relativo a un vehículo ha sido diseñada para ciertas situaciones y objetivos. Por tanto, existía una escasez de soluciones enfocadas a percibir el contexto de un vehículo de una manera global de tal forma que la información detectada pudiera ser empleada en un gran número de campos.

La presente tesis doctoral presenta la definición de una plataforma de propósito general para percibir el contexto relativo a un vehículo en un marco familiar. En este sentido, la línea de trabajo ha tenido dos vertientes. Por un lado, se ha seguido un enfoque teórico para establecer los problemas de las actuales propuestas para la percepción del contexto vehicular. A continuación, se diseñó un modelo de carácter general del contexto de un vehículo. Dicho modelo ha tenido en cuenta las diferentes características del entorno de un vehículo familiar. Por otro lado, se ha realizado un enfoque práctico con el fin de desarrollar diferentes soluciones para percibir el modelo contextual arriba indicado. La implementación de dichas soluciones se ha realizado sacando el máximo provecho de la equipación de bajo coste que un vehículo común incluye de fábrica. Dichas soluciones son descritas a continuación:

- En primer lugar, se ha desarrollado un módulo para la detección del estado cinemático de un vehículo a través de un enfoque basado en el modelado difuso. Este módulo constituye una solución precisa y ligera para inferir las maniobras longitudinales que mejora enfoques previos en la literatura.
- Además, se ha presentado una novedosa solución para descubrir la ocupación de un vehículo en base a ciertos patrones predefinidos en el flujo de datos de algunos sensores vehiculares. Este nuevo enfoque soluciona ciertos problemas de precisión e intrusivos detectados en soluciones previas.
- Por otro lado, el landmark discovery algorithm, que se centra en la detección de los lugares más importantes asociados a los itinerarios de un vehículo, ha sido también expuesto. Dicho algoritmo adapta el clustering basado en densidad para poder ser usado como una solución on-line.
- Finalmente, se ha diseñado un módulo CEP para la inferencia de atascos cercanos a un vehículo. Este nuevo mecanismo propone una nueva manera de procesar los mensajes transmitidos a través de una VANET con el fin de obtener nueva información contextual.

En resumen, a la luz de esta investigación se han presentado enfoques totalmente novedosos. Por lo tanto, desde nuestro punto de vista, el presente trabajo es un notable avance en el campo CA que abre nuevas líneas de trabajo en el marco ITS. En este sentido, la presente tesis doctoral es el punto de partida para gran cantidad de trabajos futuros.

Por un lado, los diferentes mecanismos presentados en esta tesis serán integrados mediante la arquitectura de comunicaciones vehiculares propuesta en el proyecto CENIT OASIS [1] de tal manera que puedan trabajar como un único sistema. Este proyecto tiene como objetivo el desarrollo de carreteras inteligentes tomando en consideración todos los posibles elementos envueltos en dicha infraestructura. Por lo tanto, gracias a este proyecto, será posible instalar el sistema en coches reales y, de esta manera, poder plantear nuevos experimentos. Otra línea de investigación podría consistir en integrar la información contextual percibida por el presente trabajo en la plataforma descrita en [33]. Este trabajo describe una plataforma global de comunicaciones que proporciona determinados servicios a los conductores en base a cierta información contextual. De esta forma, el nivel de percepción contextual presentado en esta tesis podría ser usado con el fin de ampliar ciertas funcionalidades de dicha plataforma.

En segundo lugar, los mecanismos propuestos en esta tesis serán ampliados a fin de procesar nuevas fuentes de datos e incrementar así su precisión en la percepción contextual. Por ejemplo, se estudiarán mecanismos de identificación tales como lectores RFID y NFC o sensores corporales para ser usados como nuevas entradas para el módulo de detección de la ocupación de tal manera que puedan incorporarse al contexto percibido determinados detalles personales tanto del conductor como de los pasajeros. Como resultado de ello, otra línea de trabajo futuro se encargará también de la aplicación de determinados sistemas de privacidad en el campo ITS como el propuesto en [26] con el fin de proteger la información personal de los usuarios finales del sistema.

Por otro lado, también se considerará el incrementar el nivel de percepción con nuevos detalles contextuales que no han sido considerados en el presente trabajo. En este sentido, enriquecer la información sobre los itinerarios frecuentes de un vehículo será uno de los puntos de interés de esta línea de trabajo. Para ello, se emplearán algunos de los mecanismos presentados en esta tesis. Por ejemplo, el estado cinemático detectado por el mecanismo basado en lógica difusa puede proporcionar información muy útil acerca del estado de las carreteras que un vehículo cubre durante sus itinerarios.

Finalmente, otra línea de trabajo se centrará en el desarrollo de soluciones CEP para inferir información acerca de las trayectorias realizadas por dispositivos móviles. De hecho, este enfoque ha sido ya empleado por el doctorando en el campo de la vigilancia marítima para detectar comportamientos anómalos de embarcaciones [13]. En particular, dicha solución será adaptada con el fin de detectar los cambios de dirección más representativos en la trayectoria de un vehículo. Esta información pude arrojar luz acerca del tipo de ruta que cada itinerario implica. Por ejemplo, si un itinerario implica multitud de giros, puede ser un signo de que dicho itinerario recorre una carretera bastante complicada. Por el contrario, si sólo implica unos pocos giros puede deberse a que el itinerario cubre una carretera más fácil de conducir (como una autopista). En resumen, el sistema será capaz de percibir más información sobre las rutas de los diferentes itinerarios de un vehículo y, por ello, proporcionar una visión más global de dichos itinerarios a las aplicaciones externas que usen el sistema.

Chapter 2

Abstract

2.1. Motivation and Goals

The *Intelligent Transportation Systems* (ITSs) aim to sort out the worldwide transportation problems by means of information and communication technologies [6]. Many ITS initiatives have been proposed for the last decades to achieve secure, efficient, sustainable and comfortable trips for both drivers and passengers.

One of the foremost ITS approaches has been the *Advanced Driver Assistance Systems* (ADASs). An ADAS pursues to help the driver when he is presented with a difficult situation while he is driving. In this context, many efforts to develop ADASs have follow a *Situation Awareness* (SA) approach [12] giving raise to the *Situation-Aware Driver Assistance Systems* (SADAS). The SA concept is *concerned with the perception of elements, of their meaning and the projection of their status in the near future* [14]. In a ITS scope, this definition can be easily adapted by replacing the term *elements* with *vehicles*. Consequently, a SADAS focuses on perceiving the role of a vehicle with respect to its environment. This way, it is possible to detect in advance certain risky situations involving this vehicle. In order to achieve that, this type of systems takes as input data sources installed inside and outside the vehicles such as on-board sensors or web services.

A SADAS can be viewed as a form of *Context-Awareness* (CA) system. A CA system intends to perceive the context of a target entity in order to provide it with useful information where the context is any type of information that characterizes the situation of that entity [3]. As for SADASs, the target entity described above is a vehicle. However, the perception of the target vehicle's context made by a SADAS tends to be incomplete as it usually focuses on perceiving only the features related to the vehicle's safety.

Perceiving the whole context of a vehicle in an accurate and enriched way will be extremely useful so as to develop in-vehicle ubiquitous services. *Ubiquitous computing* is a paradigm that pursues to deploy applications which surrounds the end users in a smooth and non-intrusive way [25]. By means of this paradigm, it will be feasible to develop in-car services to improve not only the safety but also the comfort of vehicle's trips. Taking into consideration that privately owned vehicles still are a remarkable means of transport, being able to developing that kind of services is significantly interesting for both end users and manufacturers. In that sense, several works have put forward CA systems in the vehicular scope which go beyond the SADASs, and they perceive the context of a vehicle in a more comprehensive way [11,35,42]. Nevertheless, these works are biased by the fact that they focus on a particular domain so their perception level does not give a general view about the context of a target vehicle. As result, to date no approach has clearly stated a CA solution which intends to perceive the context of a vehicle for a general purpose scope.

Taking everything into account, the main motivation of the present thesis is raised, **designing a novel general-purpose solution to manage the environment of a vehicle which covers both the theoretical and the practical issues related to the perception of the vehicular**

context. This new CA approach for the vehicular scope has been named *Intra-vehicular Context Awareness* (IvCA). Hence, this thesis intends to define and study the feasibility of the elements that are basic so as to implement a full-blown IvCA system. Such system will run as an on-board equipment and will be capable of providing high-quality contextual information of a target vehicle to a varied range of applications and services. Regarding the target vehicle, the present thesis focuses on family environment. In that kind of environments, the vehicle is used to cover a set of frequent *itineraries* which accomplish certain daily tasks like commuting or going shopping. This type of usage of a vehicle is quite common in developed societies [34].

Since perceiving the context of a vehicle is the most important element of the present work, giving a formal definition of it became a paramount task. Therefore, this thesis has put a lot of effort in order to model the contextual information related to a familiar vehicle. Due to the fact that such context definition intended to be useful for a general-purpose scope, it had to comprise a wide range of characteristics of a vehicle with different levels of detail. These characteristics did not only include technical features but also others related to the usage and goals of the vehicle. Because a familiar vehicle is driven to cover a set of itineraries, the context model took into consideration these itineraries as part of the contextual information of a vehicle.

Apart from the contextual model, another issue this thesis has paid attention to is the study of the data sources that could be used in order to perceive the vehicular context. In that sense, many proposals in the literature which aim to perceive the context related to a vehicle rely on ad-hoc sensors or specific on-board equipments installed in the target vehicle so as to accomplish their goal. In some of these cases, these elements are quite intrusive for the driver and passengers and, above all, increase the economic cost of the solution. Consequently, in order to avoid these problems, it was necessary to focus this thesis on perceiving the intended context by means of low-cost sensors or equipments that a common vehicle may include by default.

As far the development of the intended system is concerned, one of the goals of the present thesis was to come up with a modular and layered architecture where each layer perceives the context at a different level of detail. Thus, it will be possible to easily extend and adapt it. For this reason, the development process has followed an incremental approach and three levels of perception have been defined as Fig. 2.1 depicts. To begin with, the first level focuses on perceiving the *movement* of a vehicle (aka its kinematic state). This type of information is a key element of the context of a vehicle as knowing whether a vehicle is stopped, accelerating, and the like provides quite useful information about its current state. Then, this movement-perception level was extended to a second layer to widen the context perception whereby a set of modules that detect other features of the vehicular context. Since the target vehicle in the present work is a familiar one, this second layer focuses on the context related to its usual itineraries. In particular, it is in charge of perceiving two key elements that identifies an itinerary, the occupancy of the vehicle and its meaningful places.

Another aspect that is interesting to detect in a vehicular scope is the traffic conditions surrounding the target vehicle. Consequently, a third layer was designed to deal with this level of perception as Fig. 2.1 shows. Nowadays, there exist many proposals that are able to detect traffic problems in a road in a quite accurate way. Nonetheless, most of them depend on sensors installed in different parts of the road infrastructure. On the contrary, the present thesis pursues to make the most of the on-board equipment of a vehicle, but it is almost impossible to detect the traffic conditions surrounding a vehicle by relying only on its own sensors. However, that goal would be possible to achieve if the vehicles driving along a road shared the information gathered by their own on-board equipments in order to perceive the general traffic conditions of that road. Consequently, this thesis has also studied a cooperative approach so as to augment the perception of the context of a vehicle with the traffic conditions surrounding it.

To sum up, the specific goals of the present PhD thesis are the ones listed next,

1. Analyse the current state of the art of the Context-Aware approaches in the ITS field and identify possible weaknesses in order to provide general-purpose solutions.

2. Establish a formal and general-purpose definition of the context related to a familiar vehicle.

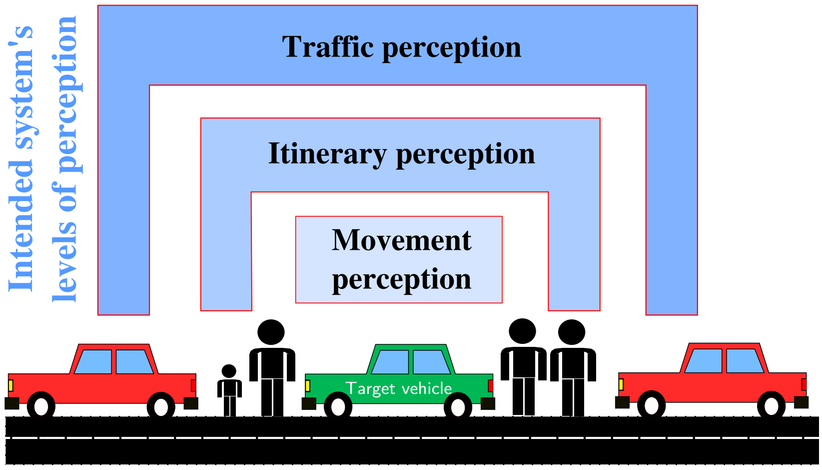

Figure 2.1: Perception levels of the intended system.

3. Identify the commons sensors of a vehicle useful to perceive vehicular context features.
4. Develop an on-board module able to perceive the kinematic state of a vehicle as part of its context whereby a set of sensors of the own vehicle.
5. Development of an on-board non-intrusive tool based on low-cost sensors to perceive the occupancy of a vehicle as part of its context.
6. Development of a real-time on-board mechanism capable of detecting the meaningful locations of a driver's frequent itineraries.
7. Develop a real-time system to detect traffic congestions related to a target vehicle which takes advantage of the information from the surrounding vehicles.
8. Validation of the proposals by means of proof-of-concept tests in order to show their suitability.

In brief, all the aforementioned goals aim to be the least intrusive as possible and make the most of the information from the on-board equipments which a common vehicle contains by default so as to perceive the vehicular context.

2.2. Results

As a result of this PhD thesis, remarkable contributions have been developed. A complete list of the different works done for this thesis can be found in section 8.2. Some of them are not deeply described here due to the regulations for this type of thesis presentation. Most of those non-deeply-described works are preliminary studies of the final solutions that comprise the present manuscript. However, they also put forward interesting proposals.

Table 2.1 sums up the goals listed in the previous section and their associated results along with an engineering classification. Moreover, the works where each result has been stated are cited as well. Hereafter, the results related to each goal are described one after another.

Hence, regarding goal 1), stated in the previous section, a study of the current approaches to perceive the context of a vehicle has been done. In particular, the present work has focused on the SA

Goal	**Result**	**Classification**
Goal 1: Analyse the current state of the art of the Context-Aware approaches in the ITS field and identify possible weaknesses in order to provide general-purpose solutions.	State of the art or the Context-Aware systems in the vehicular scope. [51–53, 56]. Definition and design of the IvCA concept [52].	Study
Goal 2. Establish a formal and general-purpose definition of the context related to a familiar vehicle.	Model of the intra-vehicular context [52].	Modeling
Goal 3: Identify the commons sensors of a vehicle useful to perceive vehicular context features.	Identification of the common and low-cost vehicular sensors feasible to be contextual data sources [51–53, 56].	Analysis
Goal 4: Develop an on-board module able to perceive the kinematic state of a vehicle as part of its context whereby a set of sensors of the own vehicle.	Module to detect the longitudinal maneuvers of a target vehicle based on fuzzy modeling [51, 55, 56].	Design
Goal 5: Development of an on-board non-intrusive tool based on low-cost sensors to perceive the occupancy of a vehicle as part of its context.	Pattern-based module for the vehicular occupancy discovery [52, 53].	Design
Goal 6: Development of a real-time on-board mechanism capable of detecting the meaningful locations of a driver's frequent itineraries.	Landmark discovery algorithm [52].	Design
Goal 7: Develop a cooperative real-time system aiming to detect traffic congestions related to a target vehicle.	CEP-based module to discover traffic congestions [49, 50, 54].	Design
Goal 8: Validation of the proposals by means of proof-of-concept tests in order to show their suitability.	Battery of simulated and real-world tests to study the suitability of the proposals [52, 54, 56].	Validation

Table 2.1: Goals of this PhD thesis and their results with the cites of the works where they have been explained.

concept and the different solutions that can be found in the literature. As a result, a comprehensive state of the art about the SADAS has been put forward. Such study concludes that the current SA-based solutions do not really perceive the whole vehicular context as they are mainly designed for safety goals.

As far as goal 2) is concerned, the study made for the previous goal allowed us to identify which dimensions of a vehicular context were or were not covered by the current SA-based solutions. Then, all these dimensions were used to define the whole characteristics of the context related to a vehicle and, eventually, come up with a formal model of it. This model has been the guide of the remain work of the present thesis.

Once the contextual model had been defined, the next step was to consider how that context could be perceived. For that reason, an overview about the different sensors and equipments a common vehicle comprises by default was made. This led us to know that it was possible to access a wide range of sensors of a vehicle by means of the *On-Board Diagnostic II* (OBD-II) interface. Basically, ODB-II makes it feasible to access different sensors and units installed in different parts of a vehicle's engine, bodywork and interior. Therefore, a varied range of in-vehicle data sources were available to detect the vehicular context. Thus, the goal 3) was accomplished by means of that overview.

Regarding the design goals, the first context-detection mechanism that was developed as part of the present work was the one related to the kinematic state of a vehicle which accomplishes goal 4) of this thesis. The previous overview about the available in-vehicle data sources put forward that it was possible to perceive the kinematic state by means of certain on-board equipments. Due to the noise and imprecision that these equipments may imply, the present PhD thesis followed a fuzzy-logic approach [46] to detect the kinematic state of a vehicle. The procedure to achieve that comprised the following steps. Firstly, the tool to combine soft-computing algorithms stated in [41] was improved with more computing capabilities. Next, such tool was implemented as an *Application Programming Interface* (API). The result of this work was stated in [55]. Then, this API was used to develop a first approach to detect the kinematic state of a vehicle by means of fuzzy modeling [51]. Finally, an improvement of that approach has been eventually included as part of this PhD thesis.

The goal 5) has been accomplished by means of a novel non-intrusive mechanism that aims to detect the current vehicular occupancy. This mechanism relies on the hypothesis that the occupancy of a vehicle can be perceived on the basis of the usual interactions between the passengers and the vehicle when it comes to get in and off such as opening or closing the doors. These interactions can be perceived by common sensors installed in doors, windows or seat belts. In particular, the proposed mechanism focuses on searching a set of pre-defined patterns in the data flow from these sensors which give insight into the current occupancy of a target vehicle. In that sense, the mechanism put forward in the present thesis continues the work introduced in [53] by overcoming certain intrusive problems.

The detection of the usual places of a vehicle that the goal 6) implies has been achieved by following a clustering approach. In that sense, a new algorithm based on the density-based clustering concept has been developed. This algorithm, named the *landmark discovery algorithm*, is able to detect the meaningful places of a vehicle's itineraries in real time with different granularities. Thus, it sorts out the problems of previous density-based approaches which makes it suitable to run as an on-board equipment.

Regarding the goal 7), this PhD thesis puts forward a novel mechanism to detect traffic congestions on a road based on the *Complex Event Processing* (CEP) technology. CEP is a novel paradigm designed to operate in environments with high rates of incoming data generated by distributed sources. One example of this type of environments are the *Vehicular Ad-hoc Networks* (VANETs). The VANETs are one of the most important platforms that enable moving vehicles to share information among them. Moreover, this type of networks has been widely studied in the literature and it has became a foremost topic in the communications field. Consequently, it was suitable to use it so as to accomplish the present goal. As a result, the CEP-based solution presented in this thesis is able to cope with the huge amount of information a VANET may generate under certain conditions. Moreover, the current mechanism is the result of a line of work that has focused on the development of CEP solutions in the ITS scope [49, 50].

In order to accomplish the goal 8) all the mechanisms proposed in the current work have been tested by means of a set of experiments. In this frame, there have been three different approaches in order to make up these experiments, the real-world, the simulation and the hybrid approach. While in the real-world experiments only the data gathered from a real environment was used so as to test the mechanism under study, the simulation-based approach relied on artificial data so as to generate the input that the mechanism intends to process. For that purpose, different frameworks which combine several existing simulation tools have been implemented. Next, the hybrid experiments also made use of simulators, but their output data is based on real-world datasets which were previously gathered. This hybrid approach has been applied when there existed real-world data but the amount of it was not enough for a whole real-world experiment. Lastly, using one or other approach has mainly depended on the availability of real-world data that the mechanism under study intends to take as input.

The results from the different experiments proof that all the solutions presented in this PhD thesis were capable of achieving an accurate level of perception of different features of the vehicular context. Besides, in some cases, the developed mechanism improved the results achieved by other proposals in the literature. To conclude, all the intended goals for the present PhD thesis have been accomplished. As a result, the foundations of a full-blown on-board CA system have been successfully defined. This will help the development of future in-vehicle ubiquitous applications which will profit from the context perceived by our solution. This will make travelling by car more comfortable, safe and sustainable.

2.3. Conclusions and Future Work

The development of on-board services in the vehicular scope is an important line of work in the ITS field. In this scope, the perception of the context is a paramount factor so as to come up with more complex and advanced services. In that sense, most of the proposals in the literature to perceive the context related to a vehicle have been designed for certain situations and specific goals. Thus, there was a scarcity of solutions to perceive a vehicle's context as a whole so that the detected information can be useful for a varied range of fields.

The present PhD thesis pursues to define a general-purpose platform to perceive the context related to a vehicle given a familiar scope. In that sense, the line of work has been twofold. On the one hand, a theoretical approach has been followed to establish the general drawbacks of the current proposals to perceive the vehicular context. Next, a general model for the context of a vehicle has been designed. Such model has mainly taken into account the different features of the environment of a familiar vehicle. On the other hand, a practical approach has been carried out to develop several solutions to perceive the target context model. These solutions have been implemented by mainly taking advantage of low-cost equipments a common vehicle includes by default. Such solutions are listed next,

- Firstly, a module to detect the kinematic state of a target vehicle developed whereby a fuzzy modeling approach has been explained. This module presents an accurate and lightweight solution to infer the longitudinal maneuvers which improves previous maneuver-detection approaches.
- Moreover, a novel solution to discover the occupancy of a vehicle on the basis of certain predefined patterns in the in-vehicle sensors' data flow has also been introduced. This new approach sorts out certain intrusive and accuracy problems of former occupancy-detection solutions.
- In addition to that, the landmark discovery algorithm that intends to perceive the foremost places of a vehicle's itineraries has been also put forward. Such algorithm adapts the density-based clustering technology so that it can be used as an on-line solution.
- Finally, a CEP module to infer the traffic jams near a target vehicle has also been stated. This new mechanism introduces a new way to process the messages broadcasted across a VANET to give insight into new contextual information.

All in all, completely novel approaches have been introduced throughout this thesis's course of action. Therefore, in our view, the present work is a remarkable advance of the CA field which opens new lines of work in the ITS scope. In that sense, the work stated in this PhD thesis can be continued in several ways.

To start with, the different mechanisms stated in this thesis will be integrated by means of the vehicular communication architecture proposed in the CENIT OASIS project [1] so that they can work as a unique system. This project pursues to develop intelligent roads by taking into account all the elements involving such infrastructure. Consequently, by means of this project, it would be possible to install this system in real vehicles and, as a result, deploy new experiments. Another line of work may consist of integrating the contextual information perceived by the present system in the platform stated in [33]. This work describes a global communication platform that provides drivers with pervasive services on the basis of certain contextual information. Thus, the present level of perception may be used in order to widen certain capabilities of such platform.

Secondly, the mechanisms proposed in the present thesis will be improved to deal with new data sources in order to increase their perception accuracy. As a matter of fact, identification mechanisms such as RFID and NFC readers or body sensors will be studied as possible new inputs for the occupancy-discovery mechanism so that some personal details about the driver and passengers can be included in the perception of the context. As a consequence, a course of further work will deal with the usage of privacy systems in the ITS field like [26] so as to protect that end users' personal information.

Moreover, further research will focus on increasing the level of perception with new contextual details not considered in the present manuscript. In that sense, enriching the information about the frequent itineraries of a vehicle will be an important topic. For that purpose, the mechanisms introduced in this thesis will be used as tools in order to accomplish this goal. For instance, the kinematic information perceived by the fuzzy-logic mechanism can provide useful information about the state of the roads that a vehicle covers in its itineraries.

Lastly, another line of work is going to centre on introducing novel CEP-based solutions to infer information about the trajectories of moving devices. Such a novel approach has already been applied by the PhD candidate in the marine surveillance scope to detect vessels' abnormal behaviours [13]. Specifically, this solution will be adapted so as to perceive the meaningful turnings of a vehicle's trajectory. That turning information might give insight into the type of path that each itinerary involves. For example, if an itinerary involves plenty of turnings, it may be a sign that this itinerary covers a rather complicated road. On the contrary, if it only implies a few turnings it may indicate that the itinerary mainly covers an easy-to-drive road (like a motorway). On the whole, the system will be able to detect further information about the paths of the different itineraries of the target vehicle and, as a result, provide the third-party applications using the system with a more comprehensive overview of those itineraries.

Chapter 3

Readers' guide

Since this thesis is presented under the scheme of compilation of publications, there exist a specific regulation with respect to the manuscript's chapters organization that has to be accomplished. Therefore, the main goal of the present chapter is to explain to the reader the structure of this PhD thesis and give an overview about the aims of each chapter in order to completely understand the manuscript.

One of the requirements for this type of thesis indicates that a summary of its motivations, goals and results has to be included in the manuscript both in Spanish and English. Hence, chapters 1 and 2 fulfil this requirement by summing up the content of this thesis in both languages. In particular, these chapters put forward the motivations and goals of this work in sections 1.1 and 2.1, and the specific results that have been achieved in order to accomplish the goals previously mentioned in sections 1.2 and 2.2. Moreover, the main conclusions and a description of further research lines which continue this work have been also stated in sections 1.3 and 2.3 so that a comprehensive summary of all the thesis is put forward.

The regulation also requires that the manuscript has to comprise an introductory chapter where all the papers composing the thesis are presented. Furthermore, such chapter has to explain the relationship among them so that it is possible to see the line of research as a whole. As a result, chapter 4 introduces the content of each article composing this PhD thesis following a layered approach where each article is presented as a specific layer of the final system which we intend to define. This way, for each paper its main contributions with respect to the goals of the present thesis are explained. In addition to that, a comparative with other proposals of the literature is also done so that the relevance of the papers is pointed out. Finally, an overview about the different technologies and tools used in each paper is also provided.

As far as chapter 5 is concerned, it comprises the three papers that composes this PhD thesis in the final format they were (or are going to be) published. These papers present the developed solutions to accomplish the goals listed in chapter 2. Specifically, each article fulfils one or more of these goals, and each goal is accomplished by one or more papers. Moreover, due to the regulation for this type of thesis, a complete reference information is included before each paper.

Regarding the particular publications composing this PhD, section 5.1 comprises the work *"An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles"*. In this article, firstly, a classification of the current solutions to perceived a vehicle's kinematic state is done on the basis of different factors. Because those systems can be viewed as a specialized type of CA systems, this article partially fulfils the goal 1 described in table 2.1. Next, the fuzzy-logic solution that this thesis proposes to perceive the kinematic state of a vehicle is put forward. By means of such mechanism the goal 4 of table table 2.1 is accomplished. It is important to recall that this mechanism is an improvement of a former maneuver-detection solution based on fuzzy logic also put forward by the PhD candidate in [51]. Finally, a set of experiments based on real-world data is done in order to test the accuracy of the proposal with respect to other solutions of the literature. Thus, goal 8 (table 2.1) of the thesis is also partially covered.

Section 5.2 contains the paper titled *"A Complex Event Processing Approach to Perceive the Vehicular Context"* which introduces three of the key proposals of the present thesis. To begin with, it puts forward the general definition of the context related to a familiar vehicle by means of an information model. This model aims to accomplish the goal 2 of the thesis (table 2.1). Then, the paper focuses on explaining the vehicular sensors that can be used as possible contextual data sources keeping in mind the aforementioned model. This way, the goal 3 of the thesis is also fulfilled. Next, on the basis of these data sources and the context model, two context-detection mechanisms are stated. The former is the pattern-based approach to detect the vehicular occupancy. As it has been previously explained, this eventual solution is a refinement of an initial pattern-based mechanism also introduced by the PhD candidate in [53]. The second stated mechanism is the the landmark discovery algorithm that is devoted to discover the meaningful places of a vehicle. Furthermore, how these meaningful places are integrated as part of the vehicular context is also stated. These two mechanisms are the thesis's results that fulfill goals 5 and 6 of table 2.1. Moreover, both mechanisms are tested by means of a battery of experiments which combine real-world data and a simulation-based approach. Hence, this paper also partially accomplishes the goal 8 of the thesis. Lastly, a state of the art about the current solutions for occupancy detection and places discovery is described as well, so goal 1 is also partially covered.

Furthermore, section 5.3 is compound of the article *"A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET"* which focuses on describing a novel solution to detect traffic jams. Specifically, this solution relies on the CEP technology to implement a cooperative module which processes the messages from VANET. As a result, thanks to this paper the goal 7 of the thesis has been achieved as well. Apart from that, goal 8 is also accomplished by this paper because the mechanism is tested by means of a simulator framework. This article is one of the results of a line of work which focuses on applying an event processing approach to solve certain ITS problems where the PhD candidate has other remarkable contributions [49, 50].

On the whole, table 3.1 summarizes the goals covered by each of the three articles composing this PhD thesis where the ✓ symbol indicates that the paper described in the row achieves the goal specified in the column.

Manuscript section	**Article**	**Goal**							
		1	2	3	4	5	6	7	8
5.1	*An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles*	✓			✓				✓
5.2	*A Complex Event Processing Approach to Perceive the Vehicular Context*	✓	✓	✓		✓	✓		✓
5.3	*A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET*							✓	✓

Table 3.1: Publications of this PhD thesis and their accomplished goals.

Since the article titled *"A Complex Event Processing Approach to Perceive the Vehicular Context"* (included in section 5.2) has not been published yet but it is *in press* state, the regulation for this type of thesis requires to include a chapter with the acceptance letter of such article. As a result, chapter 6 contains the letter for the mentioned paper.

In addition to that, chapter 7 depicts the publication relevance of the three articles included in the present thesis. This section is also a requirement of the regulation for this type of thesis. As a result, for each paper, the reference in the ISI Web of Knowledge (`http://www.accesowok.fecyt.es/`) of the journal where it has been (or is going to be) published is included. In particular, it is depicted the journal's relevance in its field along with its impact factor.

Lastly, chapter 8 is devoted to the bibliography of the manuscript. On the one hand, section 8.1 comprises the references of the works cited in the different sections of the manuscript. On the other hand, section 8.2 includes the articles that have been published so far as a result of the work done for this PhD thesis.

Chapter 4

Introduction

Private vehicles have become a very important means of transport for the last decades. Despite the fact that nowadays modern societies have a tendency to prioritize public transport over private vehicles so as to achieve sustainable development, it is also true that vehicles' economical price and the fuel's cost has caused travelling by vehicle to be affordable. This is specially true in a family environment where the family members usually travel together in the same car on a regular basis. As a result, the number of privately owned cars has incredibly grown in both developed and developing societies. This fact has given raise to many transportation challenges both public and private administrations must deal with. Those problems are quite varied and range from increasing the driver and passengers' security to using the road infrastructure in an efficient way. Therefore, they usually involve a number of complex factors which include economic, social and political interests.

In this context, *Intelligent Transport Systems* (ITSs) refer to a wide field that aims to solve those worldwide transportation's problems by making use of information and communication technologies [6]. An ITS makes use of multidisciplinary areas like sensing, robotics, communications or information systems in order to provide secure, efficient, sustainable and comfortable mobility to both drivers and passengers.

Despite its varied nature, one of the most important topics in the ITS field has been the deployment of the *Advanced Driver Assistance Systems* (ADASs). The main goal of an ADAS is to help drivers to face certain traffic situations in order to increase the driver and passenger's safety. One of the main research lines in the ADAS field is based on the *Situation Awareness* (SA) concept [12] which gives raise to the *Situation-Aware Driver Assistance Systems* (SADAS). A SADAS is an on-board system that is capable of perceiving the relevant information about the current situation of its target vehicle by taking as input data from different vehicle's sensors and other external data sources [39]. Thus, it is able to detect in advance certain risky situations and either inform the driver or take some type of proactive action to avoid them.

In the *Context-Awareness* (CA) paradigm, a SADAS can be viewed as a special type of CA system. CA systems arose in the 90's and their main feature is that they *use context to provide relevant information and/or services to the user, where relevancy depends on the user's task* [3]. A CA system perceives its surrounding context whereby a set of sensors and other input channels (video-cameras, RFID readers, GPS receivers, etc.). Afterwards, such contextual information might be presented to the end user so that he can perform some kind of action or the system can take a proactive action so as to adapt itself to certain changes in the environment. In that sense, a CA system may support three different features [3]:

- *Contextual sensing* is the capability to perceive contextual information and present it to the end user. As a result, this feature allows to augment the user's sensory system. In that sense, one of the most important challenges is to find which sensors are the most adequate to detect the context. Therefore, studying which sensors are available in the environment where the system is going to move around becomes a paramount task.

- *Contextual adaptation* stands for the system's ability to execute or modify a service depending on certain contextual changes or when the right combination of context exists. This way, the system is able to adapt itself to the current context and to provide a personalized benefit to the end user.

- *Contextual augmentation* is the ability to use the perceived context so as to infer new contextual information about the users and the environment. Two different approaches exist to support this features. The former is based on if-then rules, whereas the latter follows a machine learning methodology.

Not all the CA systems support all the aforementioned features, and this depends on the domain and goal of the target system. In that sense, a SADAS always includes the contextual sensing among its features in order to accomplish its goals. Nonetheless, its perceived context is generally not complete as it focuses on certain features related to safety of its target vehicle.

In this frame, manufacturers have been including new sensors in different parts of their vehicles for the last years. Taking into account that those sensors provide comprehensive information about the vehicle, some in-vehicle CA systems have been developed that achieve a more general perception of a vehicular context than a SADAS. These systems are usually on-board units, and the vehicle where they run and whose context is perceived is called *Ego Vehicle* (EgoV). Nevertheless, since those works focus on particular domains, like safety [11, 35] or sustainable transportation [42], their perceived vehicular context tend be incomplete as well.

Moreover, there also exist a lack of CA systems targeting *familiar vehicles*. This type of vehicles is quite common in developed societies [34] and they are mainly used by families to accomplish certain daily routines such as commuting, going shopping and the like. In this scope, the deployment of on-board ubiquitous applications which take into consideration the context of the EgoV in order to provide personalized and intelligent services to the occupants is really convenient for both motorists and manufacturers. Regarding the formers, they would enjoy more comfortable and safer trips during which, for example, their favourite music album is automatically played in the EgoV's player as soon as they get into it or suggestions about close affordable restaurants are indicated whereby the EgoV's speakers at lunchtime. Concerning the manufacturers, they would be able to enrich their vehicles with new features making their products more tempting for end users. However, in order to achieve that type of features, it is paramount to perceive the context of the target familiar vehicle in a general an accurate way.

Therefore, **the present PhD thesis introduces a novel general-purpose CA system able to perceive the vehicular context in a detailed way for a familiar vehicle so that it could be used by a varied range of services**. Due to the fact that the intended perception focuses on the context of a vehicle, this new CA approach has been named *Intra-vehicular Context Awareness* (IvCA). As Fig. 4.1 depicts, the IvCA can be regarded as an extension of the SA concept because both include the contextual sensing among their features given the vehicular scope. However, the IvCA paradigm does not only perceive the EgoV's situation context but a more comprehensive view of its context. This will support the contextual adaptation and augmentation of other in-vehicle CA systems in the future.

In order to test the feasibility of the IvCA concept, the key elements of an on-board IvCA system have been implemented. Such system intends to detect different contextual features of the EgoV whereby several of its sensors and on-board equipments. After that, the detected contextual information would be used by third-party applications so as to offer personalized services to the EgoV's occupants. Nonetheless, those applications are out of the scope of the present PhD thesis. For that purpose, a layered approach to develop the IvCA system has been followed. This way, the developed system comprises different layers each of which is responsible for a certain level of perception of the EgoV's context. To begin with, a core able to perceive quite basic contextual information has been developed. After that, such core has been extended with new layers which pursue to perceive other dimensions and features of the EgoV's context.

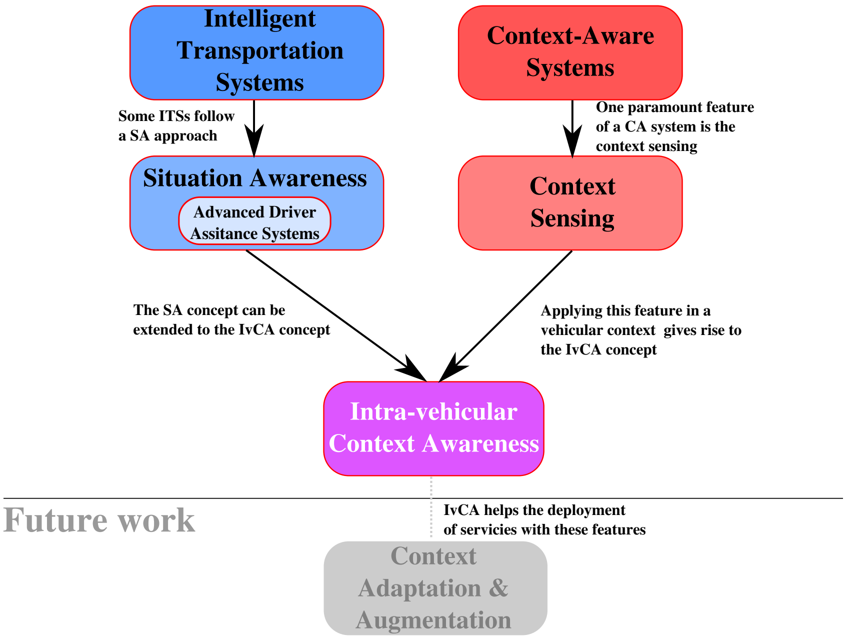

Figure 4.1: Scope of the Intra-vehicular Context Awareness concept.

4.1. Intra-vehicular Context Awareness

In order to clearly state what the IvCA concept means, giving a formal definition of the vehicular context becomes a paramount task. Therefore, one of the first goals of the present work was to clearly define a formal representation of the vehicular context. Then, this definition has been the starting point of the remain tasks of this PhD thesis.

Despite the great number of definitions for "context", the present work defines it as *any information that can be used to characterize the situation of an entity* where such entity can be a person, place or object (like a vehicle) [3]. Keeping in mind that definition, Fig. 4.2 depicts the proposed information hierarchy that defines the context for a familiar vehicle. This hierarchy was firstly stated in the article contained in section 5.2. As such model indicates, the vehicular context basically comprises two types of information, the static context and the dynamic one. The former is related to the features which do not or hardly ever change throughout the lifetime of a vehicle. These elements include technical features and information about the vehicle's ownership.

As for the dynamic context, it has been modeled on the basis of the four dimension that identifies a context according to [3], *location*, *activity*, *time* and *identity*. These dimensions answer where, what, when and who is the target entity. As a result, the meaning of each dimension in the IvCA scope is defined next,

- Regarding the *location*, in most domains this dimension is only defined by a single point indicating the current position of the target entity (like a GPS location). However, that type of information is too simple for the IvCA scope. Taking into account that a car is used to go from one place to another, it seems to be more useful to define the EgoV's location as two places or *landmarks*, the one where the EgoV comes from (origin) and the one where it is currently going to (destination). Later, in section 4.2.2, the term *landmark* is discussed. This contextual dimension is quite helpful as it can be used by some kind of driver-assistance system to proactively suggest an alternative route to the current destination if it detects a traffic jam along the usual route to it.

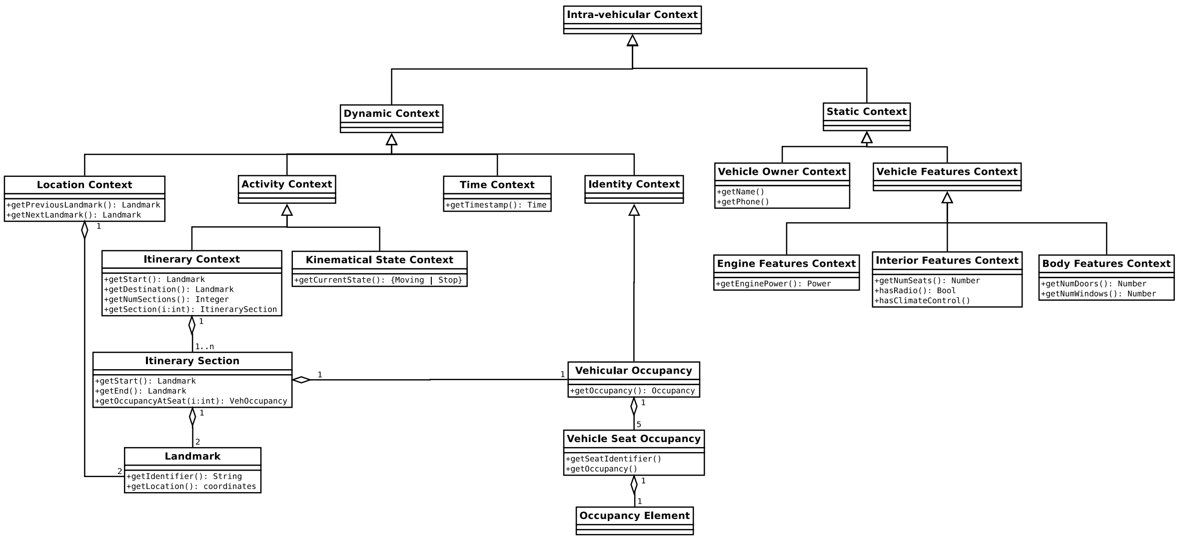

Figure 4.2: Model of the intra-vehicular context.

- Concerning the *activity*, this dimension can be viewed at different abstraction levels in vehicular environment. At a low level, a vehicle's activity can be described on the basis of its kinematic state (whether it is accelerating, stopped, etc.). From a more abstract point of view, familiar vehicles are usually used to cover a set of journeys or *itineraries* on a regular basis. Each of these itineraries has a particular goal like commuting or going to the shopping mall. Consequently, we can also see the itinerary that the EgoV is covering at a certain moment as its activity. As a result, in a IvCA scope, this dimension has a twofold characteristic. On the one hand, it indicates the kinematic state of the EgoV. On the other hand, it also indicates the *itinerary* that the EgoV is currently covering. Both characteristics are fairly useful for certain services. For instance, the kinematic state can be used by an Interactive Multi-Model (IMM) to choose which is the kinematic model which best suits the current movement of the EgoV. Then, by means of the selected model, it would be possible to predict the current location of the EgoV. This is specially useful in areas with low GPS coverage because these predicted locations could be used by the location-based services in the EgoV instead of using the GPS receiver. Moreover, the kinematic state also provides information about the road state where the EgoV is currently driving. For example, if the driver has performed many accelerations and stops for a certain period of time, then it may indicate that this road has a high traffic density or there are plenty of traffic lights along it. This information can be used by Traffic Information Systems (TIS) in order to monitor the state of the roads in an area of interest. Besides, the itinerary information is also useful for in-vehicles services. In particular, those services can profit from this information in order to suggest alternative destinations. For example, if an itinerary whose goal is "going shopping" is perceived then these services can suggest the driver and passengers to go to certain supermarkets close to the current EgoV's location.

- As for the *identity*, this dimension describes the EgoV's occupancy in the current scope. In that sense, it is possible to define different levels of detail to describe the vehicular occupancy. In the lowest level, the occupancy is detailed only in terms of the number of people inside the EgoV. In a more detailed level, the occupancy can indicate not only the number but also the type of occupants inside the vehicle at each moment. This way, it is possible to know that there are four people in the EgoV, but also that these people are two adults and two children. Lastly, the most comprehensive level comprises personal information (name, age, etc.) about the occupants of the EgoV. Choosing the most suitable level depends several factors such as the system's goal or the available data sources. Nevertheless, knowing the current occupancy of the vehicle provides several functionalities for different third-party services. For instance, this information can be used by traffic management centers in order to control which vehicles are allowed to use the High-Occupancy Vehicle (HOV) lanes. Besides, an on-board safety system could send the occupancy information to an emergency center provided that there was an accident involving the EgoV so that such center knows in advance the number of people involved in the accident. This way, the emergency resources can be handled in a more efficient way.

- Finally, the *time* is a fairly important feature to understand the context. In that sense, in an IvCA environment, it specifies the moment of the day at which the current itinerary is happening.

Table 4.1 sums up the mapping between the context dimensions and their meaning in the IvCA scope along with an example of possible values. The combination of those dimensions allow to describe in detail the dynamic context of a vehicle with different levels of abstraction. As a result, once the IvCA context has been defined, the next step is to develop the IvCA system that is able to perceive it. This system is described in the next section.

Context dimension	**IvCA meaning**	**Possible snapshot**
Location	Origin	Home
	Next destination	School
Activity	Current itinerary	Commuting
	Kinematic state	Accelerating
Identity	Current occupancy	Father & son
Time	Moment of the day	Early in the morning

Table 4.1: Mapping between the common and the IvCA context dimensions.

4.2. IvCA System

When it came to develop the intended IvCA system, the first step was to identify the data sources that could be used to perceived the previously defined vehicular context. In that sense, a vehicle includes a large number of elements in different parts of its structure that can turn out to be fairly useful for the present task. In particular, a vehicle's engine comprises many sensors that can be read and provide parameters about its kinematic state. In addition to that, some parts of a vehicle's bodywork like doors or windows can also provide data to perceive the vehicular context. Moreover, since a vehicle does not move alone in most of the cases, but surrounded by other vehicles, those vehicles can be also provide contextual information interesting for the EgoV.

Due to those varied sources of information, **the present PhD thesis puts forward that it is possible to perceive the four dimensions of the dynamic IvCA context by mainly using common or low-cost sensors of the own EgoV**. As a result, the IvCA system was designed following a layered structure. Each system's layer uses certain types of the EgoV's data sources and perceives one or more contextual dimensions. The proposed system particularly comprises three layers, the *engine layer*, the *bodywork layer* and the *traffic layer* as Fig 4.3 depicts. Whereas the engine layer focuses on the EgoV's engine sensors, the bodywork layer makes use of the sensors in different parts of the EgoV's bodywork and interior. Besides, the traffic layer takes as input certain data from the surrounding vehicles. Each of these layers extends the previous one and, as a result, the whole vehicular context is perceived.

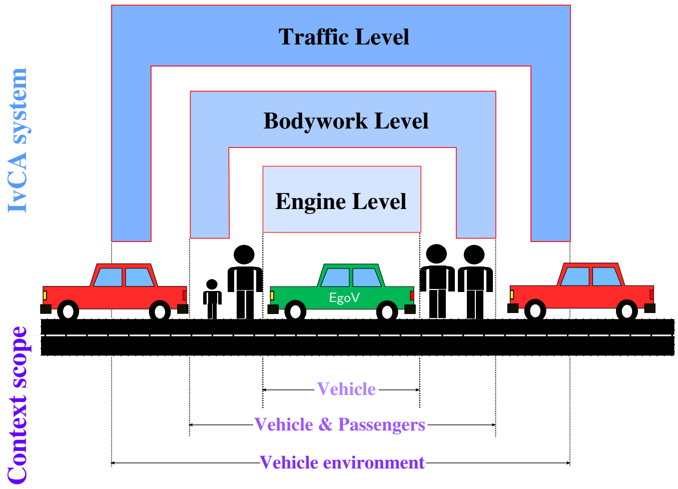

Figure 4.3: Layers of the developed IvCA system and the scope of their perceived context.

4.2.1. Engine layer

A vehicle's engine is compound of many units and sensors that provide a great number of parameters and data about the vehicle. Many works have profited from this fact and have used certain elements of a vehicle's engine as data sources. In particular, several proposals have put an effort to develop remote vehicle monitoring systems [9, 23]. Apart from that, systems to control the fuel consumption of a vehicle have also been another topic where the engine data has been used [18, 45].

The engine data has been also used by the SADASs. In particular, some of these systems pursue to detect the current maneuver of a vehicle by using common engine sensors [40]. Next, this maneuvering information is used to increase the perception of the vehicle's situation so that it is possible to detect certain risks.

Regarding the vehicular context explained in section 4.1, the activity dimension includes the kinematic state of the EgoV as one of its features. In this frame, one of the key goals of the present PhD thesis was to develop a mechanism able to perceive such kinematic state. In order to achieve that, this work has followed the maneuver-detection approach of the aforementioned SADASs, so a longitudinal maneuver detection mechanism has been developed. This mechanism is capable of distinguishing among different sorts of maneuvers (stop, accelerating, cruise speed and so forth), each of which represents a kinematic state, by taking as input the data from common engine sensors. In that sense, it is necessary to consider the noise and imprecision that this data frequently involves. Due to the fact that fuzzy rules are able to cope with this type of data [46], they are suitable for the present problem. Moreover, since the set of longitudinal maneuvers that a vehicle is capable of performing can be defined beforehand, this objective can be viewed as a classification problem.

Consequently, the present thesis introduces a novel maneuver-detection mechanism based on the *Fuzzy Rule Based Classification Systems* (FRBCSs) [22]. In particular, the proposal focuses on a FRBCS comprising a set of IF-THEN fuzzy rules. The course of action to develop this layer started by implementing a fuzzy-modelling framework which fulfilled the design of the hybrid platform stated in [41]. An overview of this API is provided in [55]. Next, this API was used to implement a FRBCS which improved previous maneuver-detection FRBCSs, like [47], by applying fuzzy modelling techniques [51]. However, the achieved system relied on input sets comprising past velocity and acceleration.

In order to overcome that disadvantage, it was generated a new FRBCS which takes as input the current EgoV's velocity and acceleration. This allows to save memory as keeping buffered information is unnecessary. Besides, the system also comprises a low number of rules. This leads to the fact that little computation time is needed in order to infer the current EgoV's maneuver. More details about this last fuzzy classifier are put forward in the article of the section 5.1. In particular, the fuzzy modelling approach is described in detail along with a set of experiments where real-world data is applied. In these experiments, our proposal clearly outperforms the results of other solutions in the literature.

4.2.2. Bodywork layer

The different elements of the EgoV's bodywork and interior like doors, windows and seat belts are quite important contextual data sources as they are used by the driver and passengers to *interact* with the vehicle such as getting in or off. Nowadays, vehicles commonly include sensors in most of these elements, and they can be read by means of the On-Board Diagnostic II interface [2]. This interface has been installed in vehicles for almost 20 years in both Europe and the United States. Furthermore, there exist many scanning tools that makes it possible to read the data from those sensors. Since it is feasible to take these elements as input, the present layer aims to perceive the features of several contextual dimensions by basically processing the data flow from different sensors in the EgoV's interior and bodywork. In particular, the bodywork layer focuses on three dimensions, identity, location and activity.

Identity detection

Regarding the identity dimension, section 4.1 describes this dimension in a vehicular scope as the EgoV's occupancy. In this frame, it is possible to find several approaches in the literature to detect the occupancy of a target vehicle [44]. One of the most important trends aims to discover certain occupancy features by installing ad-hoc sensors in different parts of the vehicle [19]. Nevertheless, one of the key downsides of these works is that the sensors are usually fairly intrusive. Another trend follows an optical approach by installing video-cameras as on-board units [29] or as part of the road infrastructure [31]. Nonetheless, due to certain constrains of this devices, these works usually are only capable of detecting the number of people who is inside the vehicle providing a rather coarse-grained occupancy information. Lastly, some works have applied biometric recognition techniques in the vehicular occupancy field [15]. However, this kind of works focuses more on the driver authentication than on the occupants discovery.

The present PhD thesis proposes a novel approach to detect the occupancy of a vehicle. This approach rests on the hypothesis that people usually perform a set of regular actions every time they get in and off a vehicle like opening the doors, fastening the seat belts and so forth as part of their daily routine. Consequently, this thesis states that is possible to detect the driver and passengers of the EgoV by means of a set of predefined patterns in the data flow from common sensors installed in the EgoV's bodywork and interior. This approach overcomes some of the drawbacks of the aforementioned proposals as it does not rely on intrusive sensors, and it is able to perceive both the number and the types of occupants inside the vehicle. As a first attempt to develop this approach, a mechanism to perceive the vehicular occupancy which combines a pattern-based module with an adaptation algorithm was proposed in [53]. Whilst the patterns give insight into certain activities of the users with the EgoV, the adaptation algorithm adjusts the occupancy inference with respect to the users' indications. That was the reason why a taxonomy that describes the different types of occupants was also proposed. After that, a new occupancy-detection mechanism was implemented following the same pattern-based approach but certain intrusive problems detected in the previous solution were overcome. Finally, this last mechanism has been the one included in the present PhD thesis.

The proposal was tested whereby a set of proof-of-concept experiments. For that purpose, the UbikSim [8] framework was used. UbikSim is a simulator of physical environments, hardware appliances and users, and it has been developed by the research group of the PhD candidate. For the present thesis, the aim of UbikSim was to simulate different types of behaviours when it comes to get in and off a vehicle. In order to define those behaviours, an on-line survey about the routines to interact with a car in a familiar environment was undertaken. The website used to undertake such survey is available on `http://encuestaocupacion.inf.um.es/`. Lastly, the paper in section 5.2 puts forward in detail this approach along with the performed experiments.

Location detection

Concerning the location, this dimension in the vehicular context implies two *places*, the place where the EgoV comes from and its current destination. It is important to recall that the present work focuses on familiar vehicles. This type of vehicles basically moves around a set of usual places (or *landmarks*) such as the family home, a workplace or a shopping mall as part of its daily itineraries. As a result, a familiar vehicle usually goes from one of these landmarks to another one. Therefore, it is necessary to identify these landmarks so that it can be used in this dimension.

There have been a large number of proposals to identify the meaningful places of person's daily routine. Most of them focus on applying clustering techniques like the K-means algorithm [5], time-based clustering [24] or density-based clustering [48] to a GPS-location trace. This trace comprises the locations of a target person which have been gathered for a certain period of time. However, these techniques need the whole trace to be available in advance. This requirement causes a lack of adaptability because the detected meaningful places depend on the GPS trace provided at the beginning and not on the current movements of the target person.

One of the goals of this PhD thesis was to go beyond the previous approaches and develop a new mechanism able to detect the meaningful places of the EgoV's itineraries in real time. As a result, a new density-based-clustering algorithm, named *landmark discovery algorithm*, has been implemented. This algorithm does not need a whole GPS database as input. On the contrary, it incrementally detects the EgoV's landmarks while it covers its daily itineraries. These landmarks are used as the elements to describe the location dimension of the EgoV's context afterwards.

The feasibility of the proposal was tested in both a simulated and a real-world environment. As for the simulated one, the road simulator SUMO [7] was used in order to simulate a set of itineraries of the EgoV in an urban environment. Furthermore, such simulator was linked to UbikSim so as to implement a simulator framework which covers a wide range of features of a vehicular environment. As for the real-world tests, the GPS traces gathered by an ongoing fleet-management project made by the research group of the PhD candidate were used. Finally, a description the algorithm, an explanation of how the landmarks are used for the location dimension and the experiments results are put forward in the paper of section 5.2.

Activity dimension

In the IvCA scope, the activity dimension has been described as the itinerary which the EgoV is currently covering. In that sense, a familiar vehicle usually has a set of itineraries that it covers on a regular basis in order to accomplish certain goals (commute, going shopping, taking the children to the school and the like). Fig. 4.4 depicts some examples of these frequent itineraries. In the itinerary 1, the drives commutes and takes his son to his school. In the itinerary 2, the driver goes to a close shopping mall after working. Lastly, the itinerary 3 shows that the driver goes back home stopping over in a relative's workplace. Apart from that, the occupancy of the vehicle can change along an itinerary. For example, the occupancy of the vehicle in the itinerary 3 changes from one person to two people when the vehicle arrives at the relative's workplace.

The present work states that an usual itinerary comprises an underlying structure which is repeated every time that itinerary is covered. In particular, an itinerary's structure is defined as a set of interconnected stretches as Fig. 4.4 shows. In that sense, a stretch is the part of an itinerary along which the vehicle's occupancy does not change. Consequently, this PhD thesis intends to detect the frequent itineraries of the EgoV along with their underlying structure as the activity dimension of the IvCA context. In order to achieve that, the maneuver-detection mechanism of the engine layer, the occupancy detection mechanism described above and the landmark discovery algorithm have been used. Finally, the article in section 5.2 states in detail the itinerary structure and the proposed

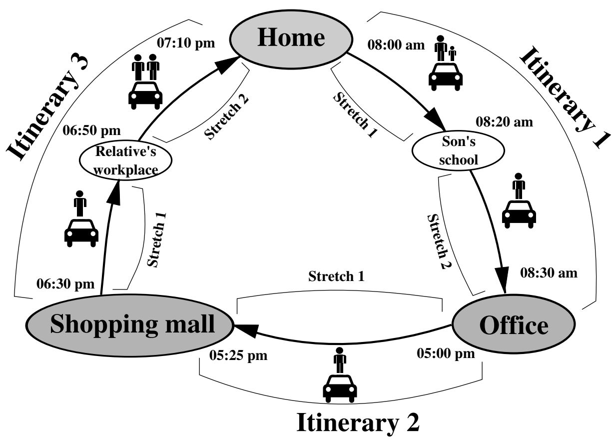

Figure 4.4: Three examples of itineraries a vehicle may cover on a regular basis.

mechanism to discover it. Furthermore, a mechanism to compare the underlying structure of two itineraries is also described. This way, once an itinerary has finished, it is possible to know whether it is a new one or just a repetition of a previous one by means of a comparative process.

Finally, as the paper in section 5.2 explains, the three contextual dimension perceived by the bodywork layer are orchestrated by means of the *Complex Event Processing* technology (CEP) [17]. For that purpose, the CEP-framework Esper has been used [16]. Thus, it would be possible to immediately inform a third-party service whenever it is perceived that any of these dimensions has just changed.

4.2.3. Traffic layer

In these days and age, traffic congestions are one of the most important problems motorists have to face with during their daily trips. They are not only rather inconvenient for drivers but also have a quite negative impact in terms of sustainability [36]. In this frame, the information about the current traffic congestions which may affect a vehicle along its way to a certain destination is extremely useful in order to plan the route to that destination. This is specially important for familiar vehicles as they are generally used to arrive at a destination as part of their daily routines. Therefore, the traffic layer is in charge of inferring the traffic congestions that might affect the EgoV as part of its contextual information. Since the information about the interesting traffic jams is related to the current location of the EgoV, this layer *augments* the location dimension perceived by the the engine and the bodywork layers with new information about the environment surrounding the EgoV.

The problem of detecting and monitoring traffic congestions along a road has been widely faced by the Traffic Information Systems (TISs) [38]. In that sense, we can find in the literature two main trends to develop this kind of systems. The former comprises the systems based on roadside equipment. These systems follow a centralized approach and rely on infrastructure sensors installed along a certain section of a road [10, 30, 43]. This allows to accurately monitor this road section, but the remain of the road, where there is not any installed sensor, are completely invisible for this type of systems. Hence, the second TIS trend focuses on a distributed paradigm and tries to sort out the scalability problems of the previous approach. In a distributed TIS, vehicles along a road collaborate among them by sharing information so as to detect certain activities of interest like traffic jams and, as a result, minimize their negative impact [27, 32, 37]. In this scope, the exchange of information among moving vehicles is usually achieved whereby a Vehicular Ad-Hoc Network (VANET) [20]. A VANET is compound of a set of vehicles driving along a road, and they send information to each other whereby wireless communication. Moreover, each vehicle in the network periodically broadcasts *beacon* messages. These messages include basic information about the sender vehicle like its current location and velocity.

One of the goals of the present PhD thesis was to develop a novel solution to discover traffic jams based on a cooperative approach. In that sense, this thesis rests on the hypothesis that the information included in the beacons of a VANET give insight into the traffic conditions of a road. Nonetheless, one of the mayor problems when it comes to process these messages is the fact that the number of them which has to be processed is considerably high under certain conditions.

In order to overcome this issue, the present PhD introduces a novel approach to deal with the beacons of a VANET by means CEP. The foundations of CEP state that certain real-world activities imply the generation of a set of events in the lowest layers of an information system (IS). As a result, those activities can be detected by monitoring pre-defined patterns in the event flow of the IS. Since this technology is centered on the events as the key computation elements of a system, it has been widely used in environments where many data sources generate a great number of events which should be steadily processed like banking [4] or RFID-based [21] systems. In that sense, it is possible to define a mapping between the three key elements of CEP (the real-world activities, the IS and the events) and the current scope. Thus, the IS is the VANET, the events are the beacon messages and the real-world activities are the traffic congestions.

Therefore, a novel line of research that proposes CEP-based solutions in the ITS field has been one of the most remarkable tasks of this PhD thesis. As a result, several publications which put forward event-based mechanisms to detect traffic problems by processing vehicular messages have been published [49,50]. Finally, the previous proposals have led to the development of the CEP-based solution included as part of this PhD thesis. This mechanism improves the previous solutions by sorting out certain scalability and accuracy problems. In order to implement it, the aforementioned Esper framework has been used. Specifically, the implemented Esper-based module takes as input the beacons of a VANET and gives insight into the traffic conditions of a road on the basis of those messages whereby a CEP approach. This way, it is able to detect different levels of traffic congestions with lane-level granularity. Moreover, it takes into account the current weather conditions whereby a fuzzy-logic tool to assess the importance of a detected traffic jam. In addition to that, it has been designed so that it can be used as an on-board equipment or as a system for a roadside management center. Besides, the developed mechanism sorts out some of the drawbacks of previous distributed TISs like the necessity of sending ad-hoc messages across the VANET (apart from the beacons) or the lack of accuracy when it comes to discover which part of a road is actually covered by a traffic jam.

In order to proof the suitability of the proposal, the VGSim tool has been applied [28]. VGSim is a vehicular network and mobility simulator which implements a whole communication stack. For the current scope, such simulator was modified so as to append the proposed CEP module as a third-party middleware. Next, several types of congestions were simulated by VGSim and the level perception of them achieved by the CEP mechanism was studied. Finally, the article in section 5.3 describes the design and implementation details of the system along with the results of the VGSim tests.

4.2.4. Technologies overview

A varied range of technologies and tools have been used so as to develop and test the three IvCA system's layers described above. As table 4.2 shows, the implementation and test tools applied in each layer can be short-listed in four categories, 1) Ad-hoc tools specifically developed to accomplish certain PhD thesis' goals (marked with the ∗ symbol in the table). 2) Inner proposals of the PhD candidate's research group (+ symbol). 3) Tools developed by external companies or research groups which were extended to fit certain extra features (‡ symbol). 4) Tools developed by external companies or research groups used with no modifications († symbol).

Regarding the implementation, the Esper framework has been the tool to develop the CEP approach in the bodywork and traffic layers. This framework was chosen because its *Continuous Query Language* is a powerful tool to implement CEP systems with quite advanced features. Furthermore, it is well integrated in Java which was the programming language used to implement the other features of the system, including the Fuzzy modelling API. Such API was the key tool to implement the fuzzy-modelling capabilities of the engine layer.

Layer	**Article**	**Technologies**	**Implementation tools**	**Test tools**
Engine	*An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles* (Section 5.1)	– Fuzzy modelling	– Fuzzy modelling API * – Java†	– Real-world data sets*
Bodywork	*A Complex Event Processing Approach to Perceive the Vehicular Context* (Section 5.2)	– CEP – Clustering – Pattern recognition	– Esper† – Java†	– SUMO‡ – UbikSim+ – J2EE† – Fleet-management GPS traces+ – Website for the family-vehicle survey*
Traffic	*A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET* (Section 5.3)	– CEP – Fuzzy logic	– Esper† – Java†	– VGSim‡

Table 4.2: Summary of the different technologies applied in the thesis. Symbols' meaning, ∗ tools specifically developed for the PhD thesis. + tools developed by the PhD candidate's research group. ‡ third-party tools modified to fit certain requirements. † third-party tools used with no modifications.

As far as the experiments are concerned, the collaboration with other proposals of the same research group of the PhD candidate was remarkable so as to achieve certain goals. For example, the adaptation of the research group's UbikSim to link it to the SUMO simulator so as to simulate a vehicular environment was a quite important task for the bodywork layer's tests. Such linkage was achieved whereby web services implemented with the Java-platform J2EE. Another example of usage of a research group's inner development were the GPS traces from the fleet-management project also applied to test the bodywork layer. Nevertheless, it is important to clarify that the full development of both UbikSim and the fleet-management project are out of the scope of the present work and, therefore, they may not be regarded as contributions of this PhD thesis.

4.2.5. Achieved level of contextual perception

To sum up, given the three IvCA layers, it is possible to perceive a varied range of elements of a vehicular context. For example, the top of the Fig. 4.5 shows a morning itinerary that a father may cover with his son every day. For this itinerary, the bottom of the figure depicts the dynamic context perceived by the three layers. Among other features, the achieved level of perception allows to detect the occupancy of the EgoV throughout the itinerary, along with its meaningful places (landmarks). This type of information is quite useful for third-party services that can make use of it in order to improve the occupants' comfort and safety. For instance, since the system is able to detect that there are two people in the EgoV and its destination is a school (labeled as *Landmark 2*) in the first section of the itinerary, a centralized service running on a mobility management center can use that information to suggest routes to the vehicles on the basis of their destination and occupancy. This way, the traffic flow can be diversify among different paths avoiding traffic congestions in a certain area of interest.

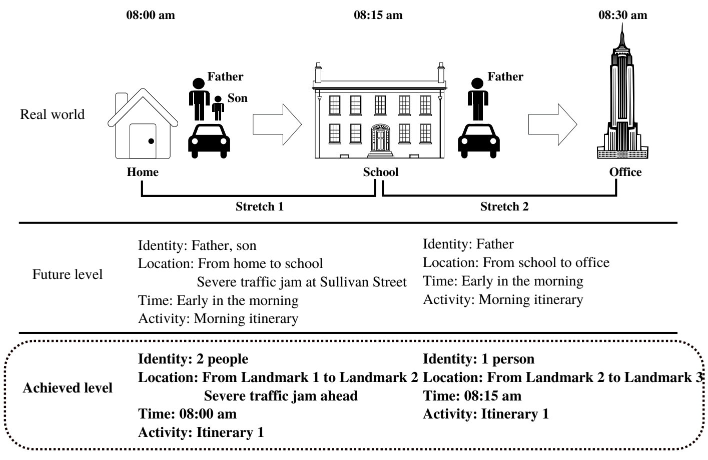

Figure 4.5: Example of an itinerary along with the achieved level of perception (in bold) and the intended one for a full-blown IvCA system.

Furthermore, the middle of Fig. 4.5 depicts the future context perception which will be achieved by a fully developed IvCA system. This system will enrich the four dynamic contextual dimensions by adding more details. Hence, the information about the landmarks will be improved whereby a location database service. This way, they will be named by means of more verbose labels instead of automatically-generated ones. Apart from that, the identity dimension can be also improved in order to specify a more accurate description of the occupants providing some kind of personal details. For that purpose, new sensors and data sources could be used such as RFID readers and body sensors. As a result, this fine-grained information will allow other applications and systems to offer more proactive and adaptable services to the occupants of the EgoV so that traveling by vehicle will be a more confortable experience.

Chapter 5

Publications composing the PhD Thesis

5.1. An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles

Title	An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles
Authors	Valdes-Vela, M. and Toledo-Moreo, R. and Terroso-Saenz, F. and Zamora-Izquierdo, M.A.
Type	Journal
Journal	Engineering Applications of Artificial Intelligence
Impact factor (2011)	1.665
Publisher	Elsevier
Pages	173-183
Year	2013
Month	January
ISSN	0952-1976
DOI	`http://dx.doi.org/10.1016/j.engappai.2012.02.018`
URL	`http://www.sciencedirect.com/science/article/pii/S0952197612000553`
State	Published

Journal details: Engineering Applications of Artificial Intelligence
Editor-in-Chief: Bernard Grabot
ISSN: 0952-1976
Publisher: Elsevier
Impact factor (2011): 1.665
Website: `http://www.journals.elsevier.com/engineering-applications-of-artificial-intelligence`

Authors – Personal details	
Name	**Dr. Mercedes Valdés Vela**
Position	Lecturer of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Rafael Toledo Moreo**
Position	Lecturer of the Department of Electronics, Computer Technology and Projects
University/ Organization	Technical University of Cartagena
Name	**Fernando Terroso Sáenz**
Position	PhD student of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Miguel Ángel Zamora Izquierdo**
Position	Lecturer of the Department of Information and Communications Engineering
University/ Organization	University of Murcia

Contribution of the PhD student
The PhD student, Fernando Terroso Sáenz, declares to be the main author and the major contributor of the paper *An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles*

Abstract

Road traffic collisions are an outstanding problem in current developed societies. This paper presents a solution to support collision avoidance based on the timely detection of the vehicle maneuvers. Since the longitudinal interaction among vehicles, with the commonly known car-following behavior, is one of the most important causes of crashes, it was decided to focus on longitudinal maneuvers, identifying the maneuvering states of cruise, accelerating or decelerating and stop. The classification is carried out by means of fuzzy rules extracted from navigational data. Therefore, in our proposal no extra sensors are needed apart from two commonly installed for navigation purposes: the odometry of the vehicle and an accelerometer. The system was tested with low-cost sensors showing good results when compared to the literature of the field.

5.2. A Complex Event Processing Approach to Perceive the Vehicular Context

Title	A Complex Event Processing Approach to Perceive the Vehicular Context
Authors	Terroso-Saenz, F. and Valdes-Vela, M. and Campuzano F. and Botia J.A. and Skarmeta-Gomez A.F.
Type	Journal
Journal	Information Fusion
Impact factor (2011)	1.467
Publisher	Elsevier
Year	2013
ISSN	1566-2535
DOI	`http://dx.doi.org/10.1016/j.inffus.2012.08.008`
URL	`http://www.sciencedirect.com/science/article/pii/S1566253512000723`
State	In Press

Journal details: Information fusion
Editor-in-Chief: Belur V. Dasarathy
ISSN: 1566-2535
Publisher: Elsevier
Impact factor (2011): 1.467
Website: `http://www.journals.elsevier.com/information-fusion`

Authors – Personal details	
Name	**Fernando Terroso Sáenz**
Position	PhD student of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Mercedes Valdés Vela**
Position	Lecturer of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Francisco José Campuzano Adán**
Position	PhD student of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Juan Antonio Botía Blaya**
Position	Lecturer of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Antonio Fernando Skarmeta Gómez**
Position	Professor of the Department of Information and Communications Engineering
University/ Organization	University of Murcia

Contribution of the PhD student
The PhD student, Fernando Terroso Sáenz, declares to be the main author and the major contributor of the paper *A Complex Event Processing Approach to Perceive the Vehicular Context*

Abstract

Nowadays, most people are used to driving their own vehicles to accomplish certain routines like com- muting, go shopping, and the like. Taking into account the increasing number of sensors vehicles are pro- vided with, the present work states that it is possible to perceive the context of a vehicle by processing and fusioning the data of some of them. As a result, an on-board context-aware application that processes the usual itineraries of the Ego Vehicle as part of the vehicular context has been implemented. Particu- larly, the system follows a Complex Event Processing (CEP) approach, and it is able to detect the vehicular occupancy along with the meaningful points of the frequent itineraries whereby a density-based-cluster algorithm. Test results from simulations and real environments show

the accuracy of the system when it comes to detect different types of itineraries.

5.3. A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET

Title	A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET
Authors	Terroso-Saenz, F. and Valdes-Vela, M. and Sotomayor-Martínez C. and Toledo-Moreo, R. and Skarmeta-Gomez A.F.
Type	Journal
Journal	IEEE Transactions on Intelligent Transportation Systems
Impact factor (2011)	3.452
Publisher	IEEE Intelligent Transportation Systems Society
Pages	914 - 929
Year	2012
Month	June
ISSN	1524-9050
DOI	`http://dx.doi.org/10.1109/TITS.2012.2186127`
URL	`http://www.sciencedirect.com/science/article/pii/S0952197612000553`
State	Published

Journal details: IEEE Transactions on Intelligent Transportation Systems
Editor-in-Chief: Fei-Yue Wang
ISSN: 1524-9050
Publisher: IEEE Intelligent Transportation Systems Society
Impact factor (2011): 3.452
Website: `http://ieeexplore.ieee.org/servlet/opac?punumber=6979`

Authors – Personal details	
Name	**Fernando Terroso Sáenz**
Position	PhD student of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Mercedes Valdés Vela**
Position	Lecturer of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Cristina Sotomayor Martínez**
Position	PhD student of the Department of Information and Communications Engineering
University/ Organization	University of Murcia
Name	**Dr. Rafael Toledo Moreo**
Position	Lecturer of the Department of Electronics, Computer Technology and Projects
University/ Organization	Technical University of Cartagena
Name	**Dr. Antonio Fernando Skarmeta Gómez**
Position	Professor of the Department of Information and Communications Engineering
University/ Organization	University of Murcia

Contribution of the PhD student
The PhD student, Fernando Terroso Sáenz, declares to be the main author and the major contributor of the paper *A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET*

Abstract

Currently, distributed traffic information systems have come up as one of the most important approaches for detect- ing traffic flow problems on a road. For that purpose, they usually make use of the location information that vehicles share among them through periodical messages that are transmitted across a vehicular ad hoc network (VANET). This paper puts forward an event-driven architecture (EDA) as a novel mechanism to get insight into VANET messages to detect different levels of traffic jams; furthermore, it also takes into account environmental data that come from external data sources, such as weather conditions. The proposed EDA has been developed through

the complex-even- t-processing technology. Simulation tests show that the proposed mechanism can detect traffic congestions, which involve different numbers of lanes and lengths with short delay.

Chapter 6

Acceptance letters

A Complex Event Processing Approach to Perceive the Vehicular Context

De: "Information Fusion" <belur.d@gmail.com>
Asunto: **IF12T01-CBFR1 Your Submission**
Fecha: 30 de agosto de 2012 17:47:56 GMT+02:00
Para: fterroso@um.es
Cc: jesus.garcia@uc3m.es, belur.d@gmail.com

Ms. Ref. No.: IF12T01-CBFR1
Title: A Complex Event Processing Approach to Perceive the Vehicular Context
Information Fusion

Dear Mr. Fernando Terroso-Saenz,

I am pleased to confirm that your paper "A Complex Event Processing Approach to Perceive the Vehicular Context" has been accepted for publication in Information Fusion.

Comments from the Editor and Reviewers can be found below.

Thank you for submitting your work to this journal.

"Note: You will be getting the proofs of your m/s for your checking and approval shortly. Please make sure that your (corresponding author) email address on line is still valid and current since the proofs will be sent via Email to the address on record. Delays in returning the proofs may result in rescheduling of its publication to a later issue."

With kind regards,

Dr. Belur V. Dasarathy, IEEE Fellow

Editor-in-Chief, Information Fusion Journal
IT consultant - http://belur.no-ip.com

Figure 6.1: Acceptance letter from Information Fusion

Full reference:

F. Terroso-Saenz, M. Valdes-Vela, F. Campuzano, J.A. Botia, and A. F. Skarmeta-Gomez. *A complex event processing approach to perceive the vehicular context.* Information Fusion, 2012. In-press. Impact factor (2011): 1.467.

Chapter 7

Publications relevance

An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles

The article entitled 'An Application of a Fuzzy Classifier Extracted from Data for Collision Avoidance Support in Road Vehicles' has been accepted in the journal of *Engineering Applications of Artificial Intelligence*, whose relevance and impact factor can be observed next,

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Journal Ranking

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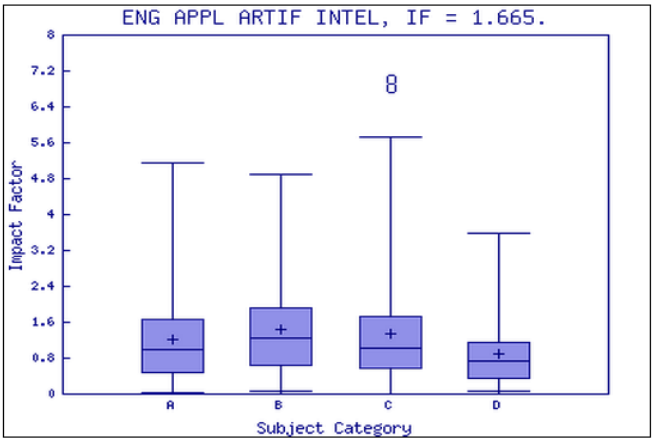
This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
AUTOMATION & CONTROL SYSTEMS	58	15	Q2
COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE	111	34	Q2
ENGINEERING, ELECTRICAL & ELECTRONIC	245	65	Q2
ENGINEERING, MULTIDISCIPLINARY	90	10	Q1

Category Box Plot

For **2011**, the journal **ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENC...** has an Impact Factor of **1.665**.

This is a box plot of the subject category or categories to which the journal has been assigned. It provides information about the distribution of journals based on Impact Factor values. It shows median, 25th and 75th percentiles, and the extreme values of the distribution.



Key

A - AUTOMATION & CONTROL SYSTEMS
B - COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE
C - ENGINEERING, ELECTRICAL & ELECTRONIC
D - ENGINEERING, MULTIDISCIPLINARY

A Complex Event Processing Approach to Perceive the Vehicular Context

The article entitled 'A Complex Event Processing Approach to Perceive the Vehicular Context' has been accepted in the journal of *Information Fusion*, whose relevance and impact factor can be observed next,

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Journal Ranking

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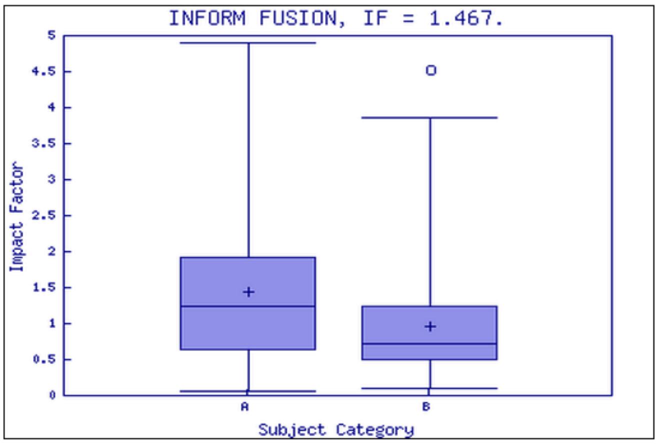
This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE	111	45	Q2
COMPUTER SCIENCE, THEORY & METHODS	99	16	Q1

Category Box Plot

For **2011**, the journal **Information Fusion** has an Impact Factor of **1.467**.

This is a box plot of the subject category or categories to which the journal has been assigned. It provides information about the distribution of journals based on Impact Factor values. It shows median, 25th and 75th percentiles, and the extreme values of the distribution.



Key

A - COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE

B - COMPUTER SCIENCE, THEORY & METHODS

A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET

The article entitled ‘A Cooperative Approach to Traffic Congestion Detection With Complex Event Processing and VANET’ has been accepted in the journal of *IEEE Transactions on Intelligent Transportation Systems*, whose relevance and impact factor can be observed next,

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Rank in Category: IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SY...

Journal Ranking

For **2011**, the journal **IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SY...** has an Impact Factor of **3.452**.

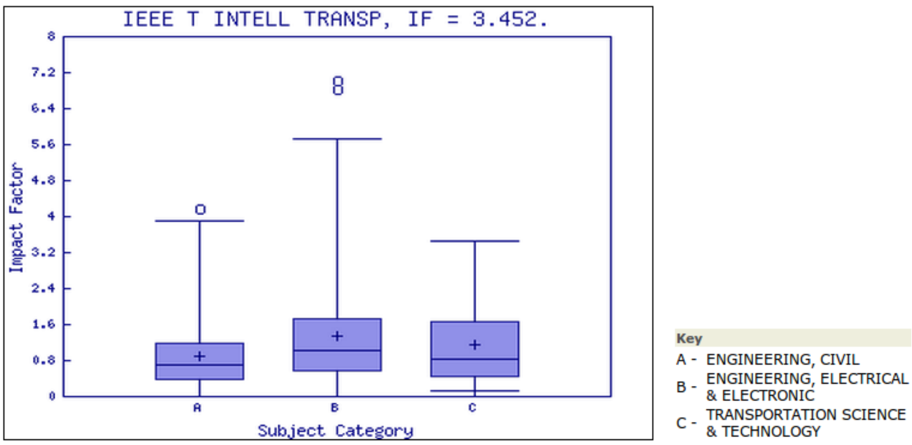
This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, CIVIL	118	2	Q1
ENGINEERING, ELECTRICAL & ELECTRONIC	245	13	Q1
TRANSPORTATION SCIENCE & TECHNOLOGY	28	1	Q1

Category Box Plot

For **2011**, the journal **IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SY...** has an Impact Factor of **3.452**.

This is a box plot of the subject category or categories to which the journal has been assigned. It provides information about the distribution of journals based on Impact Factor values. It shows median, 25th and 75th percentiles, and the extreme values of the distribution.



Chapter 8

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